Real Time Kinematic (RTK) Heave as a Replacement of Motion Reference Unit (MRU) Heave in Hydrographic Surveying Works

Mohamed Elmeligy[1], Saad Mesbah[2] and Mohamed Mohasseb[3]

[1]College of Maritime Transport and Technology, Arab Academy for Science, Technology and Maritime Transport, Abu-Qir, Alexandria, Egypt.
[2]Consultant to the Academy President for education affairs, Arab Academy for Science, Technology and Maritime Transport, Abu-Qir, Alexandria, Egypt.
[3]Egyptian Naval Hydrographic Dept., Naval Forces.

Emails: elmeligy57@aast.edu, saadmesbah@hotmail.com, mohamedmohasseb@live.com

Received on: 28 January 2023 Accepted on: 26 April 2023 Published on: 22 May 2023

Abstract

Purpose: *Heave is one of the major contributors to errors in water depth measurements. Motion Reference Unit (MRU) measures the heave signal with high-level accuracy as well as other ship motions. Unfortunately, MRU has been reported to have some of drawbacks such as heave drift error, influence of ship motion dynamic, in addition to its very expensive price. Real-Time Kinematic Global Positioning System (RTK GPS) uses dual frequency receiver and carrier phase differential technique under kinematic solution and provides very accurate position in all three components in real time. In addition, RTK GPS also calculates the low frequency changes in water level such as tidal oscillation.*

Design/Methodology/Approach: *This research is an attempt to investigate the possibility of using the RTK GPS data to deduce the heave signal from the GPS height (tides - heave) instead of heave from MRU to correct the water depth. Moreover, it aims to examine to what extent RTK heave can be used as a backup to satisfy the International Hydrographic Organization (IHO) survey order standards. A comparison between the extracted RTK heave and MRU heave signals revealed a good agreement with a strong direct correlation of 0.96. RTK heave as a replacement for MRU heave in hydrographic surveying was statistically validated using many methods of analysis such as test of the normality, paired samples t test, Wilcoxon signed ranks test, heave signals frequency adjustment, descriptive statistics for the two heave signals, descriptive statistics for each signal individually, correlation and trend, analysis between the two signals, scatter diagram and trend, standard deviation and uncertainty for soundings, characteristics of the difference between two signals and comparing the surfaces by Triangulation Irregular Network (TIN) Model.*

Findings: *The results of this analysis provided the possibility of using RTK heave as a replacement for MRU heave in hydrographic surveying. Therefore, RTK GPS is not only used to provide precise position or tidal oscillations but also, based on this study, it could be used to measure heave accurately to correct the depth satisfying IHO survey standards.*

Key-words:
Hypack -- Hydrographic Survey -- Motion Sensor - RTK GPS Heave - Height of Tide

MRT
ISSN 2812-5622
http://dx.doi.org/10.21622/MRT.2023.02.1.070

INTRODUCTION

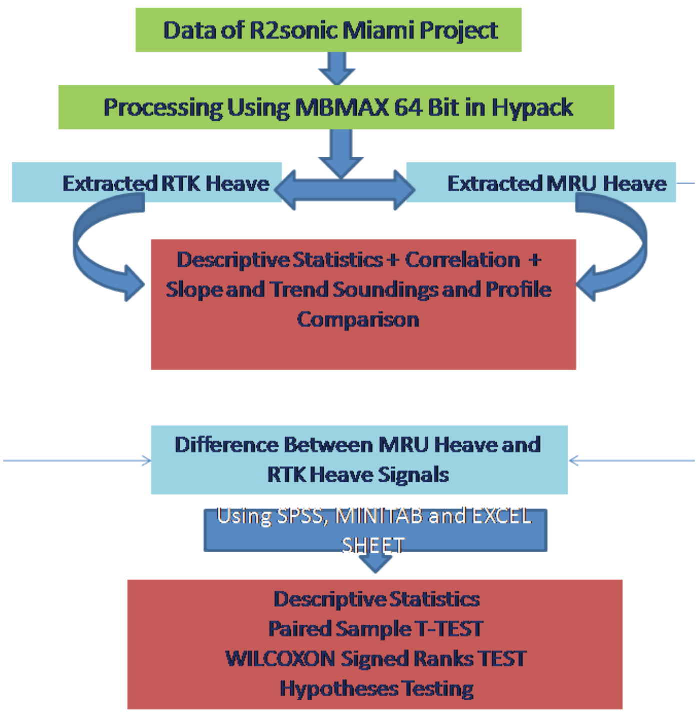

Fig. 1. Theoretical framework of research flow

Vessel at sea, is subjected to six different motions with six degrees of freedom, which are surge, sway, heave, roll, pitch and yaw, induced by the sea state. These motions are mainly due to oceanographic and atmospheric forcing (OMC international, 2005).

Heave, as a vertical displacement relative to a water level, is a major contributor to errors in water depth measurements, defined as an oscillation of rise and fall around a defined datum (mean sea level), (typically higher than 0.04 Hz) (Rapatz, 1991; Godhavn, 2000).

Many researchers have addressed movements of the ship, especially Heave Motion such as Grover (1954), Caldwell (1955), Tucker (1955), Rapatz (1991), Kielland et al. (1995), Chang et al. (2002), Wang et al. (2007), Blake (2007), and Rabah et al. (2010).

