

Determination on the sea surface height using ship-borne GPS

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ABSTRACT

Sea surface heights (SSHs) are crucial to the application of marine geodesy, and they also can be used to get the information of earth gravity field, ocean currents, tides, and geoid for the purpose of providing research data in oceanography and geophysics. In addition, they are helpful in the economic development, including offshore resource exploration, coastal engineering, marine aquaculture, and so on. Measuring SSHs areas through ship-borne GPS data in coastal won't be affected by the bad altimeter radar waveforms. Besides, it can measure SSHs linearly and provide wide-range and high resolution observations. Precise point positioning (PPP) technique can be used to determine SSHs without the need for a reference station so it can improve the work efficiency. In this study, ship-borne GPS data is used to calculate ellipsoidal height with PPP technique. The calculations will be corrected through Gaussian filter and the global ocean tide model in order to evaluate the accuracy and precision of SSHs from ship-borne GPS data. CSRS-PPP from Natural Resources Canada (NRCan) is be used to process PPP in this study, and its results after correction will be used to evaluate the accuracy and precision of SSHs by means of static tests, crossover difference analysis, and comparison with DTU10 mean sea surface (MSS) model. The static tests shows that the horizontal precision of the calculations from the ship-borne GPS data is about 12.1~15.7 cm, and the vertical precision after tidal correction is about 12.5~14.1 cm. The results of crossover difference analysis show that the values of root mean square after crossover adjustment are about 7.4~14.9 cm, and the results of the comparison with DTU10 MSS suggest that the standard deviation of the differences after crossover adjustment is about 11.9~18.3 cm.

KEYWORDS: GPS, precise point positioning, sea surface height, ship-borne

1. INTRODUCTION

The earth gravity field provides an opportunity to explore the interior and exterior mass distribution of the earth. Ocean gravity measurement can be used for national high-precision basic measurement, ocean and submarine engineering design, and ocean resource exploitation. Thus, the gravity field, as crucial geodetic data, has significant importance. Sea surface height (SSH), which is extensively involved in applications of the ocean gravity field, can be adopted for inversion of the earth gravity field, which acts as the basis for subsequent investigations in relevant disciplines. Additionally, SSH, as an alternative to acquire information on ocean current, tide and geoid, provides assistance in oceanology and geophysics.

Based on the difference in post-processing methods, shipborne GPS altimetry can be categorized into post-processed kinematic (PPK) and precise point positioning (PPP). PPP does not require the assistance of a base station, but relevant research indicates the potential influence of offshore distance on precision. Geng *et al.* (2010) performed a comparative analysis between PPP and PPK with three magnitudes of base length. The analysis revealed the superior performance of PPP with a baseline length above a threshold value, despite its dependence on offshore distance. Specifically, the precision improved relative to the differential positioning method. In addition, PPP has other advantages such as low operation cost and independence of baseline length and data quality at shore stations. Consequently, the current study employs the PPP method to calculate the ellipsoid height based on shipborne GPS data recorded in 2017. Corrections for the vertical distance between the shipborne GPS antenna and the sea surface, ocean tide and earth tide are incorporated for subsequent precision analysis (Chung *et al.*, 2016).

According to above literature review, with a sufficiently long offshore distance for shipborne altimetry—*i.e.*, the distance of the measured region to the coastline is greater than a threshold value—PPP presents similar precision to PPK. The PPP method is a better option with low measurement cost and high flexibility, under conditions of equivalent precision. Therefore, the current study is concerned with internal precision evaluation of the PPP method applied in shipborne altimetry and potential approaches for improvement. The corrected SSH is compared with DTU10 MSS to estimate the external precision, the results of which can provide insights into the feasibility of SSH measurement based on shipborne altimetry.

2. SHIP-BORNE GPS DATA AND PROCESSING METHOD

The survey ship in the current study receives only GPS data, whose precision and reliability depend on the availability of satellites. Thus, a combination of GPS and GLONASS can contribute to an enhancement in the precision of the received data. According to a comparison between the exclusive GPS data and the combined data, the obtained results from the PPP method present a trivial deviation in positioning precision, indicating the slight contribution from complementation of the GLONASS signals (Alkan *et al.*, 2017).

