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Current Velocity Impacts from Interaction of Semidiurnal and Diurnal Tidal Constituents for Tidal Stream Energy in East Flores

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Abstract. The combination of the Semidiurnal and Diurnal Tidal Constituents results in a variability of tidal range and current speed through the months of the year. Tidal stream predicted from astronomical harmonic constituents and also tidal stream is a current that its speed can be optimized as renewable energy. Constituent Semidiurnal components have huge impact on the forming of tidal stream phase. Lantuka Strait is one of the highest current velocities in indonesia waters. This study uses the method of calculating the mean least squares analysis, with the approach of the vector of the current component to the tidal harmonic constituent. Tidal velocities exceeds 3 m/s in this area, this value is very potential. The results of current and tide analysis at this area showed strong interaction. 0.73 at Formzahl value shows mixed tide type, prevailing semidiurnal. Constituent values which dominate in the forming of strong current are M_2 with value of 2.22 m/s, and another semi diurnal contituent, S_2 value at current vector is 1.11 m/s. The linkages between current velocity with tide shows advantage in the production of available maximum power in a day will varies on each tide type. An asymmetric pattern of both tidal elevation and tidal velocity can be observed during each day.

1. Introduction

East Flores Waters is an area with the dominance of narrow strait morphology. This location is very suitable to be developed as renewable energy sources [1], such as tidal range [2] and tidal stream [3]. Lantuka Strait is one of optimal strait can be optimized to converted potential tidal stream. Recent study result this area is very potential area with current velocity exceeding 3 m/s [4], another study result Lantuka Strait have tidal range almost 3 meters on spring phase [2]. There are two forms that are carried out in utilizing tidal energy, tidal range and tidal stream [5]. Tidal current energy is the most favorable renewable energy source according to the physical oceanography characteristics in East Flores Waters especially.

Tidal power was one of form of renewable energy to be used by human life [6]. Hydrokinetic resources from tide involves extracting power from moving tidal stream by fast to generate electricity. Fluid driven by tidal has a great advantage in hydrokinetic energy sources, considering that sea water has a density of 800x greater than that of wind [7].



As we know, tides are driven by the gravitational interaction of the moon (lunar) and sun (solar), and the tide causes a gradient to the water level, then the mass of waters are move, hereinafter referred to as tidal currents. Basically tidal currents can be predicted, because they have periodic harmonic constituents. The combination of the semidiurnal and diurnal tidal constituents result in a variability of tidal range and current speed through months of the year. There are dozens of other harmonic forcing constituents (components) of tide, each with a different period and amplitude [7]. In most areas in the strait morphology the semidiurnal constituents play dominant role. Previous studies describe from one of strait at East Flores Waters, Molo strait result this area has rapid change of M_2 amplitude and phase difference from java-banda sea to Indian Ocean [4]. Others similar dominant, Mansuar strait result the strong current is produced by amplitude and phase difference of the M_2 constituents, meanwhile diurnal constituent only has phase lag with small amplitude change [8]. A significant diurnal component results in different type of tidal cycles. Sites with dominant S_2 and M_2 tides show a simple pattern of two tidal cycles in a day. Areas dominated by K_1 and O_1 components have one cycle a day.[4]

As previously studies Godin, 1991 [9] [10], asymmetry in current velocity may derive from three sources; density-driven circulation, the local influence of bathymetry and topography, and non-linear interactions between tidal constituents. In harmonic analyses, this asymmetry aliases energy in the primary tidal constituents to higher frequencies (e.g., M_2 aliased to shallow water constituents M_4 , M_6 , etc.). In term of power production these harmonic analyses needed to develop how interaction harmonic constituents with strong current appearance. Advantages from this analyses is tidal current can be predicted, in some case it can be modified by wind stress acting for extended periods.

2. Research Methods

2.1. Scope

The scope of this study was to analyse harmonic components from interaction of semidiurnal and diurnal tidal constituents (M_2 , S_2 , K_1 , O_1) that possibly worked and have an impact on current velocity in East Flores waters. Data collection was carried out at the sample area, Larantuka Strait as a representation of the waters in the East Flores region. Depth averaged layers are used to analyze, tidal currents velocity that are reduced to a single dimension by neglecting vertical velocities.

2.2. Data Collection

The ADCP measurement used in this study have been obtained from instrument sea-bed mounted at Larantuka Strait, East Flores Waters. The acoustic instrument has been ran a 75kHz ADCP between October 30th, 2017 until November 13th, 2017 during 15 days (neap-spring cycle). The ADCP locations on UTM projections are 51, E 502571 N 9080955 are shown figure 1.

The ADCP-Instruments transmit sounds, commonly referred to as pings, of known frequency along three beams into water column. The ocean velocity in three dimensions are relative to the instruments [11]. The ADCP dataset use here consist 10 minutes and some 60 minutes ensembles, vertically the ADCP data are separated into 2 meters bins at 10 layers, but in this study we used depth averaged layer to determine current velocity impacts from interaction of semidiurnal and diurnal tidal constituents for tidal stream energy at site study, Configurations shown in table 1.

