Marine Current Meter Calibration Using GNSS Receivers, A Comparison with Commercial Method

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Abstract

Getting information from marine current requires that accurate and calibrated current meter is used. Current meter calibration is carried out in accordance with specific standard in calibration laboratories. To evaluate the performance and health of a current meter, one should compares velocity and heading it with a velocity and heading reference. In this paper, the innovative method for evaluate velocity and heading resulted from impeller marine current meter is presented. In this method, current meter is to be attached to buoy that is installed on it tow GNSS receivers; and by towing it in a lake, simultaneous velocity and heading of the current meter are recorded. Also data position of buoy by GNSS is recorded. Accurately calculated velocity and heading of buoy by using GNSS data to be used as a criterion to evaluate the current meter velocity and heading. Finally, the calibration equation that is known as the final result of the calibration process was determined for velocity and heading of current meter with reasonable accuracy. Also, current meter is tested in this paper evaluated commercial method in calibration laboratory. The results were compared with the results of the proposed method. The results indicated the success of the GNSS-based method for the Performance analysis of a marine current meter.

Keywords: Current Meter Calibration; GNSS; Heading; Doppler Velocity; Relative Kinematic Positioning.

1. Introduction

Current metering and getting information from marine current velocity and direction are important and essential parameters in many industrial and research projects in the field of sea, and therefore they needs to be used accurate and calibrated current meter. Calibration of a current meter means experimental determination of the relationship between liquid velocity and the velocity directly indicated by the current meter. For this purpose, the current meter is mounted on a towing carriage and drawn through still water contained in a straight tank of a uniform cross section at a number of steady speeds of the towing carriage. Simultaneous measurements of the speed of the towing carriage and the velocity indicated by the current meter are made. In the case of stationary sensor type current meters, the velocity indicated by its display unit is compared with the corresponding carriage speed to know the error in measurement. The result of current meter calibration typically expressed by calibration curve, calibration equation and calibration table. The calibration points are normally entered in a graphic system with the carriage velocity V as the vertical axis and the velocity indicated by the current meter v as the horizontal axis. The final result of calibration of the current meter is expressed in the form of one or more equations of the straight lines as a best fit for the calibration curve. These equations shall be given in $V = a + bv$, where a and b are constants determined for each equation [1].

The current meter calibration is in accordance with international standards (BS ISO 3455: 2007) and it used in calibration laboratories. In this paper, the innovative method for evaluate velocity and heading resulted from impeller marine current meter is presented. In this method, current meter is to be attached to a buoy that is installed on it tow GNSS receivers and by towing it in a Lake, Simultaneous velocity and heading of the current meter and also data position of the buoy by GNSS is recorded. Now, accurate calculated velocity and heading of buoy by using GNSS data are used to be as a criterion to evaluate the current meter velocity and heading. In addition to the velocity, heading

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current meter is also will be calibrated. In this way the calibration equation for the velocity and heading of the current meter is determined.

2. Experiment description and Data collection

To implement the method proposed in this paper, the buoy it was made as shown in Figure 1. In the buoy was considered a container for Embed GNSS receivers and as well as was inserted local to install two numbers GNSS receivers. The current meter was installed on the underside of the buoy, so that by placing the buoy in the water, water velocity and direction data can be recorded. The Current meter used for this test is the type of the impeller current meter (model 308-made in Valeport Company) and Specification it is according to the Table 1. Data acquisition in current meter is that the vector average is based on a 5 second period during which impeller counts are measured and a single compass reading is made, and the vector average is built up over the averaging period set.

