Development of a GPS-buoy for monitoring water surface elevations at estuaries

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Abstract*—This research aims to develop a tide and wave monitoring system, which can be mounted on the data buoy, for monitoring the water surface elevations at the river mouth region. Because wave data can be calculated from the raw data of GPS receiver and the gyroscope, this research also intends to compare the wave data from both sensors. A system including a data logger, GPRS modems, a RTK (Real Time Kinematic) GPS receiver and a gyroscope has been integrated and mounted on the Suao data buoy, which is operated by the Coastal Ocean Monitoring Center (COMC), National Cheng Kung University (NCKU), Taiwan, to provide the wind, wave, and current data at the coastal area near Suao. The GPS-buoy system measures the water surface elevation, the velocities and the altitude of the buoy hourly. These raw data are then analyzed to obtain the wave and tide data. The tide data obtained by the GPS-buoy are validated by comparing with those obtained from the neighboring Suao tide station. Inside the GPS-buoy, water surface elevation obtained from the gyroscope have also been compared with those obtained from the GPS receiver. This study shows that the tide data obtained from the GPS-buoy agree well with those recorded by the neighboring tide station. Furthermore, the water surface elevations measured directly by the GPS system agree well with those determined from the raw data of the gyroscope on the same GPS system.

Keywords—VBS-RTK; GPS; data buoy; real-time; water surface elevation

I. INTRODUCTION

Real-time tide data at estuary area are usually used as the boundary conditions in the simulation of river water level for justifying the flood risk. However, there is no platform or construction to setup the tide sensor at the estuary area. Data buoy has been verified to be a stable platform for ocean monitoring and has been deployed worldwide to provide the meteorological and oceanographic data. GPS-buoys have been utilized to measure the sea water level for validating the data obtained by the altimeters on satellites. However, so far the GPS-buoys have not been used for operational tide monitoring at the estuary. In Taiwan fifteen data buoys have been deployed on the oceans near Taiwan and operated by the Coastal Ocean Monitoring Center (COMC), National Cheng Kung University (NCKU). In America, NOAA installed a water column measurement instrument mounted at sea bottom and connected to the deep ocean data buoy for detecting tsunamis. Their coastal data buoys do not monitor the real-time tidal level. Thanks to the advances in GPS technologies, the accuracy of elevation measurement can reach mm level. Hence, developing a real-time GPS system to be mounted on the data buoy for measuring water surface elevation becomes possible. Consequently, both the tide and wave data can be determined from the measured elevation.

To investigate the characteristics of waves, the wave parameters need to be provided in time domain. Accordingly, raw data of water surface elevation in the time domain are required. Operational data buoy systems utilize the gyroscope to measure the motion of buoy. These data are then transformed into statistical wave data. The buoys do not provide raw data of water surface elevation.

This study develop a GPS system which can be mounted on the buoy to measure directly the real-time water surface elevations for determining both the tides and waves without establishing a RTK reference station. One goal of this study is to develop a GPS-buoy for real-time tide observation at estuaries, the other is to validate the wave data obtained from the accelerometer by comparing them with those obtained from the GPS system.

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II. RELATED RESEARCH

Harigae et al. (2005) developed a Kinematic GPS receiver, which can be mounted on a data buoy to achieve cm-level positioning in both horizontal and vertical directions. A high-pass filter was used to extract the movement of the buoy and thus minimize GPS positioning errors. The proposed GPS-buoy can be applied to measure wave, tide and tsunami. For real tests, they utilized a receiver of car navigator class instead of a kinematic GPS receiver on a buoy, because the test will be complicated and expensive.

Doong et al. (2011) utilized velocity signals of a GPS receiver on a buoy to obtain wave data. The displacement spectrum was transformed from the velocity spectrum. The GPS receiver was installed on a moored accelerometer buoy to verify wave parameters. The results indicated that using velocity signals is a reasonable alternative for measuring waves.

Herbers et al. (2012) mounted different types of sensor systems on the same buoy, including accelerometers-tilt-compass sensors (ATC), GPS receivers based on the Doppler shift in GPS signals (GDOP), and GPS receivers based on SBAS absolute position data (GPOS). They found that horizontal wave displacements are accurately resolved by all three SBAS receivers, and vertical displacements are accurately resolved by one of the SBAS receivers.