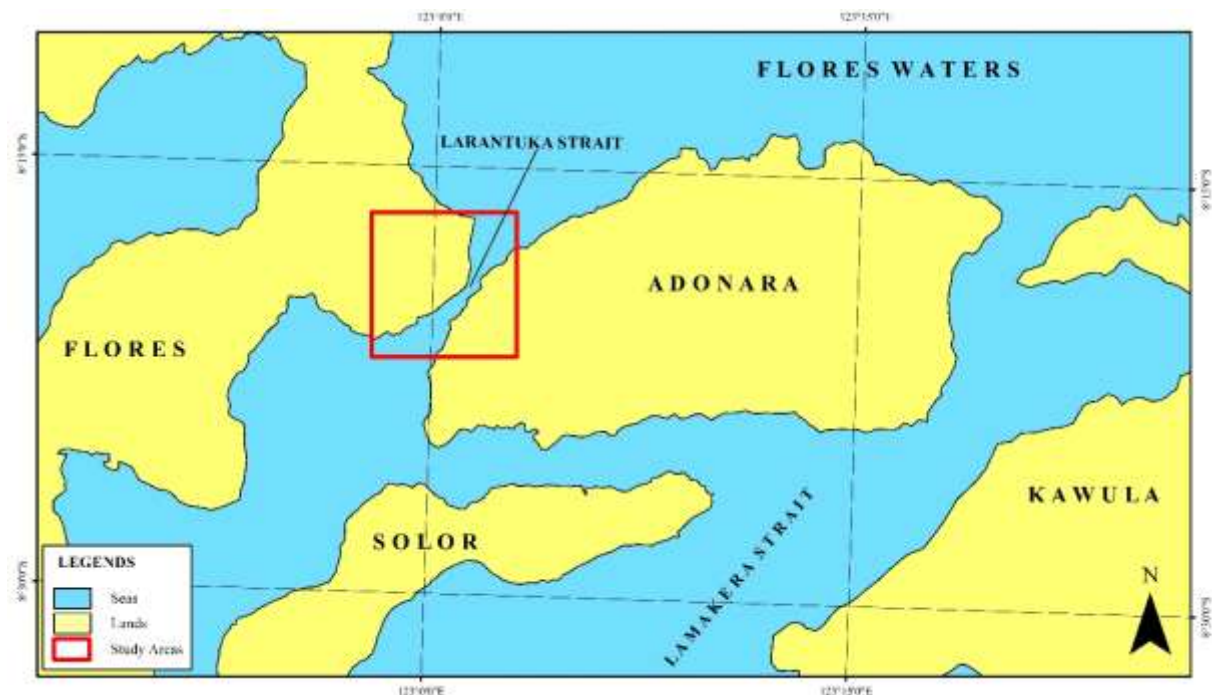


Figure 1. Study area East Flores, Larantuka Strait, between Flores and Adonara (red square). ADCP location of the ADCP recording placement area.

Tabel 1. Configurations of ADCP deployments in Larantuka Strait shown figure 1, East Flores Waters. The ADCP configuration used for these measurements is not appropriate to quantify turbulence, but a representative current trace over several days highlights its significance.

Configuration	Stasion measurement set
Deployments dates	30/10 – 13/11 2017
Durations (days)	15
Deployment depth (m)	25 meters
Vertical bin size (m)	2 meters
Layers (m)	10 layers
Ensamble interval (s)	600 s – 3600 s
Blank distance (m)	0.8 meters

2.3. Tidal Current Harmonic Analysis

Tidal current harmonic analysis are performed by MIKE 21 analyst [12]. The tidal current harmonic analysis is based on a least-squares fit of the current velocity observations that is specified at a set of m/s points. The analysis is strengthened by utilising known relationship tidal constituents found at a neighbouring reference site [13]. The least squares has similarities of analyze to Fourier analysis with linear regression, but is preferable because tidal frequencies are not integer multiples of a fundamental frequency (as is required for Fourier analysis) [10]. Measured currents are ensemble averaged over a 10 minute interval prior to harmonic analysis to smooth turbulent fluctuations. The least square method is a tidal calculation method by ignoring meteorological factors, this method essentially allow for determination of harmonic constituent factors dominant driven tidal current at site of study. As previously on section 2, tidal current streams direction in favor of speed (ebb signed negative, flood signed positive). The equations used in this method are as follows:

$$ht_i = S_0 + \sum_1^n H_n \cos[\omega_n t_1 + g_n] \quad (1)$$

$$ht_i = S_0 + \sum_1^n H_n [\cos(\omega_n t_1) \cos(g_n) - \sin(\omega_n t_1) \sin(g_n)] \quad (2)$$

$$ht_i = S_0 + \sum_1^n A_n \cos(\omega_n t_1) - \sum_1^n B_n \sin(\omega_n t_1) \quad (3)$$

$$H_n = \sqrt{A_n^2 + B_n^2} \quad (4)$$

$$g_n = \arctg \left(\frac{B_n}{A_n} \right) \quad (5)$$

Where $A_n = H_n \cos(g_n)$ and $B_n = H_n \sin(g_n)$ at set of meter poin; ht_i is elevation of current velocity - i ; H_n are amplitude component; ω is the frequency of a given constituent; t_1 are periode component, g_n is phase of component; and S_0 is still water level at set meter point. The tidal constituents that have been extracted, three category of principal constituents, are listed in Table 2 along with their respective period and frequency. Constituents are included in order of influence, as determined by equilibrium tide theory [14], a least-squares equation of the form given in equation (1) is used to characterize the harmonic currents velocity components.