Table 1. Current meter properties

Sensors	Type	Range	Accuracy
velocity	Impeller [0.27m pitch x 125mm Ø]	0.03 to 5.0 m/s	<0.15m/s, ±0.004m/s >0.15m/s, ±1.5% reading
direction	Flux gate compass [± 25° gimbal]	0 - 360°	± 0.25°

GNSS dual-frequency receivers 1200 LEICA was used in this experiment that tow receiver was placed on the buoy and a receiver as well as a fixed station was placed outside the test site. Field operations were carried out in Tehran Lake Chitgar. After installing the GNSS receivers on the buoy and connecting the current meter to it as shown in Figure (1), it thrown into the water and with a rope by boat on the lake water was drawn. Due to this draft force, velocity and direction of water flow was recorded by the current meter and at the same time GNSS receivers whit sampling rate of one second were picked up position data of the buoy.
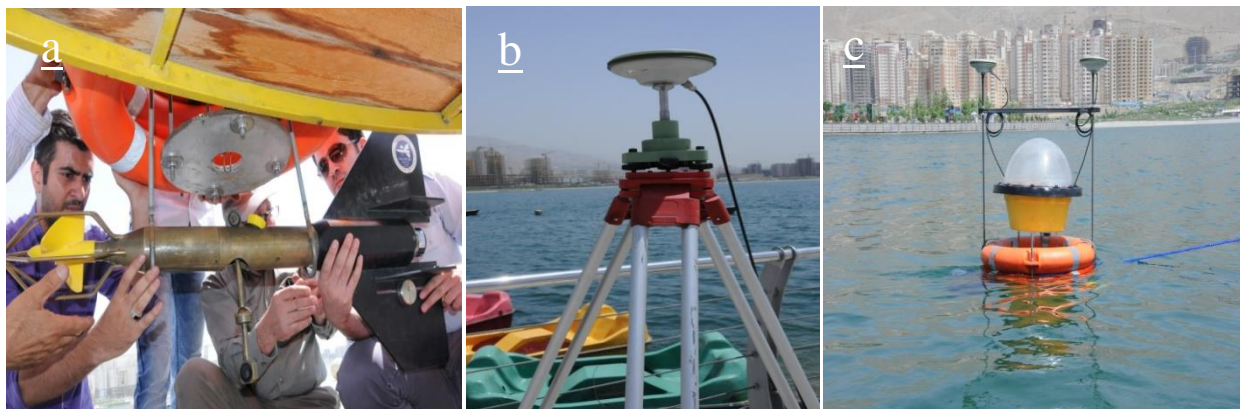

Figure 1. Field operations: a. Current meter installation. b. Reference station. c. Buoy with tow GNSS receivers.

3. GNSS Data Processing

To calculate the exact position of the buoy on the water via the GNSS, the relative kinematic positioning method was used [2]. As noted above, a location was selected as reference station and there were placed a GNSS receiver. Position receivers mounted on buoy were accurately determined relative to the fixed station through carrier phase observations and double-differential equations. All GNSS data processing is done in software Bernese 5.0, That Parameter estimation in the Bernese Software is based on Least-Squares Estimation [3]. After the calculation of the exact position of the buoy on the water, velocity and heading data of the buoy is calculated by position data. In the following will be discussed principle of the velocity and heading by GNSS data.

3.1. Velocity Determination Based on GNSS Doppler Observations

When a wave source is moving relative to an observer the perceived wave frequency is different from the emitted frequency. This effect is named Doppler Effect and has been widely used in velocity determination.
The GNSS raw Doppler shift, which is caused by the relative motion between the receiver and the satellite, is the measurement of the phase rate directly estimated from the Phase Lock Loop (PLL) output. In a first approximation, the Doppler shift between the GNSS satellite and receiver at the frequency channel can be written as:

$$D_{r,j}^s = f_j^s - f_{r,j}^s = \frac{V_{\rho_r^s}}{c} f_j^s = \frac{V_{\rho_r^s}}{\lambda_j^s} \tag{1}$$