The current study mainly utilizes the two GPS systems installed on the research vessel, Sea Searcher II, to acquire the positioning data, as shown in Fig. 1. The collected shipborne GPS data are employed for precision analysis and comparison study. First, the data collected during the 103 days between April 6 and July 17, 2017, are applied to static positioning tests. Second, according to route crossover, five voyages are chosen for PPP calculation and relevant corrections sequentially. Third, SSH measurement precision is estimated with the difference analysis at crossover points and a comparison study with DTU10 MSS.

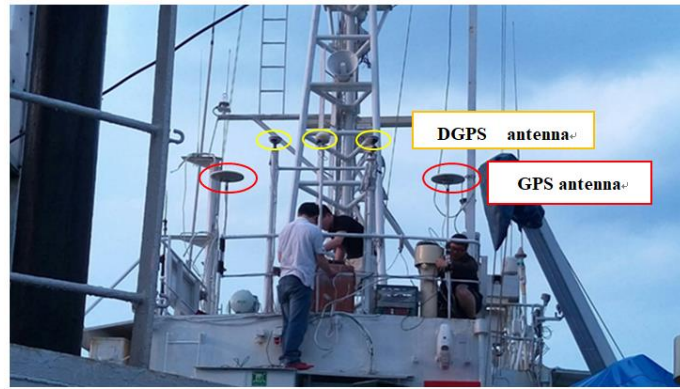


Figure 1. Image of Ocean Researcher II. The DGPS antennas are indicated by the three yellow ellipses in the middle, and the GPS antennas installed symmetrically at two sides of the DGPS Antenna are indicated by the two red ellipses.

Fig. 2 illustrates the measured region. PPP calculation can mainly be performed with online PPP tools or PPP software. The current work involves three solution tools. The first is online CSRS-PPP, developed by the Geodetic Survey Division of Natural Resource Canada (NRCan) in 2003, which has the advantages of simplicity, free charge and favorable precision (Alkan and Öcalan, 2013). The latter two are GrafNav software developed by NovAtel and Bernese software developed by the Astronomical Institute of the University of Bern, Switzerland. Payment is necessary for both GrafNav and Bernese. Bernese involves complicated operations but allows user-defined modifications (Yeh *et al.*, 2011). The current work compares the static positioning results with the three PPP solution tools to elucidate the difference in precision between the online PPP tool and the post-processing PPP software.

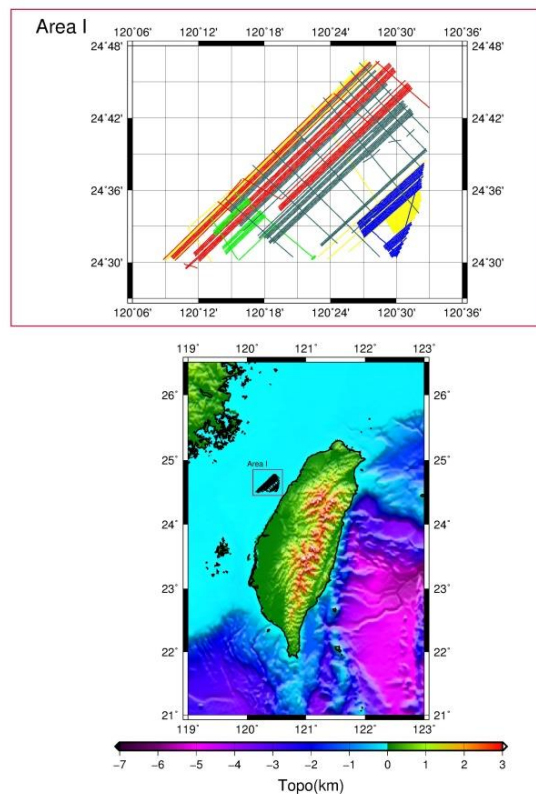


Figure 2. (upper figure) Five voyages in Area 1. The yellow, red, blue, light green, and dark green colors represent voyages A to E, respectively. (lower figure) The location of Area 1 was mainly to the west of Taiwan within Taiwan Strait.