Table 2. Tidal harmonic constituents used in the harmonic analysis, period given in hours, and frequency cycle per day.

Name of constituents	Symbol	Period (hr)	Frequency
Diurnal			
Lunar-solar	K ₁	23.9345	1.0027
Principal lunar	O ₁	25.8193	0.9295
Semidiurnal			
Smaller lunar elliptic	L ₂	12.1916	1.9686
Principal lunar	M ₂	12.4206	1.92323
Larger lunar elliptic	N ₂	12.6583	1.8960
Principal lunar	S ₂	12.00	2.00
Higher harmonics			
Shallow waters overtides of principal lunar	M ₄	6.2103	3.8645
	M ₆	4.1402	5.7968
	M ₈	3.1052	7.7291

Current harmonic hodograph is the ellipse parameters [11] are applied for semi-major and semi-minor axes of current harmonic, ellipse inclination, and greenwich phase lag. A simple illustration of the ellipse parameters is shown in Figure 2. The major and minor axes represent maximum and minimum current speeds of the given tidal harmonics, the inclination is the counterclockwise angle between the east direction and the major axis.

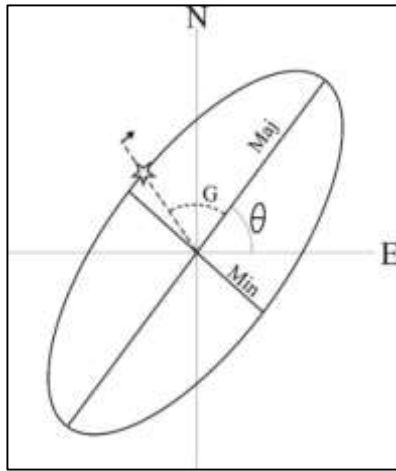


Figure 2. Illustration of a rotating tidal current ellipse and parameters. Maj is the Major axis and Min is the Minor axis. The counter clockwise angle between East and the northern major axis, is the inclination of the ellipse. The star marks where in the ellipse cycle the current is at the time of the maximum equilibrium tide at the Greenwich Meridian. [11]

A the Formzahl number is used to analyze the tidal type. The amplitude of the principal diurnal and semidiurnal constituents (lunar and solar) are compared by this number. It is expressed as [4]:

$$F = \frac{AK_1 + AO_1}{AM_2 + AS_2} \quad (6)$$

where, AK_1 and AO_1 are the amplitudes of lunar diurnal tides and AM_2 and AS_2 are the amplitudes of principal lunar and solar semidiurnal. A Formzahl number $F \leq 0.25$ indicates two tidal cycles per day, and $F > 3$ indicates a single cycle per day. Formzahl number in between create mixed tides. For $0.25 < F \leq 1$ the mix is principally semidiurnal, partly diurnal, whilst for $1 < F \leq 3$ the mix is principally diurnal, partly semidiurnal. However, complex interactions between the components can occur[4].

2.4. Power Density Analysis

The instantaneous power density of a flowing fluid incident on a tidal current turbine is given by equations following as [6]:

$$P = \frac{1}{2} \rho A V^3 \quad (7)$$

Where P is kinetic power energy of tidal stream, A are the efficiency and the area in direction of stream of the turbine, respectively, and ρ is the density of salt-water (1025 kg/m^3), and V is the current speed (m/s), by convention, kinetic power density is expressed in units of kW/m^2 , mean kinetic power density and ebb/flood asymmetry are calculated similarly to currents.

3. Results and Discussion

3.1. Tidal current analysis of velocity components

Tidal current velocity analysis on the 15-days measurements deployed at averaged dept are presented in Fig 3 and showing significant variations in time series function the site area. Over multiple fortnightly cycles shown in figure 3 harmonic features are apparent, such as the neap-spring modulation and the diurnal inequality typical of a mixed, mainly semidiurnal tidal regime. This case happen to both velocity of current component (u -component and v -component).

