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Development of a GPS Buoy for Ocean Surface Monitoring: Initial Results

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***Abstract*—**This study presents a kinematic positioning approach that uses a global positioning system (GPS) buoy for precise ocean surface monitoring. The GPS buoy data from the two experiments are processed using an accurate, medium-range differential kinematic technique. In each case, the data from a nearby coastal site are collected at a high rate (1 Hz) for more than 24 hours, and measurements are conducted in neighboring tidal stations to verify the estimated sea surface heights. The GPS buoy kinematic coordinates are estimated using epoch-wise pre-elimination and a backward substitution algorithm. Test results show that centimeter-level accuracy can be successfully achieved in determining sea surface height using the proposed technique. The centimeter-level agreement between the two methods also suggests the possibility of using this inexpensive and more flexible GPS buoy equipment to enhance (or even replace) current tidal gauge stations.

***Keywords*—**Global positioning system, kinematic GPS, sea surface height, GPS buoy, tide gauge.

I. Introduction

MALAYSIA is mostly surrounded by an ocean with a total of coastline of 4,675 km, which consists of Peninsular Malaysia at 2,068 km and East Malaysia at 2,607 km. The two distinct Malaysian regions are separated by the South China Sea. Western Peninsular Malaysia also faces the Strait of Malacca [1]. Malaysia's coastal zone has a special socio-economic and environmental significance. More than 70% of the population live in coastal areas, where many economic activities thrive, such as urbanization, agriculture, recreation, eco-tourism, fisheries, aquaculture, and oil and gas exploration. With a large percentage of the population living within 5 km of the coast, the demands for development and industrialization in these areas greatly affect resources and the coastline itself [4].

Although the coastal zone is important in Malaysian development, existing knowledge on this area is still insufficient, as is usually the case in most countries. Relevant coastal and shoreline data in Malaysia are currently collected by many government departments, agencies, private sector organizations, university scientists, and consultants. Moreover, except for tidal elevation and shore-based wind data, data on other important parameters, such as waves and currents, are hardly collected; previously collected data are tailored to a specific purpose and encompass only short durations [1].

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Offshore wave observations and information on storm surges before their arrival to the coasts are very important to coastal disaster prevention. However, coastal tide stations were supposedly the only means to observe ocean and storm surge profiles because of difficulties in offshore observation, until ten years ago [6], [8]. Recently, seabed-installed coastal wave gauges have been repeatedly reported to successfully observe various ocean profiles through continuous data acquisition [3], [5]. However, seabed-installed wave gauges are fixed in a limited area with a water depth of less than 50 m for easy maintenance. Moreover, buoy-type wave gauges with acceleration sensors cannot detect long periods of ocean and storm surges because acceleration is minimal in long-period fluctuations. Therefore, a new offshore observation system is required.

Scholars have recently developed a new offshore observation system that uses a GPS buoy, which does not require seabed maintenance by humans and can be installed in any sea area without any water depth limitation. The main objectives in designing such buoy are to increase buoy stability, create a lightweight buoy, and decrease production cost. By increasing its stability, signal loss can be minimized, and accurate results can be generated. The buoy should be lightweight for easy handling and deployment in remote areas. The buoy should also be low cost to be more affordable.

Short-term field tests on GPS buoys started in 2014 at the Kukup Port area. This study explains the initial field test results and discusses the reliability of the obtained data from a wide frequency range, including short-period wind waves to long-period astronomical and meteorological tides.

The observed GPS buoy data are compared with the Kukup Port tide station data obtained by the coastal wave stations of the Department of Survey and Mapping Malaysia (JUPEM). JUPEM is a Malaysian wave information network established and operated by the Geodesy Section of JUPEM, and the associated agencies of this network include ports and the Malaysian Meteorological Department.

II. Buoy Test Run

A GPS buoy was constructed from a rubbermaid float that served as the buoyant volume. A GPS, antenna, and amplifier were installed on the GPS buoy. A 0.9 m water pipe with about 7.5 kg of ballast and stabilizing fins was fixed at the bottom of the buoy to stabilize and minimize the motion of the buoy from ocean waves. Before it was deployed off the port, the fully assembled GPS buoy was tested in the calm waters of the UTHM Lake to check the stability, water proofing, and reaction time of the buoy when toppling, as shown in Fig. 1.

Fig. 1 Buoy test run at the UTHM Lake to analyze the buoy performance

The test results showed that the buoy was ready for field experiments at sea. Minor modifications were conducted to ensure that the buoy was capable of riding waves without being submerged. Calibration measurement was also conducted to determine the height of the GPS antenna above the water line. Two Leica GPS receivers were used in the experiment.