Where f denotes the frequency of the GNSS carrier phase observation. $V_{\rho_r^s}$ Is the radial velocity of the range between the satellite s and the receiver r. c denotes the speed of light in vacuum and λ is the wavelength. $D_{r,j}^s$ Has a positive sign when the receiver and the transmitter approach each other and a negative sign when they move away from each other. Eq. (1) for the observed Doppler shift scaled to range rate is given by:

$$V_{\rho_r^s} = \lambda_j^s \cdot D_{r,j}^s = \dot{\rho}_r^s + c \cdot \left(\dot{dt}_r - \dot{dt}^s\right) + \varepsilon \tag{2}$$

Where the derivatives with respect to time are indicated by a dot. $\dot{\rho}$ Stands for the geometric range rate between the satellite and receiver. $\dot{dt}_r$ And $\dot{dt}^s$ denote the receiver clock drift and satellite clock drift, respectively. ε Is the effect of the observational noise and all non-modelled error sources, such as errors in multipath [4,5].

3.2. Heading Determination

The attitude of a moving platform is the orientation of its body frame system with respect to a local reference system that is associated to a global reference system. The attitude parameters can be derived through the rotations, which can be expressed in the form of a rotation matrix. Therefore, the coordinate system and rotation matrix can be viewed as two fundamental elements in defining and estimating a platform attitude [6].

The local level (LL) system is used as a reference frame to measure the attitude of a moving platform. The origin of the frame is defined by the phase centre of the primary antenna in a GNSS attitude system. The z^{LL}-axis is normal to the reference ellipsoid, pointing upwards. The y^{LL}-axis pointing towards geodetic north. The x^{LL}-axis completes a right-handed system by pointing east. A baseline vector from a primary antenna to a secondary antenna is determined by GNSS in the WGS84 system. In order to use this baseline vector for attitude determination, it needs to be transformed into the local level system. The origin of the local level system is at the primary antenna whose location, for instance (φ, λ, h), is determined usually by pseudo range measurements in single point positioning mode. The transformation of a baseline vector **r** from a LL frame to the CT frame (Its origin is located at the centre of the mass of the Earth. The Z^{CT}-axis points to the North Pole, and The XZ^{CT}-plane contains the mean zero meridian, and the Y^{CT}-axis completes a right-handed system) is accomplished using the equation:

$$r^{CT} = R_{LL}^{CT} \cdot r^{LL} + r^{CT_0} \tag{3}$$

Where r^{CT} is the baseline vector expressed in the CT frame, R_{LL}^{CT} is the rotation matrix to transform the baseline vector from LL frame to CT frame, r^{LL} is the baseline vector expressed in the LL frame, and r^{CT_0} is the LL frame origin, o, expressed in the CT frame.

The rotation matrix R_{LL}^{CT} is given by [6] as follows:

$$R_{LL}^{CT} = R_3\left(-\lambda - \frac{\pi}{2}\right) \cdot R_1\left(\varphi - \frac{\pi}{2}\right) \tag{4}$$

Where, R1 is the rotation matrix about the x-axis, and R3 is the rotation matrix about the z-axis. Expanding the above equation yields:

$$R_{LL}^{CT} = \begin{bmatrix} -\sin\lambda & -\cos\lambda\sin\varphi & \cos\lambda\cos\varphi \\ \cos\lambda & -\sin\lambda\sin\varphi & \sin\lambda\cos\varphi \\ 0 & \cos\varphi & \sin\varphi \end{bmatrix} \tag{5}$$

Therefore, the rotation matrix for transforming a baseline vector r from the CT system to the LL system can be formed by transposing R_{LL}^{CT}. The equation is as follows:

$$r^{LL} = \begin{bmatrix} -\sin\lambda & \cos\lambda & 0 \\ -\cos\lambda\sin\varphi & -\sin\lambda\sin\varphi & \cos\varphi \\ \cos\lambda\cos\varphi & \sin\lambda\cos\varphi & \sin\varphi \end{bmatrix} \cdot (r^{CT} - r^{CT_0}) \tag{6}$$

Alternatively, Eq. (6) can also be expressed implicitly as follows:

$$r^{LL} = R_{CT}^{LL} \cdot \left(r^{CT} - r^{CT_0}\right) = R_{CT}^{LL} \cdot \Delta r^{CT} \tag{7}$$