Kuo et al. (2012) utilized GPS buoys using PPP (Precise Point Positioning) technique to observe high-frequency sea level variations which were identified as waves, meteo-tsunamis, and tides. The PPP technique can be used to overcome limitations of SPP (Single Point Positioning) and DGPS (Differential GPS) methods.

Joodaki et al. (2013) utilized a single GPS receiver on a buoy to measure ocean-surface waves. In that study, they used a simple high-pass filter algorithm on the GPS position data.

Waseda et al. (2011) used a GPS system developed by Harigae et al. (2005) on a drifting buoy and a moored oceanographic buoy (K-TRITON buoy) to measure surface-wave. Observations of the drifting buoy were compared with the Hiratsuka tower wave record. Both 1/10 significant wave heights and periods correlated well with the tower observations. Observations of K-TRITON and the drifting buoy were compared too and the results suggest that the K-TRITON buoy motion determined wave heights correctly.

III. METHODOLOGY

In order to get real-time and accurate tide and wave data, this study utilizes the Virtual Base Station Real-Time Kinematic (VBS-RTK) positioning technology and a compatible receiver for the GPS system. To validate the water surface elevation, procedures to generate water surface elevation data from accelerometer data and data processing of the GPS system are introduced.

A. VBS-RTK positioning technology

Real time kinematic (RTK) positioning technology is based on the carrier phase of GPS, GLONASS, Galileo positioning systems. Using corrections from reference stations, the accuracy can reach cm level. Consequently, this technology can be applied to determine the water surface elevation. RTK positioning technology uses the carrier wave to compute positions. The length of the carrier wave in L1 signal is 19 cm. Compared with that using the coarse-acquisition (C/A) code which is broadcasted in L1 signal, the accuracy of using the carrier wave in L1 signal can be improved over one thousand times. For instance, 1 % error in measurement of carrier phase corresponds to ±1.9 mm error in baseline estimation.

In this study, a dual-frequency GPS and GLONASS receiver is installed on the SUAO buoy, it's a rover station. The rover station needs real-time signals from a reference station to conduct RTK computation. After computation, the accuracy of position relative to the reference station can reach millimeters. Generally speaking, the accuracy of a dual-frequency system is 1 cm ± 2 ppm (parts-per-million) in horizontal direction, and that in vertical direction is 2 cm ± 2 ppm.

A reference station can be a physical station or a virtual station. In this study, signals from the VBS-RTK control and computing center are used to complete RTK computation. This service is established and operated by NLSC (National Land Surveying and Mapping Center) in Taiwan, and it provides dual-frequency signals of GPS. It is not necessary to setup a physical reference station for correction.

Based on this technology, this research develops a GPS system to observe real-time tide data on an operational coastal data buoy. Meanwhile, after proper arrangement on firmware of data logger, the GPS system samples water surface elevation hourly during a few days in August 2013 for study. Because these raw data of water surface elevation are measured directly, they are utilized to validate those data generated by the accelerometer.

B. Analyzing of water surface elevation data

The gyroscope, which consists of an accelerometer, an inclinometer, and a compass, is fixed in the hull and the axis of the accelerometer is set to be perpendicular to the hull plane. The acceleration is measured ten minutes long every one hour at a sampling rate of 1 Hz. Data of water surface elevation is generated through the following procedure. As shown in Fig. 1, the raw data of acceleration is transformed from the time domain to the frequency domain using the FFT algorithm. The power spectral density and phase spectrum of the acceleration is calculated, and noises are filtered out. Then the acceleration spectrum is transformed into the power spectral density by the transfer function. The power spectral densities are smoothed by a Bartlett's window with 32 degrees of freedom. The phase spectrum of acceleration is added by 180 degrees to get that of the water surface elevation. In the last procedure, the smoothed power spectral density and the phase spectrum of the water surface elevation are combined together to generate water surface elevation by the inverse FFT algorithm.