III. Field Experiments at Sea

The experiment was conducted on March 13, 2014 at Kukup Port, Pontian, Johore. A specially designed buoy equipped with a GPS antenna was deployed about 500 m off the pier. The position of the GPS buoy was estimated relative to a fixed reference GPS receiver on the roof of the building of the Faculty of Civil and Environmental Engineering at UTHM, which was about 30 km away (Fig. 2). The GPS provided real-time 3D position relative to the reference station.

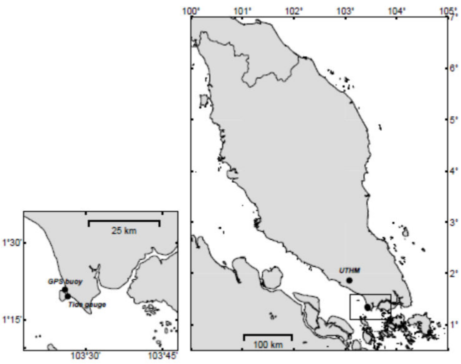

Fig. 2 Location map of the GPS buoy, tide gauge, and reference GPS station

The local vertical component of the GPS solution was one of the sea level measures compared with the "truth" obtained through the tide gauge measurement. No comparable "truth" was available for the horizontal components of the GPS buoy. Fig. 3 shows a schematic of the experiment.

The sea level was measured using a digital tide gauge for comparison with the GPS results. The JUPEM-automated tide gauge on the pier was a floater-operated digital gauge (Fig. 4). JUPEM is the government agency responsible for all survey works in Malaysia. Fifty-second interval data were obtained from JUPEM and were compared with a benchmark. The GPS buoy position solutions also measured the sea level relative to this benchmark. Thus, two independent methods of sea level measurement were established for comparison.

(a) (b)

Fig. 3 (a) GPS buoy experiment near the JUPEM tide gauge and (b) the reference GPS station at UTHM

Fig. 4 JUPEM-automated tide gauge at Kukup Port

IV. Kinematic Processing

The GPS buoy was deployed near the tide gauge and was observed for 24 hours at a data collection rate of 1 Hz. A post-processing kinematic GPS positioning software was developed by the Astronomical Institute, University of Berne, Switzerland, based on the proposed methodology. Dual frequency data were required for a linear ionospheric-free (Lc) resolution. Given that the program was designed for both post- and real-time data reduction, the GPS precise ephemeris information was used by default for data processing [11].

The satellite elevation cutoff angle was set to 5 degrees. After the phase ambiguities were successfully resolved in the initialization procedure, L1 and L2 phase measurements were used to conduct continuous epoch-by-epoch kinematic positioning [2], [9]. When the number of continuously tracked satellites was reduced to below four, this program automatically returned to the ambiguity integer identification stage to determine the correct phase ambiguities.

The buoy constantly floated near the JUPEM tide gauge during the whole operation. The Cartesian coordinates (x, y, and z) of the GPS buoy antenna reference point were readily converted to their corresponding geodetic quantities (ϕ, λ, h), and the instantaneous water level was obtained after reducing the height component h from the antenna reference point down to the water level using the known information on the antenna height.

The JUPEM digital tide gauge provided water level data every 50 seconds. The observed tidal heights were used as the "ground truth" for comparison with the GPS buoy data. The GPS buoy data were processed and filtered in a 150-second running average to reduce the effect of waves. The GPS ellipsoidal height of the buoy was then determined before it was corrected for the Earth's body tide (but not for ocean loading).

V. Geodetic Sea Height Model

A simple reference model was prepared to compare the estimated sea surface height, which was composed of a geoid height distribution model from the reference ellipsoid of WGS-84 and from tidal sea surface height changes [7]. The superposition of the changes in tidal height and the geoid height generated a simple model of sea surface height (Fig. 5). However, this model was too simple. The generated model did not consider factors, such as oceanographic effect, atmospheric pressure changes, and sea wave changes.

The typical frequency of sea waves was significantly high compared with other effects, and the vertical movement may be estimated and removed using the data from a dynamic motion sensor aboard a survey vessel. A moving average (boxcar window) was adopted in this study to remove high frequency changes [2].