In 1954, Grover addressed the early heave sensor known as "Pressure Sensors". The pressure sensor was fixed to the side of the ship and provided a continuous measurement of the pressure of the water column above the sensor. As the ship moved up and down the water, pressure at the sensor head decreased or increased according to the simple formula:

$\{P = \rho g h\}$ is used to extract the height h, where P is pressure, ρ is water density and g is acceleration due to gravity (Grover, 1954; Rapatz, 1991).

After that, in 1955, Caldwell discussed the second early heave sensor which is called "Electrostatic Strip". The electrostatic strip is used for measuring the conductivity of sea water to assist in measuring the height of the water along a metal strip attached to the side of the ship (Caldwell, 1955; Rapatz, 1991). The attempts to measure the vertical motion (heave) by different two earlier methods yielded a successful result before the world of GPS. However, there was an objection from Tucker in 1955 who investigated the previous techniques while offering direct measurement of the water height with respect to the ship's hull. However, there was no way of distinguishing whether the water level change is due to the motion of the ship such as rolling or due to changes in the sea surface as caused by waves, etc. These extraneous changes of the water level in direct contact with the hull cause significant measurement errors and limit the usefulness of hydrodynamic techniques to times when the sea surface is very calm.

After GPS usage, Rapatz, in 1991, tested a model for investigating and proving the initial suggestion about the capability of differential GPS to measure vessel heave. After that, developing the practical utilizing for this theory consisted of some practical steps such as testing the static data by usage, collecting data in the field and, finally, data processing and evaluating the results of processing. The technique used for determining heave from GPS measurements utilized the high precision with which the carrier phase signal can be measured to determine the relative movements of the GPS antenna from epoch to epoch. After determination of the motion, refining it into height changes from epoch to epoch and integration gave the height of motion over time. Appropriate datum selection and low frequency filtering to help in extracting only the heave signal not tide signal, combined with pitch and roll measurements allow the determination of vertical motion of any point on a vessel (Rapatz, 1991).

After Rapatz, another technique was conducted by Kielland et al. in 1995 who stated that a significant error source, which was encountered by hydrographers, is wave induced vertical motion of their survey vessel (heave). In heavy swells, uncorrected heave noise will degrade the accuracy of the surveyed soundings. Heave motion can be measured using inertial technology to be corrected to calm water conditions. Unfortunately, the high cost of inertial heave compensators has prohibited their widespread use. An algorithm was carried out and authorized by the Canadian hydrographic to use to determine heave corrections for a hydrographic survey vessel. The algorithm is simply a high pass filter acting on the unused DGPS vertical position record already being observed on the vessel. A low-cost pitch and roll inclinometer was used to correct for the lever arm effect between the GPS antenna and the sounder's transducer. The experiment indicated that decimeter heave compensation accuracy was obtained.

In 1995, Kielland used the GPS for measuring the heave but through an algorithm. After a few years, in 2002, Chang et al. discussed the results of the application of a vessel-based GPS system for hydrographic surveys, particularly for the collection of attitude-corrected bathymetric measurements. The kinematic solutions of the onboard GPS antennas can effectively determine and provide all parameters of attitude, including roll, pitch and heave, for the reductions of bathymetric measurements to the vertical. The accuracy of measurement can be significantly improved. The attitude correction, based on the kinematic GPS solutions from a multiple antenna configuration, has successfully shown its important role in bathymetric data reductions.

In an attempt to overcome some problems of using motion sensor Blake, in 2007, developed a heave algorithm for use with low-cost GPS receivers. This algorithm was to overcome some of the problems and limitations associated with the use of inertial sensors for the measurement of heave in three areas:

- Cost
- Stability
- Usability

This has been achieved through the development of a highly accurate velocity estimation algorithm using stand-alone low-cost GPS receivers and the algorithm has been extensively tested in both a simulated and a real-world marine environment (Blake, 2007).

With the advanced development in GPS, it was a necessary to develop the heave algorithm to adapt with the new types of GPS receivers so, Rabah et al. (2010) developed GPS heave algorithm that can be used with all types of GPS receivers, single or dual receivers; processed in Post processing mode or in Real Time Kinematic mode. The GPS heave values computed from 1 Hz GPS recorded data was found to be inadequate for the measurement of the frequency of heave motion experienced by the vessel during the trial. The results of the sea trial showed the ability of developed heave algorithm to measure heave to the accuracy required for at least the IHO survey order. The RTK GPS high update rate showed an increased level of performance over the heave solutions using 1 Hz data.

SIGNIFICANCE OF THE RESEARCH

It is of importance to look for an alternative approach for using the most recent technology for extracting heave to overcome the above-mentioned drawbacks associated with MRU heave signals, especially in hydrographic surveying operations. Thus, the research question for this study is mainly to answer the following: "to what extent can hydrographers depend on RTK GPS heave to correct water depth soundings" as an alternative way of MRU heave or as a good backup method. Also through this analysis, some hypotheses will be experimented and will answer whether applying heave from RTK GPS is efficient and whether it abided by the IHO standards or not, so the research will be validated by the following hypothesis:

The difference between MRU heave and RTK heave signals was assumed to follow approximately the normal probability distribution due to the large samples size. Therefore, parametric statistics will be used to test the significance, whether the mean of MRU heave equals the mean of RTK heave, or whether they have a significant difference.

T-Test for paired samples (RTK heave, MRU heave) will be utilized for this case considering:

- Significance level was taken 5 %
- Hypotheses testing formulation will be as follows:
- Null hypothesis (H_0) and alternative hypothesis (H_1)

H_0: $\mu_1 = \mu_2$ or $\mu_1 - \mu_2 =$ Zero

And H_1: $\mu_1 \neq \mu_2$

Using analysis software package, T-TEST for the research data of (RTK heave, MRU heave) with a confidence level 95 %.

