The “GPS/GNSS on Boat” Technique

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The opening up of the global positioning system (GPS) for non-military uses provided a new impetus for the study of the sea surface topography (SST) and geoid, especially in coastal areas which are important from the viewpoint of the climate crisis. The application of the “GPS/GNSS on boat” method, as an alternative to traditional (indirect and direct) methods, has provided detailed SST maps in coastal and oceanic areas with an accuracy of up to few centimeters.

Keywords: GPS ; GNSS ; GPS/GNSS on boat

1. Introduction

Researchers critically review the evolution of the “GPS/GNSS on boat” method, used for determining the sea surface topography (SST) and geoid, through the scientific publications that supported each contribution [1][2][3][4][5][6][7][8][9][10][11][12][13][14][15][16][17][18][19][20][21]. GPS and GNSS symbolize the so-called “global positioning system” and “global navigation satellite system”, respectively. The second is wider and involves the first one and other relevant systems which use satellites for determining the position of an object. The precise determination of sea surface heights (SSHs) and geoid in open seas and in coastal areas is one of the problems that attracts modern research interest. This is due to several factors. For example, climate change affects the height and the whole shape of the SST. Moreover, the shape of the geoid and the SST are of special interest in continental shelf areas, closed seas and sea bays [22]. Finally, precise knowledge of the SST can reveal interesting geological structures on the seabed.

Determining the SST has traditionally been achieved by either indirect or direct techniques. The indirect techniques involve astro-geodetic measurements of vertical deflection (VD) [23][24][25][26], measurements of heights using tide gauges [27][28] and gravity measurements [29][30][31][32][33][34]. Using these measurements, the SST or the geoid is calculated through mathematical models.

The direct techniques involve measurements from altimetry satellites (TOPEX/POSEIDON, Jason-1, etc.) [35][36][37][38][39][40][41][42][43][44][45] and the “laser scanner on plane” technique [46][47][48][49]. However, both indirect and direct techniques have weaknesses.

Applying the indirect methods to determine the SST and the geoid, the accuracy achieved is very low, including errors of the order of a few meters. The direct methods, on the other hand, although they directly measure the SST, suffer from double errors, as the position of the satellite or the position of the laser scanner is determined by a GPS/GNSS system in cooperation with an inertial system. Thus, the error of determining the position of the satellite or the plane is added to the inevitable error of the altimeter measurements. In particular, direct techniques face serious difficulties in coastal areas or enclosed seas, where the shape of the earth’s geomorphology creates visual obstacles. In addition, the application of direct techniques is highly expensive.

2. Application of the “GPS/GNSS on Boat” Technique

In their pioneering work, Kelecy et al. (1994) [1] used GPS for the first time for determining sea surface heights. For this purpose, they placed a GPS receiver on two different types of floating buoys (wave rider and spar design) in order to investigate whether dynamic effects related to the platform affect the accuracy of the measurements. The measurements were resolved by two fixed receivers located on the roof of the Institute of Geophysics and Planetary Physics (Scripps Institute of Oceanography) at a distance of 1.2 and 15 km from the GPS buoy positions. The measurements were carried out on two separate days for 45 min each day. Tidal noise was removed from the time series. The results were compared with marine topography measurements provided by the EIS 1 satellite altimeter. The orbit of the satellite during the two-day period of the measurements (21 and 29 November 1991) passed over the point where the two buoys were placed. The small difference in height estimation (just 6 cm) provided by the method with respect to earlier satellite estimates, showed for the first time that the use of the “GPS on boat” technique is an easy, cheap and reliable method to determine the sea surface.

The second application of a buoy with a GPS receiver was presented four years later in the work of Key et al. (1998) [2]. A GPS receiver was deployed at 16 sites along the California coast, 10 km from Texaco’s Harvest platform. A simple wave rider buoy equipped with a GPS receiver was used to estimate sea surface heights (SSHs). The results from the GPS measurements were compared with the altimetry measurements of the TOPEX/POSEIDON satellite, which measured above the buoy area during the experiments. Very small differences of a few centimeters were observed between the marine topography heights provided by the GPS buoy and the TOPEX satellite altimeter measurements. Moreover, the differences between the former estimations with the corresponding ones of the National Oceanic and Atmospheric Administration (NOAA) were also very small (1.5–2 cm). This agreement indicated for the second time that the use of floating GPS can be a reliable alternative method of measuring SSHs.