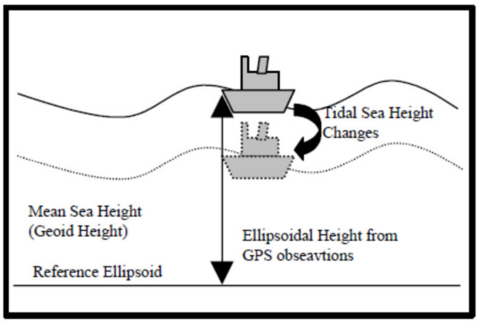

Fig. 5 Schematic image explaining the geoid height, tidal height changes, and height estimation using the kinematic GPS technique

VI. Data Analysis and Results

The position of the GPS buoy relative to the distant site was calculated every second. Fig. 6 shows the mean water level relative to the UTHM reference station (35 km). The figure clearly shows that the variation of low and high tides was approximately 2 meters, and the root mean square was 2.7 cm. The large increase in the last 8 hours could have been caused by an imperfectly corrected cycle slip. Both methods were able to observe semi-diurnal tides. Day tides were more dominant than night tides, in which the difference obtained from both methods was 0.6 m. Low and high tide variations were evident through the tide gauge (1.6 m to 2.2 m) and the GPS buoy (1.8 m to 2.4 m). The difference was 0.2 m.

The tidal record from the Kukup tide gauge was compared with the change in buoy height, which was 1 Hz solution, after using 150 seconds of running average to eliminate the effect of waves. Fig. 7 shows the ocean tide at the Kukup Port gauge. The actual tide during that time had just crested and was starting to descend. The tidal variation during that period was very minimal. However, the mean GPS-determined height was corrected for solid earth tide, also slightly changed, but in the opposite direction. This result diverged from the tidal record by 20 cm.

The wave height recorded by the GPS buoy, which was 0.2 m to 0.4 m, depended on tidal changes. This result was true for this area based on the historical data from the Malaysian Meteorological Department.

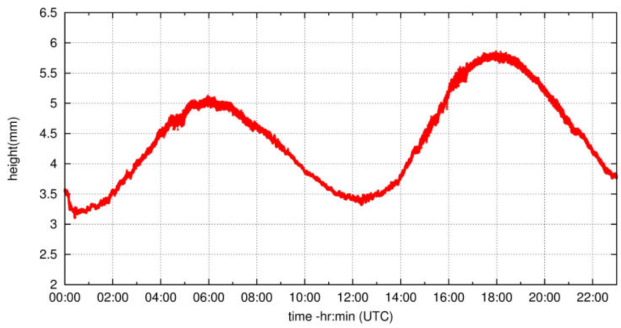

Fig. 6 Waves and tides during the test at Kukup, as observed by the GPS buoy: processing strategy (medium baseline differential solution)

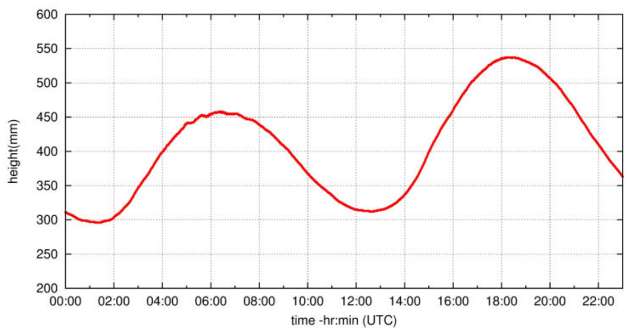

Fig. 7 Change in sea height during the test, as recorded by a local tidal station

VII. Conclusion

A small systematic bias appears as a non-zero mean in the discrepancies between the tide gauge and the GPS buoy water level measurements, as shown in Fig. 4. This bias suggests that further calibration between the two systems is required. One of the possible causes for the bias may be an imprecise height reduction from the GPS antenna reference point to the water level. The antenna height reduction is based on the assumption that the GPS antenna and water level reference points are at the same normal location perpendicular to the surface of the reference ellipsoid. However, this assumption is not necessarily true because ocean waves surrounding the GPS buoy can constantly change the buoy movement. When applications require high accuracy in the post-processing of height determination, the instantaneous behavior of the buoy should also be monitored. This monitoring can be accomplished using an onboard GPS antenna array that consists of at least three GPS antennas with known relative geometric relations [10].

In conclusion, this experiment demonstrates that the precise determination of sea surface height can be successfully achieved using the post-processing kinematic GPS technique. The centimeter-level agreement between the results of the two methods in ocean surface monitoring also suggests the future possibility of using this inexpensive and more flexible GPS buoy to improve (or even replace) tide gauge stations.

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