MATERIAL AND METHODS

Material

Data of Multibeam Echo-Sounder (MBES) hydrographic survey was made available by HYPACK Company (USA) as shown in Figure 2. That was conducted in LUMUS ISLAND TB, Miami, USA. Data contained 3 MBES lines with total length of 2 km. Having a minimum depth of 3 feet (0.91 cm) and the maximum depth reached 70 feet (21.336 m).

- The MBES angle limit was setting out to 60 degrees.
- The Applanix MRU (POS MV) was used for both positioning and heave.
- The Sonic 2024 MBES was used for sounding. The grid used was state plane NAD_83 with

ellipsoid WGS 84 in one FL-0901FLORIDA EAST.

- Collecting data and processing using HYPACK software.

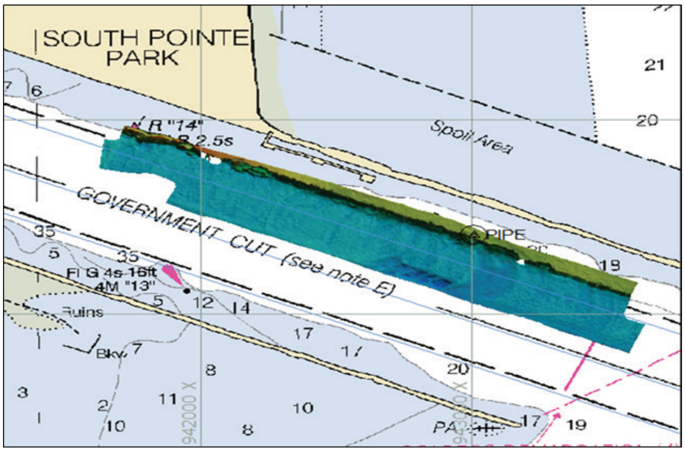

Fig. 2: R2Sonic Miami snippets survey project (HYPACK Software)

The survey data were conducted using heave from two different sources (MRU and RTK GPS) at the same time to compare between the two signals. The RTK GPS height usually contains two superimposed frequencies: one is low frequency changes (tides) and the other is high frequency changes referred to as (heave).

Methods of Analysis

Method of calculating RTK GPS height

Figure 3 shows a survey boat using RTK GPS to measure and determine the current water level correction (RTK GPS Tide). In this example, the pre-determined reference ellipsoid (a) is 100m above the chart datum which is a given and fixed value for each part of the earth.

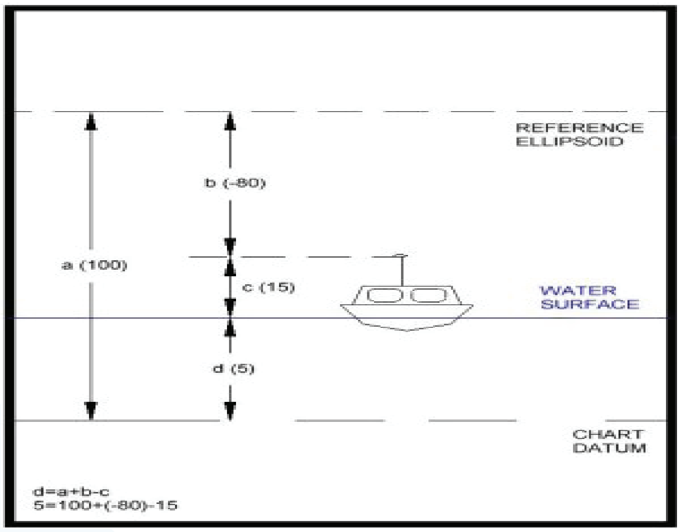

Fig. 3. HYPACK method for obtaining real time water levels (HYPACK user manual, 2015).

$$d = a + b - c \quad \ldots\ldots (1)$$

$$d = (100) + (-80) - 15 = 5m$$

Where (d) is the height of water surface above the chart datum (RTK GPS Tide) which is required to be measured.

(a) is the height of the reference ellipsoid above the chart datum.

(b) is the height of the GPS antenna relative to the reference ellipsoid (This is automatically measured by RTK GPS).

(c) Is the height of RTK GPS antenna above the static water line (This is measured manually from the antenna to the sea level).

When HYPACK is configured correctly, it computes this value at each RTK GPS update and saves the position and the tide correction to the raw data file. The sign of value (d) is negative by HYPACK to be consistent with the normal tide correction values.

When the raw data file from the survey program is read into the multibeam editor, each sounding will have an RTK tide correction, based on the method shown above (HYPACK, 2013c).

Methods of analysis for both of signals (RTK GPS heave and MRU heave)

Analysis and comparison have to be made first, between the two simultaneous heave signals: (RTK GPS) and (MRU). The second comparison was conducted after applying heave correction to the created soundings surfaces and profiles to validate the results.

For each signal of heave whether from RTK or MRU or from the difference between them statistical analysis was conducted, and correlation analysis were obtained using statistical programs:

1- SPSS,
2- Minitab program, and
3- MBMAX 64-bit module in HYPACK software.

The methods of analysis were conducted as follows:

1- Heave Signals Frequency Adjustment,
2- Descriptive Statistics for the Two Heave Signals,
3- Descriptive Statistics for Each Signal Individually,
4- Correlation and Trend Analysis Between the Two Signals (Hr, Hm),
5- Scatter Diagram and Trend,
6- Standard Deviation and Uncertainty for Soundings,

7- Characteristics of the Difference between Two Signals,
8- Test of the Normality Paired Samples T Test,
9- Wilcoxon Signed Ranks Test,
10- Comparing the Surfaces by TIN Model,
11- Hypotheses Testing, and
12- Limitation of RTK GPS.