This innovative, for that period, platform enabled coverage of an area of 20.0 × 5.4 km. The analysis of the data was based on two static GNSS receivers on land whereas the GeoGenius software was used applying the D-GPS/GNSS) method. Data from GPS was filtered using a Vondrak filter with a period of 120 s. Comparing the results taken from the two GPS receivers and the measurements of tide gauges revealed insignificant differences, with standard deviations from 1.9 to 2.7 cm. Taking all parameters into account, the final SST estimated accuracy was about 2 cm.

Rocken et al. (2005) [4] presented their work on the floating GPS technique that was applied for the first time in the open sea (Caribbean Sea). Two experiments were carried out (in 2002 and 2003) with a GPS receiver mounted on a 138,000 ton ship. A second GPS receiver was also mounted for confirmation. Moreover, the PPP method was used for the first time for processing the experimental data. This method proved to be ideal for applications in open seas, far from land [50]. After removing the tide, the authors determined the SSHs and the geoid over the ship’s path. Comparing their results with the local CARIB97 geoid they found a 32 cm mean difference between them.

Marshall & Denys (2009) [5] attempted to estimate the accuracy of the GPS buoy method in the determination of sea heights. For this reason, two GPS buoys were placed in close proximity to existing tide gauges at Chalmers harbor and Dunedin pier in New Zealand. The GPS data collection period was four days. The aim of the work was to find out the difference in height estimates obtained from the GPS buoys and tide gauges in order to estimate the accuracy of the former. The difference in precision and mean difference in height between the tide gauges and buoys was estimated to be less than 1 mm (as an average value), while the standard deviation was estimated to be ±2 cm. This indicated that the GPS buoy technique works well with a high level of accuracy and thus it is suitable for determining sea heights.

The next contribution concerning the evolution of the “GPS/GNSS on boat” method concerns the work of Foster et al. (2009) [6]. The method was applied on a research ship for the first time. The authors noted that changes in the ship’s inclination and movement due to the waves caused serious difficulties in obtaining accurate results. Thus, they proposed a complex methodology based on the simultaneous use of GPS and a radar water level gauge installed onboard the ship. This was the first time that a second measuring instrument had been implemented on a ship. The joint use of the aforementioned apparatus on a research ship allowed the successful determination of the SST at a distance of 200 km from the coast. The ship used in this mission was equipped with a Trimble NetRS single-frequency GPS receiver (Westminster, CO, USA) recording at a sampling rate of 1 Hz and a VEGAPULS62 radar scanner (Schiltach, Germany), recording at the same frequency. The GPS data were analyzed using the TRACK module of the GAMIT program [51]. To remove the effect of tides and the medium-term climate effects, they used a five-minute moving average filter. The distance of the ship (in port) from the GPS reference station (on land), through which the kinematic differential solution was performed, was approximately 25 km, while that from the nearest tide gauge, through which the ocean tide was subtracted, was approximately 2.5 km. However, despite this small initial distance, the ship moved distances of up to 200 km from the reference stations and this resulted in greater uncertainty in the estimation of SSHs. The initial estimate of the standard deviation of the SSHs, in the unfiltered data, reached 69 cm but after moving average filtering, it dropped to 13.3–16.1 cm. The relatively high uncertainties of the SSH estimations were due to both the high ocean tide and the multipath effect as well as to the use of a single-frequency GPS receiver.

The paper published by Bouin et al. (2009) [7] concerns the shipboard GPS SST mapping in the sea around Santo Island, Vanuatu. This brought together the results from three research campaigns in 2004, 2006 and 2007, and provided a detailed local map of the SST with an accuracy of 5–15 cm. A GPS with a sampling frequency of 1 Hz was used and an area up to 80 km from the coast was covered. The GPS data were processed using the GAMIT 10.32 software, while for the application of the D-GPS/GNSS method they exploited a free network of permanent GPS ground stations, including nearby stations (Santo, Port Vila, and Noumea).

While processing the data, the researchers noticed that the height of the GPS antenna on the ship changed depending on the speed of the ship. Thus, they proposed, for the first time, a methodology to overcome this difficulty. To link the position of the ship's GPS antenna to the surface of the water they used a second GPS mounted on a specially designed buoy.