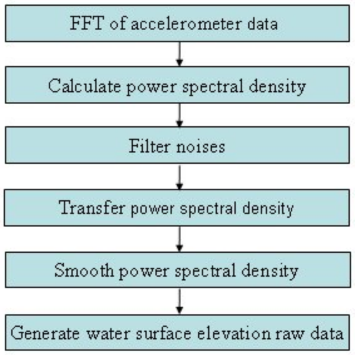

Fig. 1. Procedure to obtain water surface elevation from the accelerometer of a data buoy.

C. *Analyzing of tide data*

Data of altitude, velocities, and the quality index for RTK computation are sampled at 1 Hz for 10 minutes long every one hour. The altitude data are quality controlled by the quality index in each record before they are used. In the data quality control procedure for the altitude, only data with quality index equals to "RTK fixed" are utilized.

D. *Analyzing of errors*

Quantitative errors for comparing are the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE), which are defined in Eqs. (1) and (2), respectively. In Eqs. (1) and (2) y_t and $\hat{y}_t$ represent the observation of the tide station and the GPS-buoy. N is the number of observations.

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(y_t - \hat{y}_t)^2} \tag{1}$$

$$MAE = \frac{1}{N}\sum_{t=1}^{N}\left|y_t - \hat{y}_t\right| \tag{2}$$

IV. RESULT AND DISCUSSION

A. *Test data in the laboratory*

Figure 2 shows the flow chart for carrying out the laboratory test. In the GPS system, the GPS receiver provides the altitude and quality index to the receiving system in 1 Hz. Data from the GPS system are transmitted to the receiving system for quality control and analyzing. Notably from Fig. 2 that if the signals from satellites, the GPS receiver, the GPRS modem, the GPRS network and the VBS-RTK control and computing center are all working normally, the RTK computation will be successful and the data quality index will be equal to four. If any is abnormal, the data quality will not be four and the altitude data will not be used.

Both the static and dynamic tests were conducted in the laboratory. In order to have a clear sky view, both tests were conducted on the thirteenth floor of a building. During the tests, the data of altitude above the geoid are acquired from the GPS system. For the laboratory test, the time zone used in Figs. 3 and 4 is the Taiwan Standard Time. The goal of the static test is to evaluate the accuracy of the GPS system in static state. The standard deviation is computed. The time series of the altitude above geoid is plotted in Fig. 3, and the results are analyzed.

Due to the sheltering effect, the GPS signals obtained from the ground floor are of poor quality and will not be used for further data analysis. Hence, both the static and dynamic experiments were carried out on the plane roof of a thirteenth-floor building. Because the rotating machine with an arm can not be transported to the thirteenth floor, the dynamic test is conducted by using the human arm to simulate the mechanical rotating arm. Although it is not so accurate to validate the data of elevation as utilizing a machine, the circular motion can be checked and the average period can be checked with a clock.

During the static experiment on August 24 13:00 – 25 08:00 in 2012, the test was conducted continuously for about 19 hours. There are totally 68,400 samples of altitude data acquired at a sampling rate of 1 Hz. In the records, numbers of samples with quality index not equaling to four are 3,843. These data are not used for further analyzing. The average altitude data above the geoid is 67.226 m, the standard deviation is 0.012 m, the maximum is 67.291 m, the minimum is 67.042 m and the full range is 0.249 m. Based on the specification of the GPS receiver, the RMSE in the vertical direction is 1.5 cm ± 1 PPM. As the RMSE under static condition is smaller than the specified one, the accuracy of altitude data is proved.

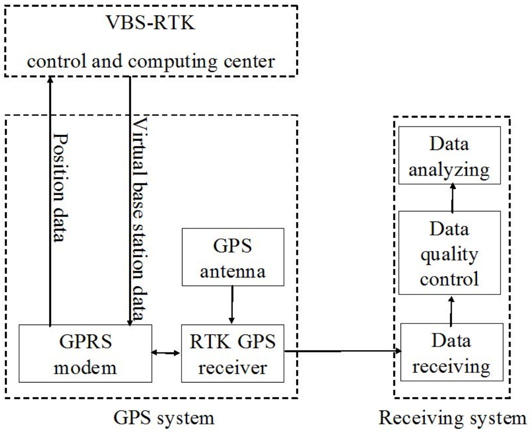

Fig. 2. Flow chart for obtaining the position data in the laboratory test.