RESULTS AND DISCUSSION

The heave is a major contributor to the uncertainty in depth measurements due to the effect of the wind and waves on the free water surface. Motion Reference Unit (MRU) is responsible for measuring the heave, but it has some drawbacks, problems and errors as reported by several studies, such as Böder (2008), which were mentioned in the introduction.

RTK GPS measures and calculates the Heave in addition to the Tide. This can be done using MBMAX 64bit module in HYBACK software package. It is possible to decide on selecting the heave either from MRU or RTK using MBMAX 64bit to apply it during data processing.

The Main Results of the Analysis

Heave Signals Frequency Adjustment

An independent comparison could be done but there is a problem that both the initial H_m and H_r are not at the same time tag because the sampling frequency of MRU is greater than the sampling frequency of RTK. RTK heave is delayed than MRU heave due to GPS processing time. For these reasons, both heave signals were found to have similar amplitude but with a time shift between both of them, although both signals have equal length of record but different in samples number as shown in Figure 4.

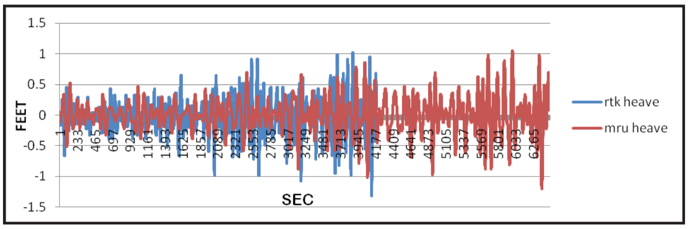

Fig. 4. Time series segment of MRU heave and RTK heave for line 1, demonstrating shifting in time (length of record is 4.4 minutes)

By using Visual Basics software this problem was figured out by using time alignment between both heave signals: RTK and MRU. After that, the two heave signals for MRU (H_m) and RTK (H_r) was adjusted to have the same time tag as shown in Figure 5.

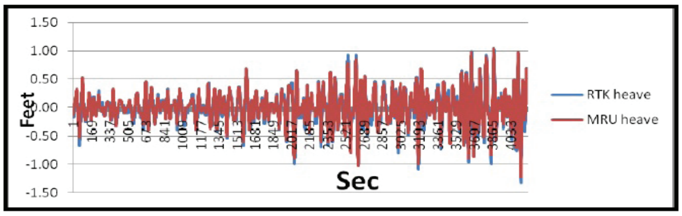

Fig. 5. Heave for MRU and RTK having the same time tag for line 1

Descriptive statistics of the two heave signals

Table 1: Processing Summary for RTK and MRU Data Points

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
RTK	9618	100.0%	0	.0%	9618	100.0%
MRU	9618	100.0%	0	.0%	9618	100.0%
RTK-MRU	9618	100.0%	0	.0%	9618	100.0%

To conduct a comparison between RTK heave signals and MRU heave signal, it was necessary to understand the attitude of signals itself through descriptive analysis of each signal individually.

Descriptive statistics was conducted using SPSS program and the results showed that the number of validated samples to be tested was 9618 values and under confidence level 95%, the mean for MRU heave was -.0005 ft while the mean for RTK heave was -.0163 ft.as shown in Table 1.

The median for RTK heave or MRU heave was .000 for both signals which means that the middle of all values after arrangement is zero level for the heave which is the sea level. Thus, confirming that the rise and fall oscillations of both heave signals are around zero value (sea level).

Standard deviation for MRU heave was .30 ft and for RTK was .31 ft. It was deduced from these values that the standard deviations for both data are almost the same despite the fact that they are measured by two different equipment at the same position and the same time. Also descriptive analysis indicated that the measured heave values using MRU were varying between 1.48 ft (45.1 cm) and -1.57 ft (-47.9 cm) and the measured heave using RTK was varying between 1.45 ft (44.2 cm) and -1.61ft (-49.1 cm) as shown in Table 2 and Figure 6.

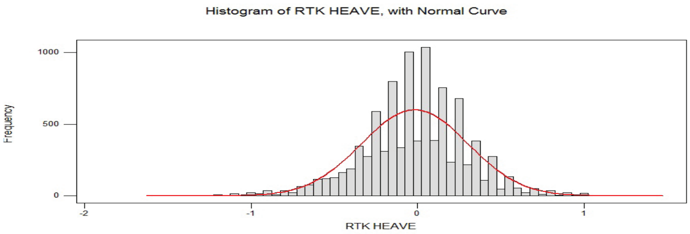

Fig. 6. Histogram of RTK with normal curve

Table 2: Descriptive Statistics for RTK Heave

	Overall project		Statistic	Std. Error
RTK	Mean		-.0163	.00325
	95% Confidence Interval for Mean	Lower Bound	-.0227	
		Upper Bound	-.0099	
	5% Trimmed Mean		-.0127	
	Median		.0000	
	Variance		.102	
	Std. Deviation		.31887	
	Minimum		-1.61	
	Maximum		1.45	
	Range		3.06	
	Interquartile Range		.36	
	Skewness		-.199	.025
	Kurtosis		1.664	.050

Table 3 and Figure 7 showed the minimum values for RTK and MRU to be (-1.61, -1.57) and the maximum values to be (1.45, 1.48). These values seem to oscillate around zero where the values for each signal of RTK and MRU fall between -1.61 ft and 1.48 ft. This has been confirmed also by the median value of both signals when it becomes zero. Descriptive statistics also showed that the mean for RTK heave is -.0163 ft with standard error .00325 ft and the mean for MRU heave is -.0005 ft with standard error .00307 ft.