Where,

$$R_{CT}^{LL} = \begin{bmatrix} -\sin\lambda & \cos\lambda & 0 \\ -\cos\lambda\sin\varphi & -\sin\lambda\sin\varphi & \cos\varphi \\ \cos\lambda\cos\varphi & \sin\lambda\cos\varphi & \sin\varphi \end{bmatrix} \tag{8}$$

By using a GNSS twin-or multi-antenna system, the attitude of the GNSS antenna body frame with respect to the local level frame can be precisely computed at each observation epoch. To describe the relationship between the body frame and the local level frame, the parameterization of the platform attitude is of concerns. A baseline vector **r** is transformed from the local level coordinate frame to the body frame using the formulae of rudimentary vector algebra.

Since the body and local level frames theoretically share the same origin and scale, the relationship between the two becomes:

$$r^{BF} = R_{LL}^{BF}.r^{LL} \tag{9}$$

Where, r^{BF} is the baseline vector expressed in the body frame R_{LL}^{BF} is the rotation matrix to transform the baseline vector from the LL frame to the BF, and r^{LL} is the baseline vector expressed in the LL frame. The rotation matrix R_{LL}^{BF} can be described in terms of quaternion form or in terms of the Euler angles of yaw (heading), pitch, and roll. The usual practice for the transformation from the local level frame to the body frame is accomplished first by a rotation about the Z^{BF}-axis by the yaw angle, then about the x^{BF}-axis by the pitch angle and finally about the y^{BF}-axis by the roll angle, yielding the following equation:

$$R_{LL}^{BF} = R_2(\phi)R_1(\theta)R_3(\psi) = R_{312}(\psi, \theta, \phi) \tag{10}$$

Where,

$$R_1(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \tag{11}$$

$$R_2(\phi) = \begin{bmatrix} \cos\phi & 0 & \sin\phi \\ 0 & 1 & 0 \\ -\sin\phi & 0 & \cos\phi \end{bmatrix} \tag{12}$$

$$R_3(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{13}$$

To compute attitude parameters using a twin-receiver (or multi-antenna) system, two sets of coordinates are needed for a baseline vector. One set is in a local reference frame, the other set is in an antenna body frame. The reference frame coordinates are derived by GNSS measurements for each epoch in a local level frame with the origin at the primary antenna. The antenna body frame coordinates, on the other hand, are assumed to have been determined through an initialization process and remain unchanged in all kinematic movements [6, 7]. In this section, the attitude of a GNSS antenna platform computed directly using only the local level coordinates derived by GNSS is derived. As shown in Figure 2, as the main antenna is fixed station and In fact, it is the Origin the local level coordinate system and tow baseline L1 and L2 are determined in the local level coordinate system. Resultant of these two vectors (L), that vector is in the body frame coordinate system that rotated relative to main antenna (in local level coordinate system) by the following rotation matrix:
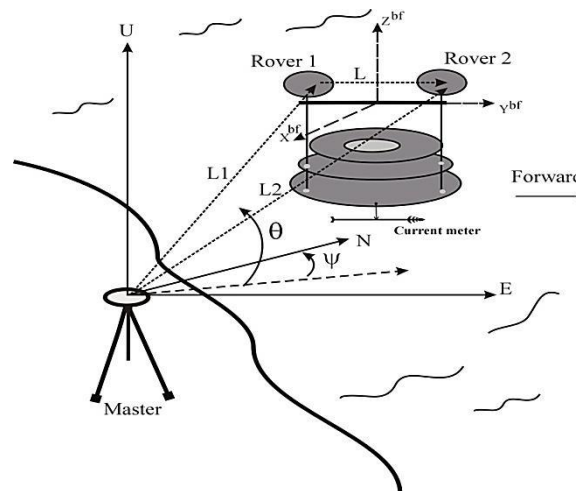
$$L^{BF} = R_{312}(\psi, \theta, \phi). L^{LL} \tag{14}$$