3. COMPARISON OF THE PPP SOLUTION

A comparison study is carried out among the solutions from the three PPP tools—CSRS-PPP, GrafNav and Bernese—as shown in Table 1. The root sum square for the standard deviations of latitude and longitude coordinates is used to estimate the planar positioning precision at different anchoring areas. The calculation results exhibit a precision of 12.1 to 15.7 cm for CSRS-PPP, while the precisions for GrafNav and Bernese are 16.4 to 25.1 cm and 12.2 to 16.5 cm, respectively. This result reveals that CSRS-PPP and Bernese have comparable planar positioning precisions, which are superior to that of GrafNav. In addition, the height positioning precision is evaluated by the standard deviation of ellipsoid height with correction of ocean tide, for the sake of a comparative analysis of the positioning performance at three harboring areas. The corrected positioning precision is 12.5 to 14.1 cm for CSRS-PPP and 9.7 to 18.9 cm for Bernese. Notably, the precision of GrafNav in the Taichung area is up to 93.7 cm, which is greater than the uncorrected level. This result indicates an anomaly in the calculation based on the data in the Taichung area with GrafNav. Therefore, the ellipsoid height data in the three areas with the three PPP tools are compared, as shown in Fig. 3. On May 16, 2017—i.e., beyond 86,400 s in Fig. 3—the solution with GrafNav obviously deviates from the actual case, and the deviation might be associated with the measuring environment, data reliability and software algorithm. It is speculated in the current study that the aggressive filtering treatment in GrafNav produced excessive smoothing for the solution of the ellipsoid height. In contrast, CSRS-PPP and Bernese exhibit a generally similar tendency in the calculation results in terms of ellipsoid height.

Table 1. Planar and height precision with three PPP methods for anchoring in north, west and south areas on different dates.

Time	Area	Software	Horizontal precision (cm)	Vertical Precision before correction (cm)	Vertical Precision after correction (cm)
2017/04/30	North	CSRS-PPP	12.1	31.8	12.5
		GrafNav	16.4	33.2	21.2
		Bernese	12.2	30.7	11.2
2017/05/15	West	CSRS-PPP	15.7	125.3	14.1
		GrafNav	25.1	84.7	93.7
		Bernese	16.5	126.5	18.9
2017/05/20	South	CSRS-PPP	14.4	27.8	12.5
		GrafNav	17.3	28.9	13.7
		Bernese	14.1	25.9	9.7

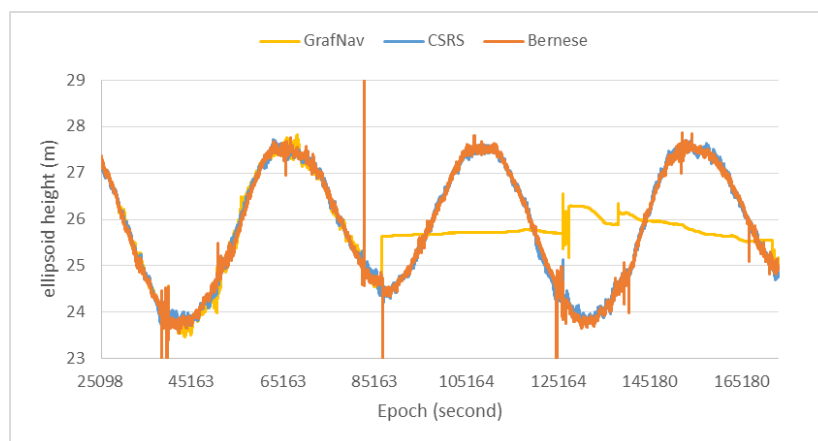


Figure 3. Comparison of the calculation results obtained using three PPP tools.

Fig. 4 illustrates the comparison of planar and height positioning precision at varied areas with the three PPP tools, and the data are reproduced from Table 1. The poorest precision is observed in the Taichung area irrespective of the applied PPP tools. This result indicates that the anchoring at Taichung might suffer from influences such as ocean tide and sea bottom topography. According to the height map of Taiwan, the western seas have comparatively low depth, and the maximum tidal range causes massive error in the acquired data, which is responsible for the overall decreased precision of each tool. According to the height comparison among solutions with the three tools, the solution precision of CSRS-PPP is at the same level as Bernese and slightly better than GrafNav. Considering the advantages of CSRS-PPP, such as convenience, simplicity and free use, the following analyses adopt the CSRS-PPP tool.