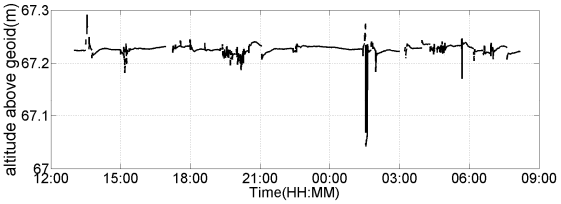

Fig. 3. Altitude above geoid obtained in the static test.

The goal of the dynamic test is to check the accuracy of the measured amplitude and period of the circular motion. The line in Fig. 4 demonstrates that the GPS system can detect the circular motion. A ruler was utilized to measure the highest and lowest position of the GPS antenna. They are about 2.04 m and 0.9 m, respectively. This corresponds to a diameter of about 1.14 m. According to the data shown in Fig. 4, the estimated difference in elevation is about 0.92 m. Both are roughly identical. In Fig. 4, sixteen periods of circular motions are displayed and the total duration is about three minutes, so the average period is about 11.2 sec. The actual rotating period estimated by a stopwatch is about 9.0 – 10.0 sec. Both are roughly the same.

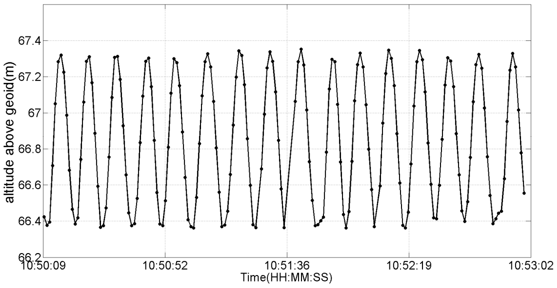

Fig. 4. Altitude above geoid obtained in the dynamic test.

B. *Arrangement of field test*

For the field test, the GPS system was installed on the data buoy deployed at Suao. Figure 5 shows the outlook of this GPS-buoy in situ. This buoy provide physical data, such as wave, current, wind, air and water temperatures, barometric pressure, etc., and is operated by COMC, NCKU since 1999. The buoy hull is of discus type with a diameter of 2.5 m.

Fig. 5. Outlook of the Suao data buoy in-situ.

The position of Suao buoy is shown in Fig. 6. The water depth is about 20 m and the nearest distance to the coast is 2.1 km. Suao tide station is located in Suao harbor and run by CWB (Central Weather Bureau), Taiwan. The real-time tide data can be acquired from the CWB homepage and are utilized for comparison with those obtained from GPS-buoy. Distance between the Suao buoy and the Suao tide station is 4 km and the latter is located at a degree of 194 (clockwise) with respect to the former.

During the field experiment, two typhoons, TRAMI and KONG-REY, pass through east of Taiwan. Tide and wave data collected from various sensors were collected and compared.

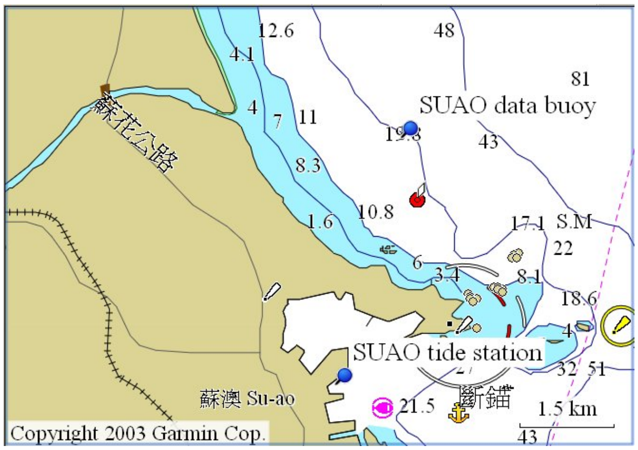

Fig. 6. Locations of the Suao data buoy and the Suao tide station.