Figure 2. Principle of local level and body frame coordinate system for buoy

Where ψ, θ and ϕ are buoy's heading, pitch, and roll, respectively. Using orthogonality of the attitude matrix R312 (ψ, θ, ϕ) as shown in Eq. (10), the formulae for computing heading and pitch are immediately obtained as follow:

$$\psi = arctan\frac{\Delta E}{\Delta N} \tag{15}$$

$$\theta = arctan\frac{\Delta U}{\sqrt{\Delta E^2 + \Delta N^2}} \tag{16}$$

where ΔN, ΔE and ΔU are the three components of the baseline vector between two antennas determined from GNSS in north, east and vertical direction in the local level frame respectively [6, 7].

4. Result of Calibration

Velocity of the buoy was calculated through Doppler observations GNSS receiver mounted on it. Standard deviation of velocity buoy is calculated 0.0021 m/s in the East and 0.0039 m/s in the North. Table 2 is a calibration table that in it is shown the Velocities range tested. In this table, velocity indicated by the current meter shown by V_C and velocity of the buoy (or velocity from GNSS) shown by V_G, also, their differences are shown by ΔV.

Typically during calibration, the measurement output of the current measurement device is evaluated at a stable velocity against the comparison standard [8]. The discrepancy between the indicated velocity for the current meter and actual current (velocity determined by GNSS) is used to calculate percent of error (offset) as follows:

$$error\ \% = \frac{100(V_C - V_G)}{V_G} \tag{17}$$

The level of error detected during the calibration represents the positive or negative offset of the current meter from the actual current. If the offset of the current meter is beyond the bounds of $\pm 10\%$ of the calibration standard, adjustment of the current meter to bring it within these bounds is appropriate and should be attempted and calibration rechecked. If the current meter shows a high level of inaccuracy beyond these bounds, display an inability to repeat a measurement (within the same bounds), or calibration to within $\pm 10\%$ cannot be attained, a faulty current meter or non-standard installation may be indicated and more in-depth investigation and current meter repair/replacement may be warranted [8]. Percentage of errors is shown in Table 2 for different velocities. Calibration curve Along with its calibration equation can be seen in Figure 3, As well as, is shown the relationship between percentage error and the reference velocity (GNSS velocity) in Figure 4 and the relationship between ΔV and the reference velocity in Figure 5.

Table 2. GNSS-based calibration

Number	V_C(m/s)	V_G(m/s)	ΔV(m/s)	error %
1	0.130	0.132	-0.002	-1.5
2	0.187	0.203	-0.016	-7.8
3	0.244	0.253	-0.009	-3.5
4	0.301	0.301	0.000	0
5	0.358	0.357	0.001	0.2
6	0.416	0.394	0.022	5.5
7	0.474	0.470	0.004	0.8
8	0.532	0.531	0.001	0.1
9	0.590	0.572	0.018	3.1
10	0.648	0.645	0.003	0.4
11	0.706	0.708	-0.002	-0.2
12	0.764	0.769	-0.005	-0.6
13	0.822	0.834	-0.012	-1.4
	Mean		**-0.00021**	**-0.497783851**