Table 3: Descriptive Statistics for MRU Heave

			Statis-tic(ft)	Std. Error
MRU	Mean		-.0005	.00307
	95% Confidence Interval for Mean	Lower Bound	-.0065	
		Upper Bound	.0055	
	5% Trimmed Mean		.0026	
	Median		.0000	
	Variance		.091	
	Std. Deviation		.30125	
	Minimum		-1.57	
	Maximum		1.48	
	Range		3.05	
	Interquartile Range		.32	
	Skewness		-.180	.025
	Kurtosis		2.123	.050

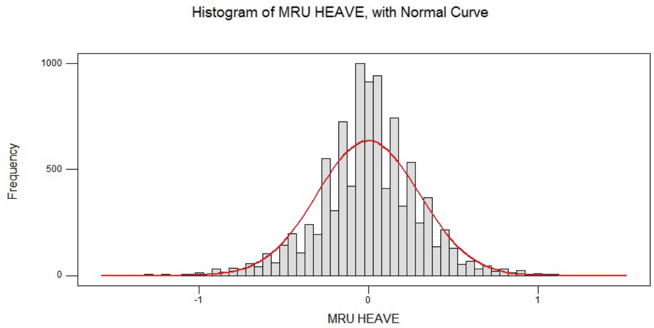

Fig. 7. Histogram of MRU with normal curve

Skewness is a measure of symmetry, or more precisely, to test the lack of symmetry. A distribution for a data set is symmetric if it looks like a mirror; i.e. the same to the left and right of the center line. So, based on both the skewness of RTK heave -.199 with standard error 0.025 and the skewness of MRU heave -.180 with the same standard error 0.025, it is clear to notice that both data have a negative skewness slightly to the left with the same standard error.

One of the most commonly used measures is standard deviation. This value gives information on how the data values are deviating from the mean of the data set, using the following formula:

$$s.d = \frac{\sqrt{\sum(x-\bar{x})2}}{\sqrt{n-1}} \text{ .... } (2)$$

Where: Σ = sum of,
X = individual values and $\bar{x}$ = mean of the values,
n = number of data points

Large standard deviation indicates that the data points are dispersed far from the mean and a small standard deviation indicates that they are clustered closely around the mean. The standard deviation of the RTK heave was 0.31ft and the MRU heave was 0.30 ft which revealed that both MRU heave and RTK heave dispersed around the mean almost with the same standard deviation.

Correlation Analysis

The correlation coefficient between MRU heave and RTK heave for overall the 3 lines using SPSS analysis program gave 0.96. This correlation coefficient value indicated a strong and direct proportional relationship between the two considered signals.

Both of RTK heave and MRU heave data were plotted on a scatter diagram to see the rate of the change between MRU heave and RTK heave. If the slope of the linear regression equation between MRU heave and RTK heave shows almost 45° line or close (i.e., slope is equal or close to 1.0), it indicates the great association between both signals. The slope is defined as the ratio of the vertical change between two points (the rise), to the horizontal change between the same two points (the run) and it comes from the following formulas:

$$\text{Slope } = \frac{\text{opposit}}{\text{adjacent}} = \frac{Y2-Y1}{X2-X1} \text{.......................................} (3)$$

The regression equation is Y = 1.018 X, showing a trend passing through origin and almost equals to 1.0. The explained variance R^2 is 0.92 i.e., 92% as shown in Figure 8.

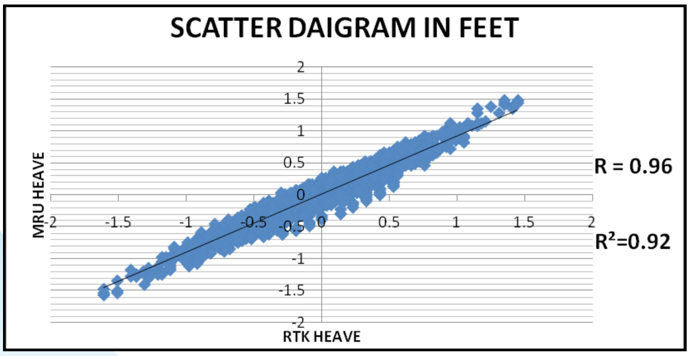

Fig. 8. Trend and correlation coefficient between RTK heave and MRU heave values for overall project lines

Scatter Diagram and Trend

A scatter diagram is plotted to check linearity between RTK and MRU heave which demonstrated a strong correlation (96%) for the overall signals and direct proportional between them. The linear equation for the analysis between RTK heave and MRU heave signals is Y = 1.018x with no intercept. If the slope (1.018) is close to (1), then the changes in Y = changes in X, as the regression line passes through the origin (0,0) as shown in Figure (8) and in this case almost Y X because of the high similarity.

The index of determination is R2= 0.9253 known also as the explained variance so, the r= $\sqrt{0.9253}$ = 0.96. Close to one indicating high similarity between them.

Standard Deviation and Uncertainty for Soundings

Standard deviation is a measure of dispersion of a set of data around its mean. The calculated standard deviation for the difference between soundings surface applied MRU heave (s1) and soundings surface which applied RTK heave (s2) is 0.18 ft (5.5 cm), which means the uncertainty for the difference between the two soundings surfaces 2 = 2 x 5.5 =11 cm with confidence level 95 %. According to equation 4,

Uncertainty in depth = $\pm\sqrt{a^2 + (b \times d)^2}$.................(4)

Uncertainty in depth = $\pm\sqrt{(0.25)^2 + (0.0075 \times 13.72)^2}$ = 27 cm.