In figure 3 show result from the analyzed least-square, we can see non-harmonic features emerge (green line). The result shows the harmonic feature are dominant to generate current component at both velocity, residual currents (green line) are only a small portion of the contribution has an impact on the emergence of the current, the residual given as negative or positive value to each current velocity (u or v velocity). Figure 3 indicated that v -velocity of currents are main current direction which shows the character pattern at the time of measurement, exceed 3 m/s . Meanwhile, u -velocity component shows similar condition, where harmonic components are dominant to current measurement appearance. U -velocity component have lower capacity of tidal velocity then v -velocity

with 0.8 m/s at the spring phase, it shows that current pattern is not capable, at the previously section has been explained non-harmonic features emerge caused density, local influence (bathymetry/morphology), and non-linear interactions [9][10].

Figure 3 top panels, shows v -velocity the dominant of harmonic features about 81.67%, and non-harmonic component emerge around 18.3%. u -velocity the dominant of harmonic features emerge about 86.2%, and non-harmonic component emerge around 13.8% from total current measurement at time series function.

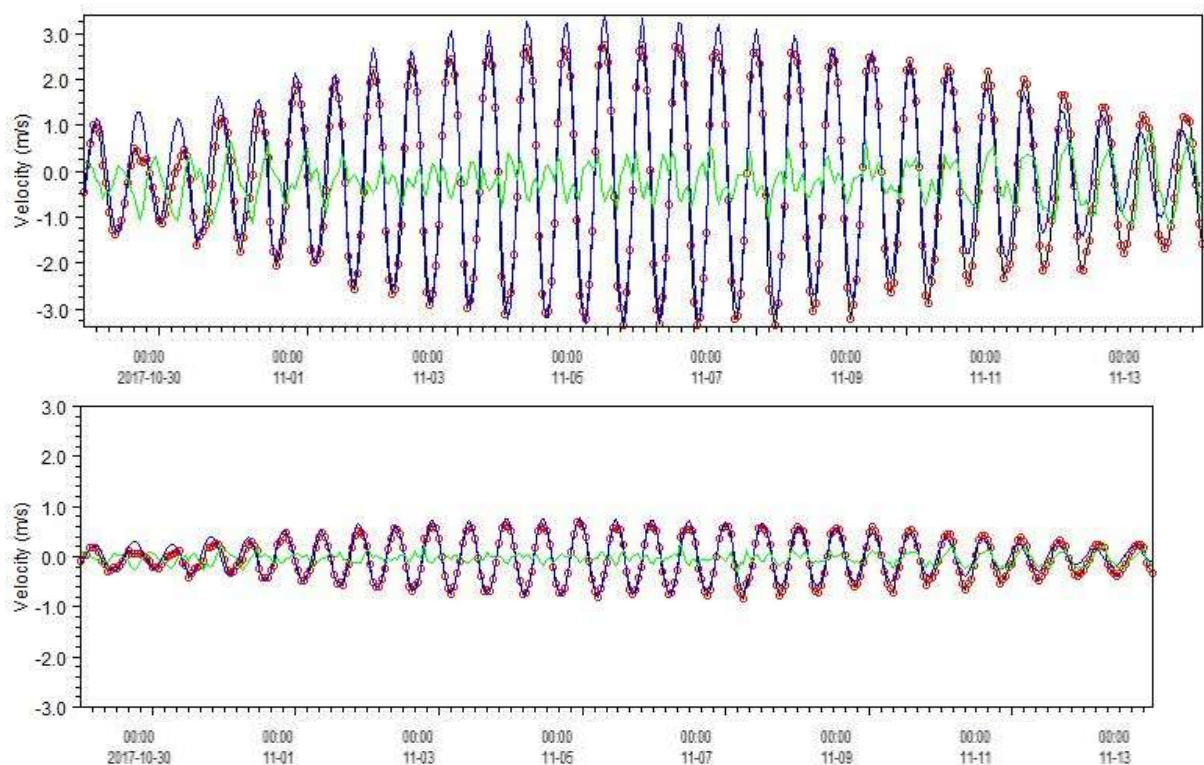


Figure 3. Tidal current analysis is applied to component v -velocity (top panel) and component u -velocity (bottom panel) to see the harmonic features and non-harmonic features emerge to generate current total at time series function. Red line shows tidal current, green line shows residual current curve and blue line shows observational current.

Tidal current have linkage to tide level change, tidal current are produced by the large quantities of water moving toward or away from site as the tide change. Figure 4 shows the elevation of tidal range and currents velocity are compared at time series function each velocity component (v and u velocity). The figure 4 shows elevation of tide have the mixed principally semidiurnal by type, is characterized by two tidal cycle a day with two high tides and two low tides are unequal in height. V -velocity from figure 4 (top panel) explained during flood tide, when the water level is rising between peak low and high tides, the tidal current flows toward shore. During an ebb tide, when that water level is falling between high and low tides, the tidal current moves from north to east of Larantuka Strait. The greatest tidal currents occur midway between high and low tide.

Analyzed results are a slack tide is when there is no current. slack tides occur near peak high and peak low tide when the flow of water is changing direction. Figure 4 v -velocity at the top panels shows that slack time occur at the peak level of ebb -1.40 m the v -velocity level shows no current with 0.096 m/s . Similar condition shows at u -velocity slack time occur at peak level of tide ebb show current with 0.056 m/s . as theoretically this condition occur cause tidal generator force, in this condition equilibrium occurs so that no momentum transfer occurs, which results in the absence of a period of moving water.