Figure 3. GNSS-based calibration

$Y = 0.9958X + 0.002222$
$R^2 = 0.9978$
$RMSE = 0.01093$

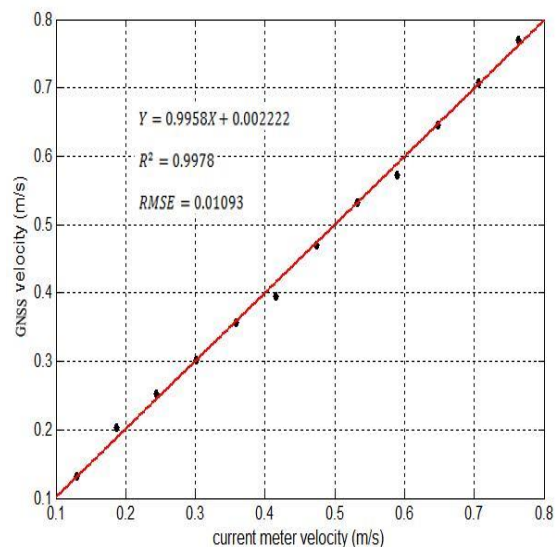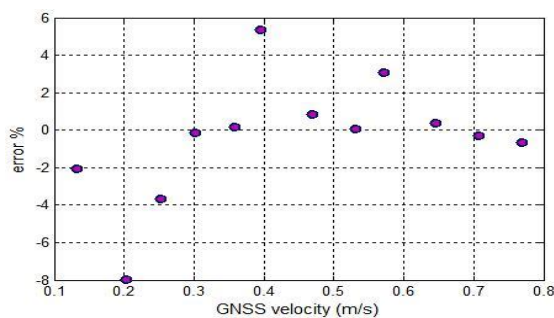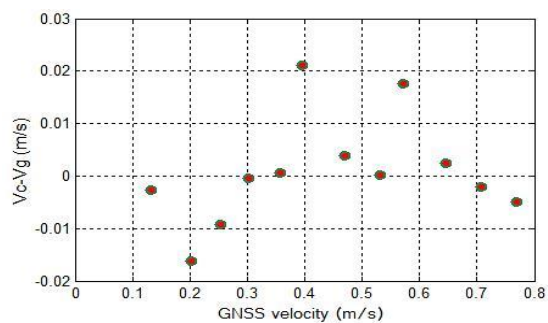**Figure 4. Relative difference**

Figure 5. Mean reported minus actual velocity

Heading of the buoy were calculated through tow GNSS receiver with standard deviation Equal to 48.27 second and compared with the heading resulted from the current meter. It was observed that considerable difference there is at about ± 180 degree among the headings calculated and current meter headings. This indicates that the compass has technical fault and needs adjustment. This error is positive in the angle of 0 to 180 degrees and is negative in the angle of 180 to 360 degrees, that According to Figure 6, we have two calibration equations for headings.
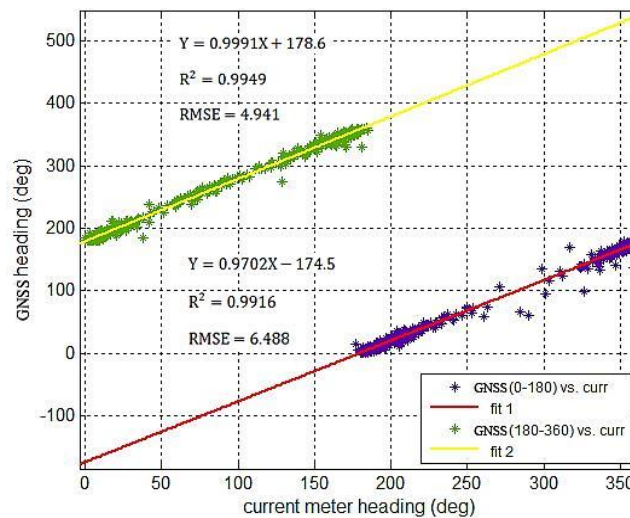
Figure 6. Calibration by equations calibration

Method executed in this paper, could properly evaluate the performance of the marine current meter, but to validate the method presented in this paper, current meter tested in this study, was sent to the laboratory calibration of the Water Research Institute for calibration to the common commercial method. The method used in the laboratory in accordance with the standards described in the introduction section. In the laboratory, current meter was connected to a carriage on a water tank, and was dragged by operator at different velocities and with regard to know the velocity carriage, velocity directly by the current meter was compared with it and finally, the result was achieved in Table 3. Also, the calibration curve with its equation shown in Figure 7. As can be seen, velocity range tested in calibration table is like proposed method, in this table, velocity indicated by the current meter shown by V_C, velocity of carriage shown by V_{ca}, their differences are shown by ΔV and the percentage of error is shown. It can be seen that the percentage of error is within standard range ($\pm 10\%$) And this means that velocity sensing performance of device is correct. Heading resulted from current meter has not been evaluated in commercial method and this can be a disadvantage of this method in check the health of the current meter because the heading parameter is important as well as velocity parameter.