The uncertainty of the differences between two soundings surfaces i.e., basically between the two heave signals for RTK and MRU fall was found to within the limit of Total Vertical Uncertainty (TVU) for the overall project which was estimated as 27 cm with confidence level 95 % following the IHO special order standards.

Characteristics of the Difference between Both Signals

The differences between MRU heave signals and RTK heave signals are conducted to obtain the descriptive measures between the difference between RTK GPS Heave and MRU Heave using SPSS and MINITAB analysis programs as shown in Table 4.

			Statis-tic(ft)	Std. Error
RTK-MRU	Mean		-.0158	.00089
	95% Confidence Interval for Mean	Lower Bound	-.0175	
		Upper Bound	-.0141	
	5% Trimmed Mean		-.0170	
	Median		-.0100	
	Variance		.008	
	Std. Deviation		.08735	
	Minimum		-.33	
	Maximum		.44	
	Range		.77	
	Interquartile Range		.10	
	Skewness		.371	.025
	Kurtosis		1.566	. 050

Table 4: Descriptive Statistics for the Difference between MRU Heave and RTK Heave Signals

Based on confidence level 95 %, the mean of the difference between MRU heave and RTK heave is -.0158 ft (-0.5 cm) and the standard deviation for the differences is .087 ft which means that all the differences fall between (0.0158 + 2 x 0.087) = 0.19 ft and (0.0158 - 2 x 0.087) _0.16 ft with a confidence level 95%.

Test of the Normality

In order to test the hypotheses, the normality test, known as Kolmogorov-Smirnov-Lilliefors test was conducted to detect which tests will be used whether parametric or non-parametric tests in analyzing the signals of difference. According to the test, as shown in Figure 9, normality is not achieved (since $sig < 0.05$) for the overall data sets whether for RTK or MRU. Normality is considered one of the conditions required for conducting parametric tests such as T-Test. However, based on central limit theory (CLT) and due to a large sample size (n=9618), the researchers will be able to use T-Test as a proximately test or to use the non-parametric tests such as Wilcoxon Signed Ranks Test.

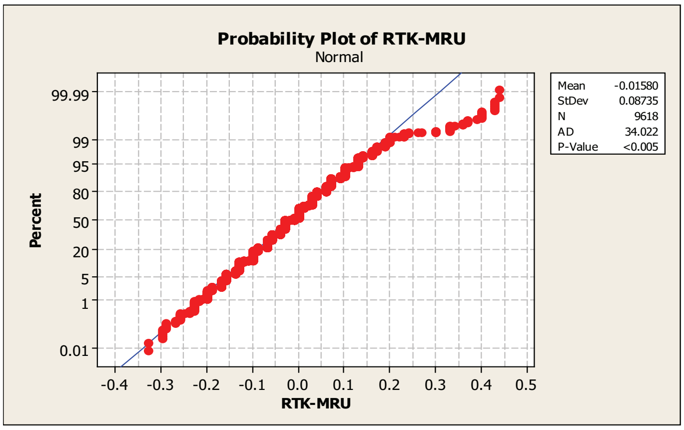

Fig. 9. Testing the Normality

Paired Sample T-Test

Parametric statistics could be used to test the significance, whether the mean of MRU heave equals the mean of RTK heave or whether they have a significant difference, T-Test for paired samples (Hr, Hm) are utilized for this case considering:

- Significance level is taken 5 %
- Hypotheses Testing formulation will be as follows:
- Null hypothesis (H_0) and alternative hypothesis (H_1)

H_0: $\mu_1 = \mu_2$ or $\mu_1 - \mu_2 =$ Zero
And H_1: $\mu_1 \neq \mu_2$

Paired samples T-Test displayed P-value (sig) which is .000 that is less than significance level (p-value $< .05$) , which means that the mean difference -.0158 is a significant difference. Therefore, null hypothesis H_0 is rejected that assumed μ_1=μ_2, , that is to say; there is a significant difference between the two signals with a confidence level 95%. The analysis rejects the null hypothesis which assumed that there is no significant difference between MRU heave and RTK heave and cannot reject the H_1 which assumed that there is a significant difference between RTK heave and MRU heave and the mean of this difference was -.0158 ft (0.5 cm). The mean of difference falls between -.01755 ft and -.01406 ft as displayed in Tables 5-8 with confidence level 95 %. This difference is demonstrated in tables 5 and 6.

Table 5: Paired Samples Statistics

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	RTK	-.0163	9618	.31887	.00325
	MRU	-.0005	9618	.30125	.00307

MRT
ISSN 2812-5622
http://dx.doi.org/10.21622/MRT.2023.02.1.070

Table 6: Paired Samples T-test

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	RTK - MRU	-.01580	.08735	.00089	-.01755	-.01406	-17.741	9617	.000

Wilcoxon Signed Ranks Test

Another test which deals with the samples as ranks not as values to calculate the asymptotic significance based on significance level .05 to check the hypothesis testing as shown in Table 7.