Other analyzed shows that current emerge when tidal level at near 0, as example from site measurement shown at *v-velocity* graphs (figure 4) maximum value -3.41 m/s and water level -0.013 m , from *u-velocity* maximum value of current is 0.845 m/s at water level -0.013 m . Moving waters toward and away through strait are usually the strongest current, in addition strait morphology and bathimetri have influenced occur moving current by strong.

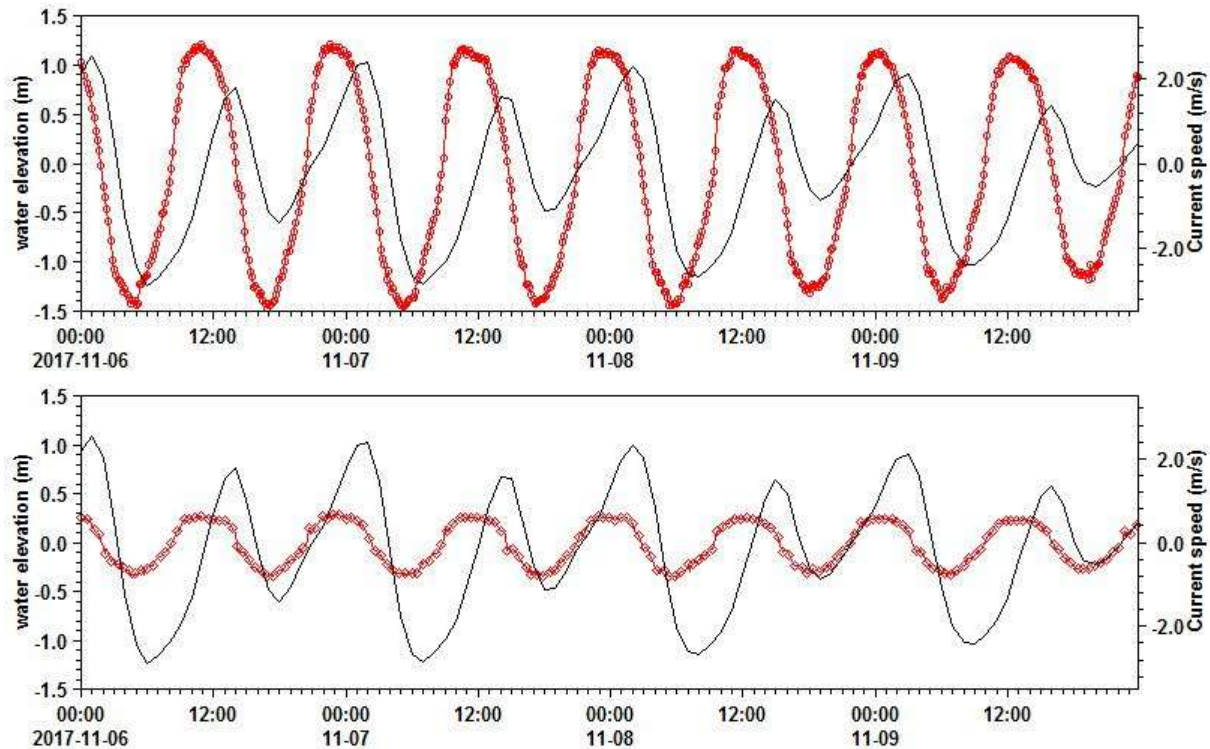


Figure 4. Comparison between tide level (black line) and current velocity (red dot) at component *v* (top panels) and component *u* (bottom panels).

3.2. Tidal curen analysis of harmonic components

Least-square analyzed for tidal level measured by ADCP result show at figure 5. Figure 5 show type of tidal is mix is principally semidiurnal, with formzhal value is 0.73. In a mixed tidal cycle the tides also occur twice daily, but the two high tides and two low tides are unequal in height (figure 5.). It mean tidal velocity with strong current emerge twice at ebb current, and twice at flood current, and slack water condition emerge each peak condition, ebb or flood condition.