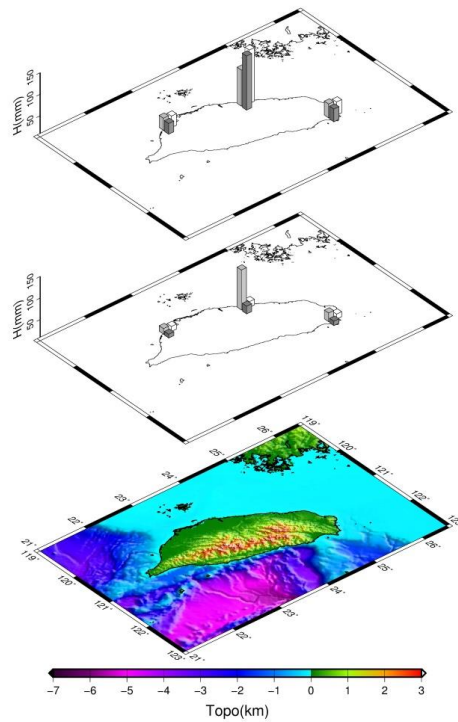


Figure 4. Comparison of positioning precision for anchoring in the harbor with the three tools. The black, gray and white colors correspond to Bernese, GrafNav and CSRS-PPP. The upper figure represents results without correction, and the lower figure represents the corrected results.

4. COMPARISON OF CORRECTION MODELS

Sea vessels not only oscillate due to the effect of wind waves but also fluctuate as a consequence of ocean tides. Thus, the height positioning of the PPP method also suffers from wind waves, noise and ocean tides, so filtering and an ocean tide model must be incorporated to correct the calculated ellipsoid height. The current study utilizes the NAO.99b ocean tide model and Gaussian filtering. The filter smooths the height data and enables error suppression and noise removal, as shown in Fig. 5.

For anchoring vessels, the ocean tide exhibits a higher influence on height positioning than wind waves. Accordingly, the positioning precision at varied anchoring times in different areas was compared based on the CSRS-PPP solution at the anchoring period in the current study. The ellipsoid height was corrected with the NAO.99b ocean tide model. The original height standard deviation ranging from 12.8 to 125.3 cm was reduced by the correction of

ocean tide to 7.5 to 14.1 cm, indicating an impressive improvement, as shown in Fig. 6. The correction of the ocean tide effectively suppressed the height standard deviation, particularly in the west area with high tidal range, where the decrease was up to 88.7%.

Three anchoring periods are selected from each of the three areas—*i.e.*, north, west and south. Four treatments are performed for the CSRS-PPP calculation results in terms of the standard deviation of the ellipsoid height: no correction, correction of ocean tide alone, correction with filtering alone, and dual treatment with filtering and correction of ocean tide. The main objective is to investigate the performance of correction methods regarding height positioning, as shown in Fig. 6. According to Fig. 6, correction with filtering alone produced a negligible effect on the height standard deviation, irrespective of the area. This result indicates that the improvement due to filtering was limited for height standard deviation, mainly due to the stable wind waves and comparatively weak noise within the harbor. However, the dual treatment produced the minimum standard deviation. The subsequent analysis will employ difference analysis at crossover points to evaluate the necessity of filtering during voyage for data acquisition. Effective promotion of height positioning in the harbor can be achieved after the dual treatment, with a standard deviation of 9.7 to 14.6 cm, corresponding to suppression of 53.7% to 88.9%.