C. *Data Acquiring and processing of field test*

Figure 7 shows the flow chart of the data acquiring and processing for the field test of the GPS-buoy. In the GPS system, the GPS receiver provides the altitude, quality index data, etc. These data are stored in the data logger in digital form. The acceleration data produced by the gyroscope are transmitted to the data logger through RS-232 interfaces. The data sampling rate at the data logger is 1 Hz. Above-mentioned data are sampled every one hour for 10 minutes long and are stored in a compact flash card. After sampling 600 points of data, these raw data are transmitted via the GPRS modem to the receiving system located at COMC, NCKU.

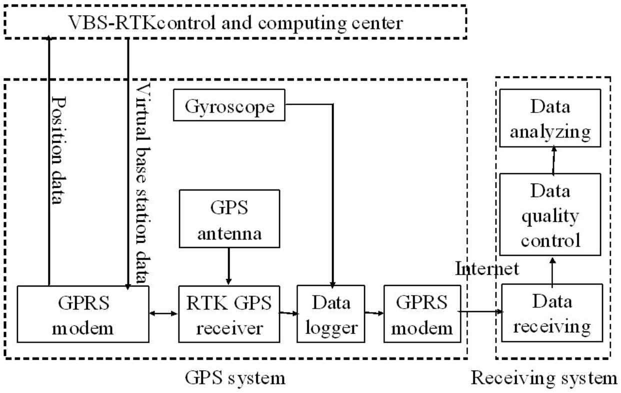

Fig. 7. Flow chart of data acquiring and processing for the field test of GPS-buoy.

D. *Tide data*

Figure 8 compares the hourly tide data obtained from the conventional tide gauge and the GPS-buoy from August 20 to 22, 2013. Corresponding comparison from August 29 to 31, 2013, was shown in Fig. 9. The time zone in both figures is Taiwan Standard Time. In Figs. 8 and 9, the tide data obtained from the GPS-buoy and Suao tide station are denoted by dotted line with squares and circles, respectively. Meanwhile, the percentage of good altitude data is defined as the ratio of number of data with "RTK fixed" quality index to number of all data from the GPS-buoy. This percentage is also displayed as dotted line with diamonds in both figures. The datum used for the Suao tide station is TWD97. In order to compare tide data on the same datum, altitude data of the GPS-buoy is adjusted to have the same datum as that of Suao tide station.

Notably from Figs. 8 and 9 that the real-time tide data from the GPS buoy fits well with those from the Suao tide station. Some tide data from GPS-buoy is missing in Figs. 8 and 9, because the lack of good quality. Notably also that almost every high tide measured by the GPS-buoy is lower than that of Suao tide station. Only on Aug. 30 the tide elevation measured by the GPS-buoy is larger than that of Suao tide station. The reasons for these differences may be due to that during the data sampling procedure the tide station is fixed, while the buoy keep moving. The pitch and roll motion of the buoy may introduce fluctuation to the real water surface elevation. Besides, the two sensors are located at different locations.

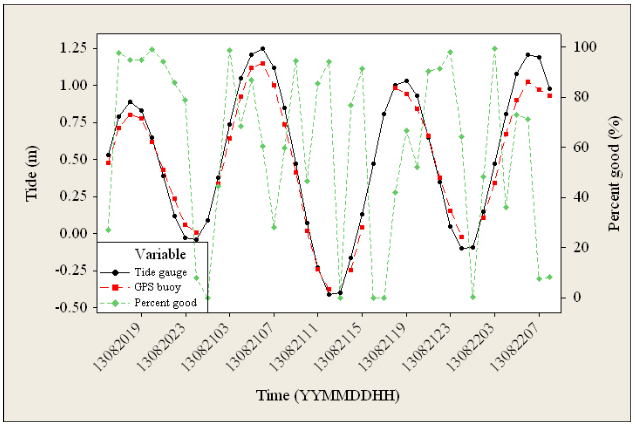

Fig. 8. Comparison of tides obtained from GPS-buoy and tide gauge (Aug. 20-22, 2013).