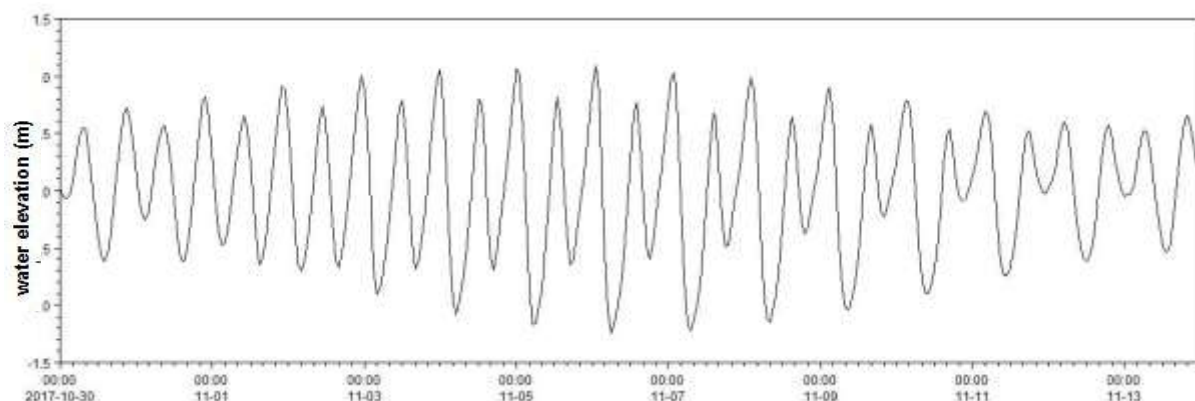


Figure 5. Tidal level from ADCP recorded at Larantuka Strait, East Flores Waters

Figure 6 describe the two major semidiurnal an two major diurnal tidal constituents from our least-square analyzed of the measurement data recorded. M_2 as principal lunar semi-diurnal tidal constituents, as the dominant constituent. Maximum M_2 value tidal current speeds are 2.22 m/s show at figure 7 top panels its about 63.3% from total speed probability, and has overall average 1.1 m/s. The ellipses are generally elongated with the major axes oriented approximately meridionally of our measurement site.

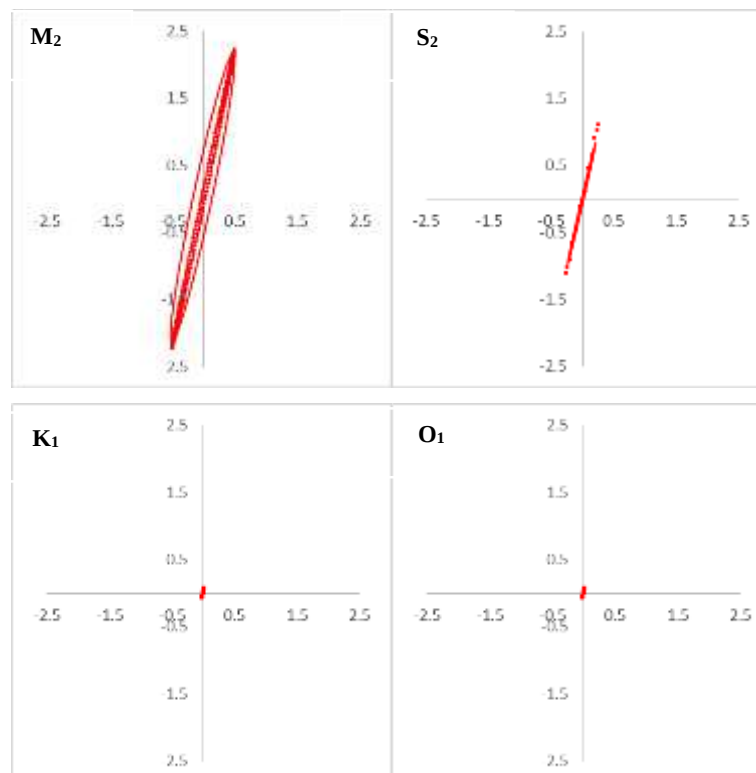


Figure 6. Tidal ellipses of the main semi-diurnal constituents M_2 (left top panels), and S_2 (right top panels), and the main diurnal constituents K_1 (left bottom panels), and O_1 (right bottom panels). Ellipse parameters are calculated from current measured by ADCP.

The M_2 harmonic component from tabel 3 shown have major axis 2.21 m/s and M_2 minor axis is primarily negative and most ellipses therefore rotate clockwise, with value is -0.028 m/s. This component also where we find influence harmonic the strongest tidal current. the inclination about this harmonic component can describe water moving directional, M_2 inclination is 77.3° with the counterclockwise angle between East and the northern semi-major axis. The phase of the maximum tidal current of the M_2 in around site measurement Strait Larantuka, East Flores Waters is 13.2°, as generally this current direction to the northeast, we conclude from figure 7 top panels, v -velocity is predominant current velocity then u -velocity, see figure 7 bottom panels.

The second most dominant harmonic component is S_2 , the principal Solar semi-diurnal tide. Overall, the maximum S_2 tidal current speeds at the positions of the ellipses in Figure 6 are approximately half speed of the maximum M_2 current speeds. These condition also describe at figure 7 all panels showed by blue line curve. Accordingly, the greatest S_2 tidal current speeds are 1.11 m/s or 31.6% from total current measurement. The major axis of the S_2 ellipses are oriented more or less meridionally. The phase of the S_2 tidal current is quite variable, revealing no clear propagating pattern compared to that we see in the phase of the M_2 tidal current [9], with phase 335.9°, semi-major axis from S_2 components is given 1.15 m/s and minor axis is -0.018 m/s. Inclination for S_2 harmonic component from least-square is 76.9°.