Table 3. Commercial calibration

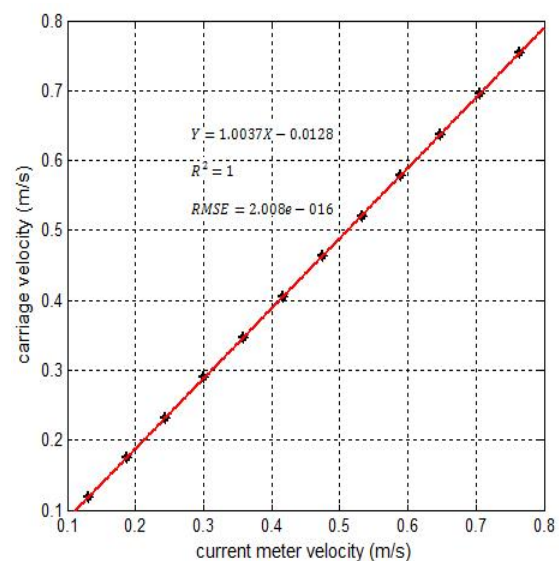| Number	V_C(m/s)	V_{Ca}(m/s)	ΔV(m/s)	error %
1	0.130	0.117	0.013	10
2	0.187	0.174	0.013	7.4
3	0.244	0.232	0.012	5.1
4	0.301	0.289	0.012	4.1
5	0.358	0.346	0.012	3.4
6	0.416	0.404	0.012	2.9
7	0.474	0.462	0.012	2.5
8	0.532	0.521	0.011	2.1
9	0.590	0.579	0.011	1.8
10	0.648	0.637	0.011	1.7
11	0.706	0.695	0.01	1.4
12	0.764	0.754	0.01	1.3
13	0.822	0.812	0.009	1.1
		mean	**0.011043**	**3.428219755**

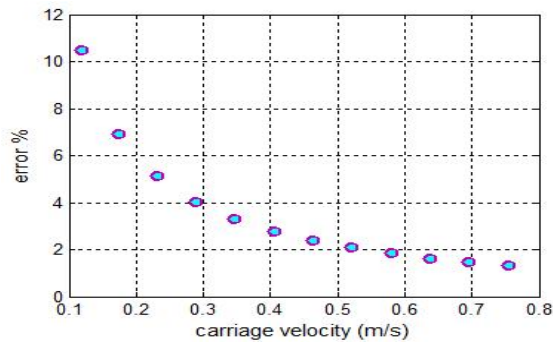**Figure 7. Commercial calibration.**
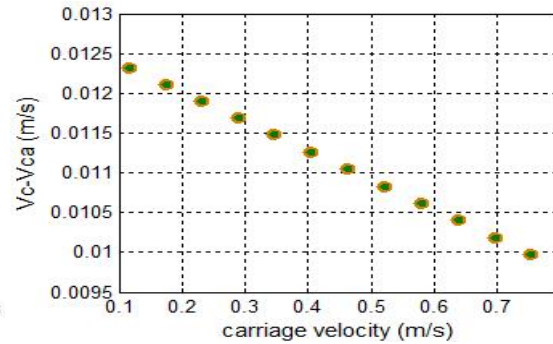
Figure 8. Relative difference.

Figure 9. Mean reported minus actual velocity.