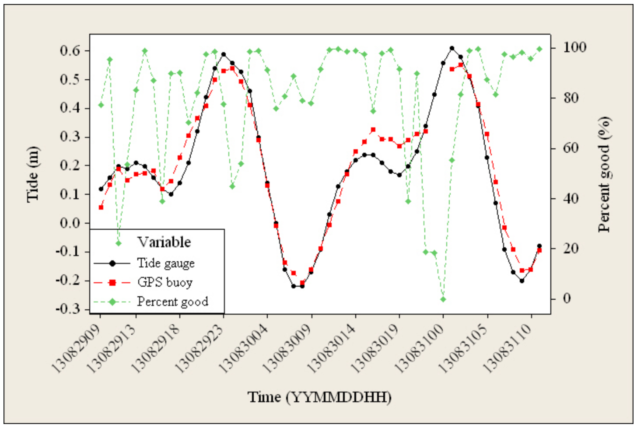

Fig. 9. Comparison of tides obtained from GPS-buoy and tide gauge (Aug. 29-31, 2013).

E. Wave data

Figures 10 to 12 compare the water surface elevations obtained from the GPS and the accelerometer on the buoy under various significant wave heights. The value in Fig. 10 is 0.65 m and increases to 1.47 m and 2.81 m in Figs. 11 and 12, respectively. The quality indices for the GPS data are also shown in the figures to provide more information. Notably that when the quality equals to one, the water surface elevations from the GPS contain noises. Except unsuccessful RTK computation, Figs. 10 to 12 show that the water surface elevations obtained from the accelerometer fit well with those directly measured by the GPS receiver in the same system. The comparisons in Figs. 10 to 12 indicate that both the raw data and the method for transforming the raw data of the accelerometer to the water surface elevation are correct.

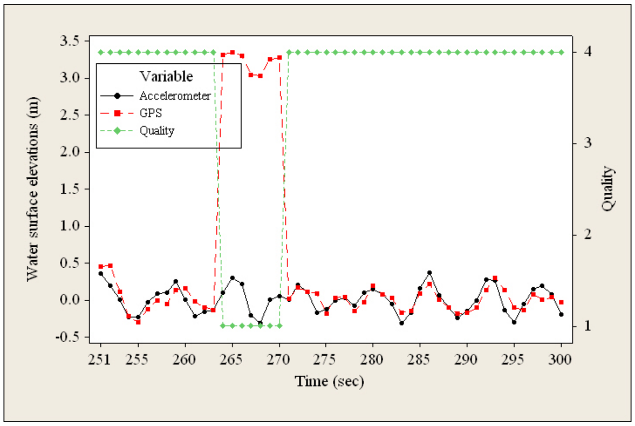

Fig. 10. Comparison of water surface elevations obtained from GPS and accelerometer on a data buoy with a significant waveheight of 0.65 m (Aug. 31, 07:00, 2013).

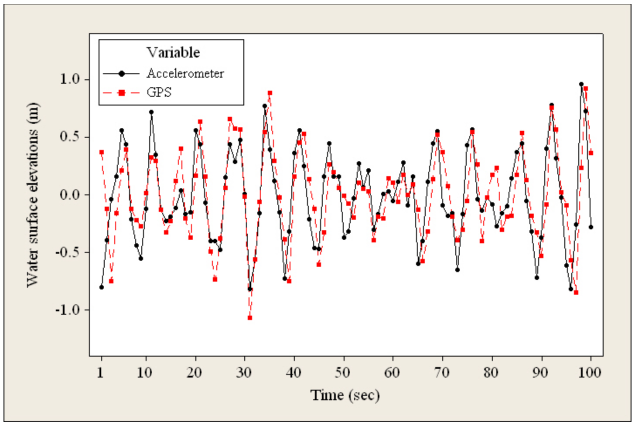

Fig. 11. Comparison of water surface elevations obtained from GPS and accelerometer on a data buoy with a significant waveheight of 1.47 m (Aug. 20, 17:00, 2013).