The two main diurnal tidal constituents K_1 and O_1 on average, both have their respective maximum speeds (see figure 7, top panels) that are 0.124 m/s (2.85% from total current measurement) and 0.07 m/s (1.99% from total current measurement). The orientation / inclination of degree of the ellipses of the diurnal constituents is quite similar with semi-diurnal constituents, that are 75° for K_1 and 76.1° for O_1 constituents. The two main diurnal tidal constituents K_1 and O_1 have major axes that are 0.127 m/s and 0.091 m/s , and minor axes are -0.003 m/s and 0.004 m/s . Overall maximum current speed for M_4 , M_6 and M_8 are approximately 0.021 m/s , 0.100 m/s and 0.032 m/s this value is lower than the magnitude of M_2 , respectively.

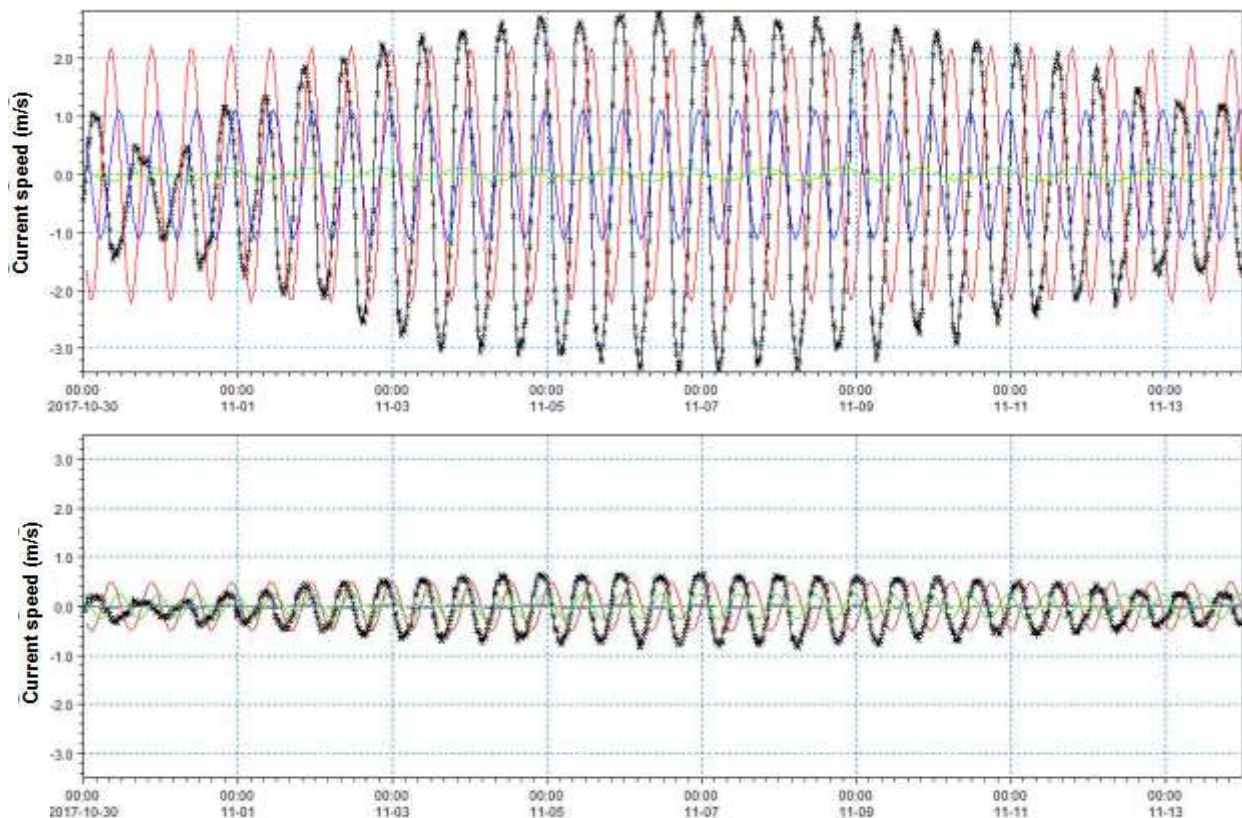


Figure 7. Comparison between 4 tidal constituent semi-diurnal and diurnal predominant for velocity of current measurement, v -velocity describe top panels, u -velocity describe bottom panels. M_2 (red line), S_2 (blue line), K_1 (green line), O_1 (orange line)

Tabel 3. Ellipse parameters harmonic constituents calculated from measurement analyze used Least-square method. Measurement depth is 25 meter below surface water, semi-major and semi-minor axes are listed in m/s , inclination is listed in $^\circ$ counter clockwise from east, phase lag listed in $^\circ$.