Lycourghiotis and Stiros (2010) [8] applied the "GPS on-boat" method in a large coastal area in the Gulf of Patras and the southern Ionian Sea (Greece). Measurements took place between June and July 2008 on a 43 ft long sailing boat using a Topcon HipperPro type GPS receiver. Throughout the experiment, weather data was systematically collected, such as intensity and wind direction, atmospheric pressure, temperature and moisture and the slope of the boat. GPS data was analyzed using Pinnacle software, while four land GPS stations were used, for the application of the D-GPS/GNSS method, located at the University of Patras, the Village Valmi, Lefkada and Kefalonia. Using a three-step methodology, three types of noise were removed from the SSHs data: (a) outliers, (b) systematic offsets with amplitude of 10 cm and (c) random noise using a moving average filter. Taking into account all the types of uncertainty, it was estimated that the SSHs error was smaller than 15 cm.

The work of Reinking et al. (2012) [9] is the next major contribution to the "GNSS on boat" methodology. This introduced the following innovations: (a) the use of GNSS methodology, i.e., the utilization of satellites beyond those of the GPS system, (b) the use of PPP methodology for the analysis of GNSS data and (c) the use, apart from the main ship, of an escort vessel with a GNSS receiver. Thus, the data were collected from one route. The researchers installed Trimble 4700 GNSS receivers on the 252 m long vessel. The ship was sailing at a maximum speed of 40 knots. Another receiver, a Trimble 4700, was mounted on the escort ship, which followed the ship at a distance of 0.5 nM. All receivers recorded at a frequency of 1 Hz. The long distance of the base stations from the ship's course led them to adopt the PPP methodology for the kinematic resolution of the GNSS data. Tide subtraction was performed using data from tide gauges. Noise removal was performed using a moving average filter. Finally, the authors estimated that the accuracy achieved in calculating SST was about 5 cm.

The work proposed the use of the "GPS/GNSS on boat" technique in the determination of SST through the utilization of ships performing oceanic routes around the planet. This could have important applications as ship routes cover a large part of the ocean surface, whereas due to their repeated routes the accuracy of the results could be significantly improved. The latter idea would be fully utilized a few years later [21].

Ocalan and Alkan (2012, 2013) [10][11] attempted to investigate the limits of the PPP technique in the context of the "GPS on boat" method, comparing their results obtained using PPP with the corresponding ones using the D-GPS/GNSS method. It was the first time that both methods had been used comparatively. It was also the first time that the "GPS on boat" method had been applied in a closed bay. In fact, they took measurements over a two-hour period in Halic (Golden Horn) of Istanbul (Turkey) using an Ashtech Z-Xtreme GNSS receiver (Mumbai, India) mounted on a small boat. It was found that the web service solutions of the PPP method were consistent with the results of the kinematic differential method. Thus, it was proved at a certain level of certainty that PPP can be used successfully in the context of the "GPS on boat" method.

Guo et al. (2014) [12] estimated, for the first time, the SSHs following a complex procedure which involved the joint use of a GNSS on a boat and a ship-borne gravimeter. The ship gravimeter and the GNSS measured anomalies in gravity and SSHs along the ship's track, respectively. The new method was applied on the coastal sea of the Shandong Peninsula in China. Deflections of the vertical (DOVs) on the ship were estimated from the measured gravities using the least squares co-location method.

The next contribution comes from the work of Morales Maqueda et al. (2016) [14]. For the first time, the "GPS on boat" method was applied on a lake while the GPS receiver was installed in a wave glider. The experiment took place on the famous Loch Ness lake (Scotland) under mild weather and the GPS "traveled" 32 km along the length of the lake for about 25 h. The PPP method was applied for the calculation of the SSHs. The D-GPS/GNSS method was also applied for quality control using the static GPS reference stations at Fort Augustus and Inverness. The GPS receivers were logging at 1 Hz. Moving average filters of 3 and 900 seconds were used to remove noise from the data. The calculation of SSHs along the lake revealed a shape of SST with a slope of −0.03 m/km which was in very good agreement with the EGM2008 geoid. After removing the geoid heights from the GPS SSHs, the height anomalies revealed a cyclic variation of ~2.5 cm. It was notable that the calculated accuracy of the GPS SSHs was found to be around 5 cm.