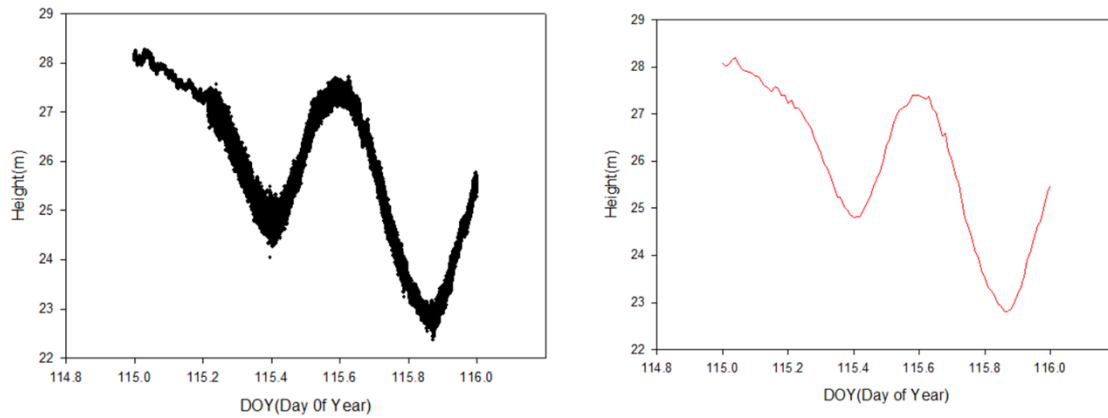


Figure 5. (left) Height map without filtering; (right) filtered height map.

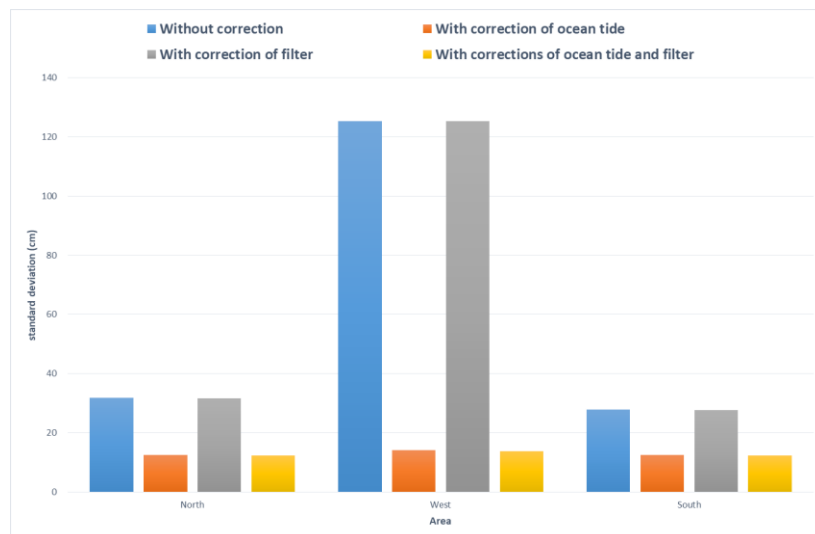


Figure 6. Static positioning precision based on the calculation results with CSRS-PPP and three treatments, including correction of ocean tide alone, correction with filtering alone, and dual treatment with filtering and correction of ocean tide.

5. CONCLUSIONS

In the current study, shipborne GPS data were employed to first test the stability of three PPP methods by static positioning tests. Calculation results with the CSRS-PPP tool were processed with filtering, correction of ocean tide, and correction of the vertical distance between the shipborne GPS antenna and the sea surface to obtain SSH data with precision comparable to those achieved by satellite altimetry. SSH measurements were evaluated in terms of precision via difference analysis at crossover points and comparative analysis with DTU10 MSS. With these calculations and analyses, the following conclusions are drawn.

According to the internal precision analysis, the precision with correction of ocean tide was 12.5 to 14.1 cm for CSRS-PPP and 9.7 to 18.9 for Bernese. The precision with correction of ocean tide was 13.7 to 21.2 cm for GrafNav under normal conditions. This result indicates that the online CSRS-PPP tool exhibits comparable precision to Bernese and GrafNav. CSRS-PPP is favored for its simplicity, convenience and free use. GrafNav and Bernese enable advanced calculation and complex parameter configuration, which are useful for specific cases. In addition, the NAO.99b ocean tide model was employed to correct the calculation results with the CSRS-PPP tool, and the height positioning precision during anchoring was improved to 7.5 to 14.3 cm. A significant improvement in SSH measurement precision was achieved with the correction of ocean tide, and the maximum improvement was 88.7%.

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