Name	Major (m/s)	Minor (m/s)	Inclination ($^\circ$)	Phase($^\circ$)
Z_0	0.215	0	79.2	180
MSF	0.031	0.006	64.5	310.8
Diurnal Constituents				
O_1	0.091	0.004	76.1	227.5
K_1	0.127	-0.003	75	255
Semi-diurnal Constituents				
M_2	2.21	-0.028	77.3	13.2
S_2	1.15	-0.018	76.9	335.9
Shallow Water Constituents	0.032	-0.004	77.9	105.6

M ₃				
SK ₃	0.047	0.005	83.9	35
M ₄	0.023	-0.002	49.7	163.2
MS ₄	0.043	-0.013	77.7	73.7
S ₄	0.034	0.001	78.2	182.8
2MK ₅	0.009	-0.003	108.9	127.9
2SK ₅	0.018	-0.005	82	270
M ₆	0.1	0.002	81	248.6
2MS ₆	0.141	0.004	81.7	217.2
2SM ₆	0.079	-0.002	79	146.2
3MK ₇	0.012	0.002	58.2	115.9
M ₈	0.032	-0.004	74.4	191.5

3.3. Power Density

Figure 8 shows kinetic power density from conversion measurements result by equation 7 (smoothed to remove the effect of residual or non-harmonic constituents), the harmonic generate from 4 tidal constituents are dominant, and residual between harmonic constituent and measurements for kinetic power density. The reason for use of a reduced number of tidal constituents (on this case we provide from 4 constituents M₂, S₂, K₁, O₁) use principally to simplify interpretation of data, also this constituents are semi-diurnal and diurnal predominant generate velocity with strongest current.

Harmonic from 4 tidal constituents predominant are describes the major features of kinetic power density, there are no residuals of up to 1 kW/m², maximum kinetic power density from residual appearance is 0.876 kW/m² throughout the tidal cycle. This condition occur caused these residuals have little effect on operational metrics, as shown in the first column of Table 3. Figure 8 is describe peak flood and ebb currents have maximum average kinetic power density are also well-described. Spring condition have maximum kinetic power density with 21.7 kW/m² from measurement conversion, 21.2 kW/m² generated from 4 tidal constituents semi-diurnal and diurnal predominant (M₂, S₂, K₁, O₁), also 0.876 kW/m² for residual current conversion of kinetic power density. We analyzed these condition caused metrics for speed and power density are comparable, even with the cubic dependence of power density on speed. Also see equation 7 describe velocity of currents are directly proportional with kinetic power density [6], these condition applied for whole tidal cycle. From these results, we conclude that harmonic analysis provides a robust fit to measured currents in the context of tidal energy potential.

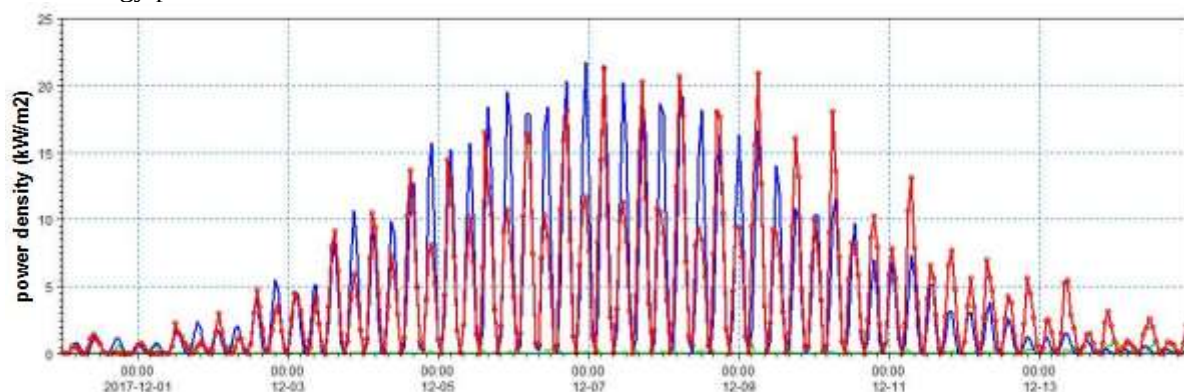


Figure 8 Comparison between kinetic power density, result conversion equation 7 from measurement (red line), four tidal constituent dominant (M₂, S₂, K₁, O₁) (blue line) are compared by harmonic, residual current (green line)

4. Conclusion

The analyzed with which the tidal stream show current velocity is impact from interactional semi-diurnal and diurnal tidal constituent, although other variable components also influence the emergence of current velocity strongly.

From these result we conclude Larantuka Strait, East Flores Waters have 0.73 of formzhal value, means type of tide is mix is principally semidiurnal. Semi-diurnal constituents are dominant caused current velocity; M_2 2.22 m/s show (63.3%), S_2 is 1.11 m/s (31.6%), K_1 is 0.124 m/s (2.9%) and O_1 is 0.07 m/s (1.9%). From the fourth constituents estimation of kinetic power density obtained 21.2 kW/m². Harmonic analysis provides a robust fit to measure currents in the context of tidal energy potential. Harmonic constituents from interaction of semidiurnal and diurnal tides have impacts on faster current velocity.

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