Lycourghiotis (2017) [15] presented an outline of the progress of the "GNSS on boat" method in view of the results of four different experiments which took place in different places over several years. One or more innovations were employed in each experiment. These concerned: (a) The installation of a GNSS receiver on a sailing boat in the Ionian Sea [8]. (b) The installation of two GNSS receivers on a plastic boat in the Corinthian Gulf [16]. (c) The development of a catamaran platform with four GNSS receivers as escort ships in the Gulf of Patras [17]. (d) The installation of a GNSS receiver on a passenger ship for six months [23]. The step-by-step development of the method by using these innovations in different environments allowed, in effect, the improvement of the method's accuracy.

After the aforementioned first application of the "GNSS on boat" method in the Ionian Sea [8], the second application was made in the Corinthian Gulf (Greece) [16]. It was the first time that two GNSS receivers recording together had been used, in order to improve accuracy. Moreover, this area had been studied in the past with the "laser scanner on plane" method [46]. The study took place in the central-eastern part of the Gulf of Corinth and was conducted using a small boat carrying two GNSS receivers at a low altitude from the sea surface (1.1 m) to avoid excessive boat oscillations. Two Topcon HiperPro type GNSS receivers were mounted on a 16 ft long motorboat. Data analysis was based on a double-way path. The D-GPS/GNSS method was used in the first path and PPP in the second. Results from the two different methods were compared with each other and the results from the D-GNNS were confirmed by PPP. Tide effect was removed taking into account data from the "Posidonia" tide station. Using the "transmission of errors" formula the SSHs accuracy was found to be equal to 3.76 cm. Finally, an SST map of the study area was produced.

Recognizing the difficulties that exist especially in coastal areas, where the proximity to land and complex dynamics creates complications for the calculation of SSHs. Chupin et al. (2020) [19] presented two pioneering kinematic systems, based on GNSS, able to map the SSHs at the centimeter level: (1) A GNSS mounted on a floating carpet towed by a boat (named CalNaGeo); and (2) a combination of a GNSS antenna and an acoustic altimeter (named Cyclopée) mounted on an unmanned surface vehicle (USV).

To test both systems a number of field works were performed. To estimate the effect of speed on the water height measurements a first attempt was made, in the context of the so-called static mode, without horizontal movement, in the context of kinematic mode. GNSS was functioning at 1 Hz and the tests were carried out in two coastal zones in the Pertuis Charentais area (France) and in the Noumea lagoon (New Caledonia). After a systematic analysis of their data, the authors concluded that, although the ability of the CalNaGeo GNSS carpet and the Cyclopée systems to precisely measure SSH in motion had been demonstrated, there were yet uncertainties concerning the accuracy, both in terms of system biases and of GNSS processing.

Wanlin et al. (2020) [20] conducted an experiment near Zhiwan Island (South China Sea) in order to determine the SSHs under the HY-2A altimetric satellite track. Two GPS mounted on a twined trimaran plastic platform was designed to measure the SSHs.

The experiment covered an area of 6 km × 28 km. GPS data were calculated with GAMIT software in the context of the D-GPS/GNSS method using three GPS reference stations on land. One tide gauge was also used in order to remove tide effect. The work provided an image of the SST in the experimental area with a surface slope of about 1.62 cm/km. Taking into account all parameters, such as tide gauge time-series, they calculated SSHs with an accuracy of 1.5–4.0 cm with a standard deviation of 0.2–2.4 cm.

The work of Lycourghiotis (2021) [21] constitutes the most recent contribution concerning the methodology "GNSS on boat". GNSS measurements were performed for a period of six months utilizing the repeated route of a passenger ship between Patras (Greece) and Brindisi (Italy), exploiting for the first time the idea of gaining more accurate data by repeated measurements in the same area. The main pursuit was the improvement in accuracy of the SST estimation. The data, collected during the six-month period, was elaborated by adopting a double-path methodology and using the D-GPS/GNSS and PPP analysis jointly. A novel technique was developed and applied jointly with numerical filtering techniques and multi-parametric accuracy analysis to remove the meteorological tide factors.

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