It can be seen in Figure 10 calibration curve and equation for marine current meter to both the commercial and proposed method. Equation offered for velocity calibration of the current meter from Water Research Institute is Accordance with *V= 1.0037v-0.0128* and calibration equation resulted from GNSS-based method is Accordance with *V=0.9958v+0.0022*. Figure 11 shows comparison between residuals or ΔV's for both methods.
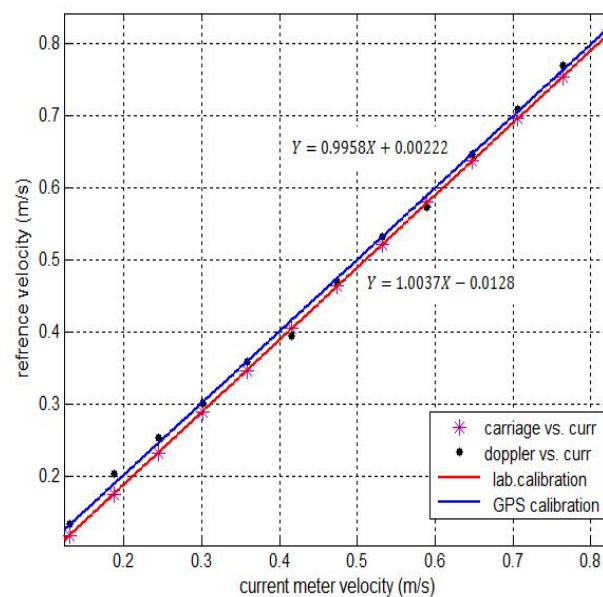

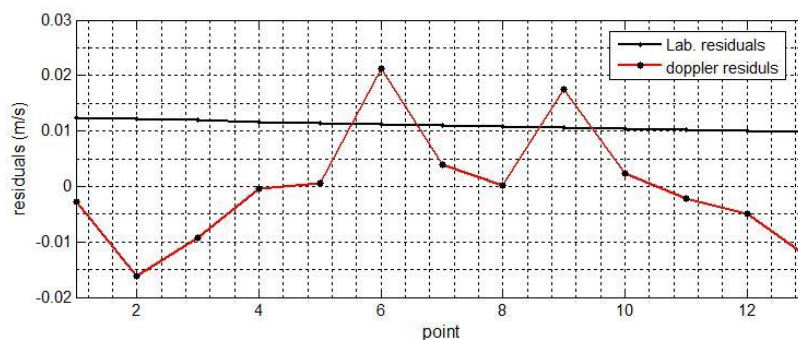**Figure 10. Calibration of commercial and GNSS**

Figure 11. Residuals comparison

5. Conclusion

Current meter calibration usually is conducted in accordance with international standards in calibration laboratory that have their own advantages and disadvantages but in this paper, a new approach presented for marine current meter. In this method, through connecting current meter to buoy equipped with GNSS receivers and Drag it into the lack, velocity and heading resulted from current meter were compared with velocity and heading of the buoy (resulted from GNSS) and calibration equation were presented for current meter. Unlike commercial method that usually is not evaluated heading resulted from compass of current meter, in this method, buoy headings that accurately calculated through tow GNSS receivers, was used as a criterion for assessing heading of the current meter, It became apparent

there is difference of about ± 180 degrees between headings of GNSS and current meter And surely Compass has a problem and does not display the correct heading. Velocity of the buoy was calculated as a criterion for assessing velocity of the current meter through Doppler observations of the receivers and compare with velocity recorded. To validate the GNSS-based method, current meter tested in this study, were sent to the laboratory calibration and there evaluated by common calibration method and finally, equation calibration was determined for velocity resulted from current meter. It can be seen from the comparison of results of two methods, the difference between the reference velocity with the velocity of the current meter in GNSS-based method in some points, is much lower than difference velocities in commercial method. Also, the percentage of error in GNSS-based method is lower than that of the commercial method. Evaluation heading of current meter at different angles in GNSS-based method is the advantage of this method compared to commercial method. In general, the method implemented in this paper As well as evaluated the performance of an impeller marine current meter and it can be considered an appropriate method for field controls the marine current meters.

6. Acknowledgements

7. References

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