Table 7: Wilcoxon Ranks

Ranks

		N	Mean Rank	Sum of Ranks
MRU - RTK	Negative Ranks	3474a	3969.66	13790598.50
	Positive Ranks	5055b	4467.97	22585586.50
	Ties	1089c		
	Total	9618		

a. MRU < RTK

b. MRU > RTK

c. MRU = RTK

The positive ranks of (MRU-RTK) heave in Table 7 is larger than the negative ones, that was proven earlier by comparing the two means of signals. Both signals are tied (equal) for 1089 out of 9618 showing

MRU = RTK for a ratio 11%

Comparing the Surfaces by TIN Model

The final method of comparing the soundings is carried out by volume calculation technique through TIN model in HYPACK software by loading two xyz files and creating two surfaces one of them is MRU surface *Sm* and other one is RTK surface *Sr* by TIN MODEL (Triangulation Irregular Network) which merges the two models to determine where they overlap with each other and to generate statistics on the differences between them as shown in Figure 10.

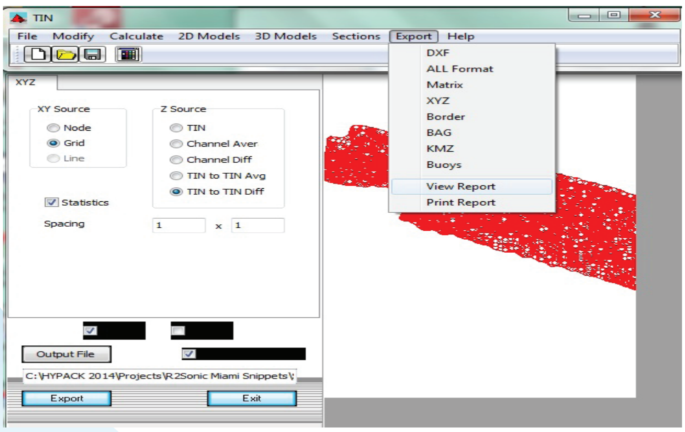

Fig. 10. Export XYZ Data in TIN MODEL

The mean difference between soundings data used MRU heave and the soundings data used RTK heave and the standard deviation for the differences were calculated as follows:

Arithmetic means for differences ($\bar{x}1$ - $\bar{x}2$) was: 0.00

Standard deviation for the difference (s1-s2) was: 0.18 feet (5.5 cm)

The mean and standard deviation were calculated for the differences between two processed surfaces of soundings using (TIN to TIN) module in HYPACK software. The mean showed no difference between both surfaces while the standard deviation was 5.5 cm. The standard deviation for this difference between two surfaces of 5.5 cm has to be checked if it is within the limit of uncertainty of the project.

According to the minimum standard for hydrographic survey (IHO SP44, 2008), the maximum allowable TVU for the special order is calculated based on the IHO standard equation:

Uncertainty in depth = $\pm\sqrt{a^2 + (b \times d)^2}$ .... (5)

Where the term (a) denotes the constant error limit and the term (b x d) denotes the depth dependent error limits, given as (a) = 0.25 m, (b) = 0.0075 m and (d) =13.72 m. The measurement of heave and tide, along with other less significant errors, are considered to form part of (a) (Imahori et al., 2003; IHO standards, 1998). So, the maximum allowable TVU for the project based on the equation 5 is:

Uncertainty in depth = $\pm\sqrt{(0.25)^2 + (0.0075 \times 13.72)^2}$ = 27cm.

The standard deviation for the difference between the two surfaces is 1 = 5.5 cm and the uncertainty for the difference between two surfaces is 2 = 2 x 5.5= 11 cm using 95% confidence level compared with the limit of the uncertainty in depth for the project TVU (27 cm according to IHO standard for the special order). That is to say, that the calculated uncertainty for the project is within the permissible uncertainty by IHO standards.

Hypotheses Testing

The mean difference between MRU heave and RTK heave was tested using paired samples T-Test and Wilcoxon signed ranks Test using SPSS and MINI TAB programs. The hypotheses testing results were deduced from both tests as follows:

From Table 5-7, the mean difference between RTK heave and MRU heave was -0.0158 ft (.48 cm) which is less than 5 mm and P-value was 0.000 with confidence level 95%.

Because the P-value <.05 , so null hypothesis H0 which assumed that there is no significant difference between MRU heave and RTK heave was rejected and cannot reject H1 which assumed that there is a significant difference between the mean of MRU heave and the mean of RTK heave.

Based on statistics analysis, this significant difference is -0.0158 ft (0.48 cm) just only 4 mm with confidence level 95% which means both heave signals are not perfectly the same due to the difference of equipment to measure heave (GPS OR MRU). However, according to the IHO standard and the maximum allowable TVU in equation (4), the uncertainty in depth was calculated to be 27 cm compared with the difference between RTK heave and MRU heave which did not exceed 0.5 cm, i.e., still within the limit of uncertainty of the special-order project, which is 1% from the maximum value of the heave (-1.61 ft (49 cm)). According to confidence level 95 %, 0.5 cm is not considered significant for the overall research.

Therefore, all the above revealed the possibility of using:

- RTK heave as a replacement of MRU heave in hydrographic survey or as
- An alternative source for getting heave as a backup system for getting heave as long as, the differences do not exceed the maximum allowable total vertical uncertainty.

LIMITATION OF USAGE OF RTK HEAVE

The First Problem

Despite the benefits of using RTK heave as a replacement of MRU heave or heave compensator, this replacement may face one drawback because of the possibility of having RTK outage because of the radio link. However, hereafter some of suggested solutions to avoid the RTK outage:

The First Solution

Using Post Processing Solution (PPS) when collecting RTK data to overcome the RTK outage. In case of using the RTK heave and MRU heave together as a double check or as a backup. A GPS outage occurs when fewer than four valid satellite measurements are available at each update. The longer the outage time, the less accurate navigation solution is obtained. In this case, it is possible to take the advantages of the INS system as self-content equipment, especially the heave signal measurement (vertical component) to bridge the GPS height gaps during the hydrographic survey operation and taking advantages of both systems characterizations by spectrally fusing both signals to have a single signal with all vessel's dynamics included (El-Assal, 2009).