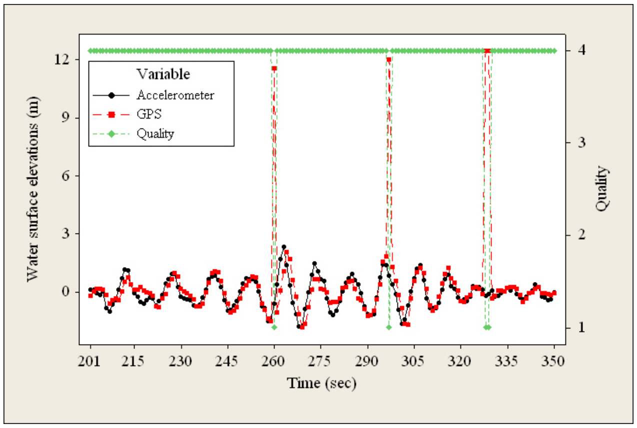

Fig. 12. Comparison of water surface elevations obtained from GPS and accelerometer on a data buoy with a significant waveheight of 2.81 m (Aug. 21, 15:00, 2013).

V. CONCLUSIONS AND FUTURE WORK

A. Conclusions

Two goals of this study are achieved. First, the developed GPS system mounted on an operational data buoy is able to monitor the real-time tide in the estuary and coastal areas, if the GPS signals are corrected by the signals from the VBS-RTK control and computing center. The accuracy of tide data is within 8 cm. Second, the water surface elevation calculated from the raw data of accelerometer is validated to fit well with that measured directly by the GPS receiver in the same system. Both the raw data from the accelerometer on the GPS-buoy and the method used to transform these raw data to the water surface elevation are demonstrated to be correct.

B. future studies

Based on this study the developed GPS-buoy can be deployed at the estuaries for operational monitoring of the water surface elevation. The tide and wave data can be further determined from the observed data. In Taiwan, during the typhoon period, extreme significant wave heights over 10 m are often detected by the operational data buoys deployed in coastal areas. The GPS-buoy can be used as an alternative means to monitor the extreme wave height during the typhoon period and compare with the data obtained from the data buoy.

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The GPS system was installed on Suao data buoy, which belongs to WRA (Water Resources Agency), ministry of economical affairs, Taiwan. The authors would like to thank WRA for supporting COMC to operate the coastal ocean monitoring network for Taiwan. Without these data buoys we will have to launch another data buoy for carrying out this research.

REFERENCES

[1] D. J. Doong, B. C. Lee, and C. C. Kao, “Wave measurements using GPS velocity signals,” Sensors, vol. 11, pp. 1043-1058, 2011.

[2] M. Harigae, I. Yamaguchi, T. Kasai, H. Igawa, H. Nakanishi, T. Murayama, Y. Iwanaka, and H. Suko, “Abreast of the waves: open-sea sensor to measure height and direction,” GPS World, 16, 5, ABI/INFORM Trade & Industry, pp. 16-27, 2005.

[3] T. H. C. Herbers, P. F. Jessen, T. T. Janssen, D. B. Colbert, and J. H. MacMahan, “Observing ocean surface waves with GPS-tracked buoys,” J. Atmos. Oceanic Technol., Vol. 29, pp. 944–959, 2012.

[4] G. Joodaki, H. Nahavandchi, and K. Cheng, “Ocean wave measurement using GPS buoys,” Journal of Geodetic Science, 3(3), pp. 163-172, DOI: 10.2478/jogs-2013-0023, 2013.

[5] C. Y. Kuo, K. W. Chiu, K. W. Chiang, K. C. Cheng, L. C. Lin, H. Z. Tseng, F. Y. Chu, W. H. Lan, and H. T. Lin, “High-frequency sea level variations observed by GPS buoys using precise point positioning technique,” Terr. Atmos. Ocean. Sci., 23, pp. 209-218, doi: 10.3319/TAO.2011.10.05.01(Oc), 2012.

[6] T. Waseda, M. Shinchi, and T. Nishida, H. Tamura, Y. Miyazawa, Y. Kawai, H. Ichikawa, H. Tomita, A. Nagano, and K. Taniguchi, “GPS-based wave observation using a moored oceanographic buoy in the deep ocean,” Proceedings of the Twenty-first International Offshore and Polar Engineering Conference, Maui, Hawaii, USA, pp. 365-372, 2011.