The Second Problem

In this research the RTK GPS provides the high frequency movement (heave) but does not provide the other degree of freedom (movement of ship) which is (roll, pitch, yaw, sway, and surge) and all six degree of freedom is very important for Multi-Beam Echo Sounder (MBES) work.

The Second Solution

RTK GPS heave is completely suitable for single beam echo sounder survey and as a backup for MRU heave in MBES survey.

CONCLUSION

Heave is a major contributor to the uncertainty in depth measurements because of the wind and waves on the free water surface. MRU measures heave, but it has some drawbacks, problems and errors as reported by several studies such as heave drifts error. MRU was influenced by vibration and the magnetic field beside it is very expensive (Böder, 2008). Nowadays, RTK GPS is not only used in positioning (x, y and z) with centimeter accuracy nor for getting tide in real time related to the ellipsoid, but also it can be used for measuring and calculating heave signals.

Descriptive statistics, correlation, testing the normality, paired samples t-test and Wilcoxon signed ranks tests to compare RTK heave signals with MRU heave signals were done to investigate the possibility of using RTK heave instead of MRU heave and the results are:

- Based on statistical analysis, the difference between RTK heave and MRU heave has a difference which is -0.0158 ft (less than 0.5 cm) with confidence level 95%. The small difference between both heave signals can be referred to the different equipment measuring heave (RTK GPS and MRU), their difference in accuracy and sampling frequency in addition to their different techniques for measurements. However, according to the IHO standard and the maximum allowable TVU in equation 2, the uncertainty in depth was calculated 27 cm for average depth of 13.72 m compared with the uncertainty for the difference between RTK and MRU heave signals which still lies within the limit of uncertainty as specified by IHO special order for the project.

- The difference between RTK heave and MRU heave did not exceed 5 mm (i.e. about 1% from the maximum value of the heave (-1.61 ft (49 cm)). The calculations were based on confidence level 95 %.

- Using RTK heave is easy to apply and install on any rubber boat or small boat in all hydrographic surveying conditions. No consideration for magnetic and vibration problems if RTK GPS heave utilizes MBMAX 64bit module HYPACK software package.

- Therefore, all the above revealed the practical possibility of using RTK heave as a replacement of MRU heave in hydrographic survey that works as an alternative source for getting heave as a backup system for getting heave and as long as the differences do not exceed the maximum allowable total vertical uncertainty.

Acknowledgments (All sources of funding of the study must be disclosed)

We would like to thank Mr. / Pat Sanders and HYPACK Company for sponsoring and supporting this research by free license of the software for three years and we appreciate that one of the researchers was the first hydrographer to use the MBMAX 64 bit module and took part in its improvement while testing it. The researchers would also like to thank the ARAB ACADEMY for SCINCE, TECHNOLOGY and MARITIME TRANSPORT (AASTMT) for the fund.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

S. Blake, C. Hill, T. Moore, C. Hide, and D. Park, "A heave compensation algorithm based on low cost GPS receivers," *Journal of Navigation*, vol. 61, no. 2, 2008, doi: 10.1017/S0373463307004651.

C. C. Chang, H. W. Lee, and I. F. Tsui, "Preliminary Test of Tide-Independent Bathymetric Measurement Based on GPS," *Geomatics Research Australasis*, vol. 76, 2002.

J. M. Godhavn, "High quality heave measurements based on GPS RTK and accelerometer technology," in *Oceans Conference Record (IEEE)*, 2000. doi: 10.1109/oceans.2000.881277.

IHO, *Manual on Hydrography. Publication M-13*. 2005.

I. H. O. IHO, "STANDARDS FOR HYDROGRAPHIC SURVEYS - Special Publication No. 44," *International Hydrographic Bureau*, 2008.

P. Kielland and J. Hagglund, "Using DGPS to measure the heave motion of hydrographic survey vessels," in *Proceedings of the Annual Meeting - Institute of Navigation*, 1995.

A. A. Gasm Elseid, A. Osman Hamza, and A. Fragoon, "DEVELOPING A REAL TIME ALGORITHM FOR DIAGNOSING GLAUCOMA," *ICTACT Journal on Image and Video Processing*, vol. 9, no. 2, 2018, doi: 10.21917/ijivp.2018.0269.

Böder, "Investigation of Attitude Sensors for Hydrographic Applications," 2008.

J. M. Caldwell, "The Step Resistance Wave Gauge."Proceedings of the First Conference on Coastal Engineering Instruments," California, 1955.

A. N. , A. E.-R. and S. M. A. 5- El-Assal, "On spectral fusion of GPS and heave data in support of Multibeam hydrographic surveying," Cape Town, South Africa, 2009.

Grover, "Observations on Ship Motions at Sea."Proceedings of the First Conference on Ships and Waves.," Hoboken, New Jersey, Oct. 1954, pp. 351–363.

Marine Services Department, "INDYNAMIC UNDER KEEL CLEARANCE," pp. 4–4, 2005.

P. J. V. 13- Rapatz, "Vessel Heave Determination Using the Global Positioning System. M.Sc.E," University of New Brunswick, New Brunswick, 1991.