Int. j. adv. multidisc. res. stud. 2026; 6(4):1694-1699

Received: 06-07-2026
Accepted: 16-08-2026

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Power Waveforms Analysis for Sea Wind Speed Estimation from GPS Reflected Signals

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Abstract

In this paper, it is focused the power waveforms of GPS signals to understand the nature of sea surface and then from these waveforms sea wind speed is estimated. The waveforms are analyzed and tested for different sea wind speed conditions. The concept of GNSS remote sensing is used to achieve information from ocean surface. Because, this concept has been utilizing since last two decades for retrieving information from Earth's surface. The waveforms are produced by scattering model using the direct and reflected signals of GPS satellite data. Actually, two models are utilized to generate these waveforms. Firstly, it is used the wave spectrum model to retrieve the ocean surface slopes i.e. up & cross variance. Secondly, Z-V scattering model is used to simulate the power waveforms in where up and cross variance are used as input of this model. From the analysis, it is found that the amplitudes of these power waveforms are changing according to sea wind speeds. It means that there is a relationship between the amplitude of the waveforms and sea wind speeds. The real wind speed of the data campaign site is collected to fit with the amplitudes of waveforms. The linear regression method is used to discover a relation between waveforms and wind speeds. This relation is used to estimate the sea wind speed. From the results, it is obtained that estimated sea wind is matched with collected true wind and the outputs of the model waveforms perform nicely with real data waveforms.

Keywords: GPS, Power Waveforms, Reflected Signals, Scattering Model, Wind Speed

1. Introduction

The concept of GNSS remote sensing technique is first proposed by Martin-Neira in 1993 (Martin-Neira 1993) [19]. The concept is called as Passive Reflectometry and Interferometry System (PARIS) to measure sea surface height, GNSS-R (Global Navigation Satellite System Reflectometry) as a new remote sensing tool was widely studied (Katzberg and Garrison 1996; Garrison *et al*. 1998 [7]; Clarizia *et al*. 2009 [5]). At present, GPS reflected signal processing has become a hotspot in global navigation and positioning research area (Lu *et al*. 2009) [17]. In the last decade, airborne and LEO (Low Earth Orbit) satellite GNSS-R data is collected successfully to measure earth surface parameters, including sea surface wind speed and direction, significant wave height, sea altimetry, soil moisture and so on (Clarizia *et al*. 2009; Zavorotny and Voronovich 2000; Hammond *et al*. 2020; Li *et al*. 2021; Asgarimehr *et al*. 2022; Guo *et al*. 2022) [5, 25, 10, 15, 2, 9]. During the last decades, Global Navigation Satellite System Reflectometry (GNSS-R) has been extended to observe, e.g., sea state (Zavorotny and Voronovich 2000; Marchan-Hernandez *et al*. 2010; Li *et al*. 2023; Xia *et al*. 2025; Zhou *et al*. 2026) [25, 18, 16, 24, 27], soil moisture (Arroyo *et al*. 2014) [1], sea ice (Fabra *et al*. 2012) [6], and sea level (Roussel *et al*. 2015; Zhang *et al*. 2015) [21, 26].

Monitoring the ocean and its rapidly variations is a great challenge for recent society. Even the measurement of sea wind speed from water surface is more challenging due to non-coverage are of synoptic observations (Hammond *et al*. 2020; Li *et al*. 2021; Guo *et al*. 2021; Asgarimehr *et al*. 2022; Guo *et al*. 2022) [10, 15, 8, 2, 9]. Moreover, with the impact of global climate change on the sea level by, e.g., melting of large masses of ice in polar and subpolar regions and bringing fresh water into the ocean, thermal expansion of sea water, and the changes in atmospheric and ocean circulation, these areas are highly exposed (Bindoff *et al*. 2007) [3]. With an anticipated sea level rise, the occurrences of these extreme events are increasing and it is predicted that by the end of the 21st century, up to 332 million people living in coastal and low-lying areas will be directly affected by flooding from sea level rise (Watkins *et al*. 2007) [23]. Today sea level is measured both locally with tide gauges, which has been used during the last centuries (IOC 2006) [11], and globally by satellite altimetry, which has been the dominating technique for the last 25 years.

During the last decade, a number of airborne experiments have been performed to study the feasibility of the GNSS reflection technique to measure ocean surface winds (Rodriguez-Alvarez *et al*. 2012) [20]. It has been widely demonstrated that the signals emitted from Global Navigation Satellite System (GNSS) constellations (GPS, GLONASS, and Galileo) can be used not only for positioning, but also for remote sensing (Clarizia *et al*. 2009; Li *et al*. 2023; Zhou *et al*. 2026) [5, 16, 27]. The main advantage of this technique is the larger number of simultaneous observations providing an exceptional spatial–temporal sampling capability over the earth surface (Li *et al*. 2016; Asgarimehr *et al*. 2022; Li *et al*. 2023; Xia *et al*. 2025) [14, 2, 16, 24]. The use of reflected signals from GNSS systems as a source of opportunity for remote sensing, known as GNSS-R technique, has been a research field of interest (Li *et al*. 2014) [13]. Its main principle is to receive and further extract information from the GNSS signals which is reflecting of the water surface. The concept can be extended that the receiver receives multiple signals simultaneously from different transmitters, in which case, it is multi static radar. GNSS-R works as a bistatic radar, in which the transmitter and the receiver are separated by significant distance, comparable to the expected distance to the target (Zhou *et al*. 2026) [27].

The sea state condition is crucial for providing the sea weather bulletin, especially sea wind forecast-ing. Because, it is very important ocean parameter and early warning systems, sea wind pattern is more considerable (Li *et al*. 2021; Asgarimehr *et al*. 2022; Guo *et al*. 2022; Xia *et al*. 2025) [15, 2, 9, 24]. The simple linear regression method is used for wind speed estimation. The independent values of the power waveforms are fitted to dependent wind speeds. The results are also clarified to actual collected wind speed.

The remainder of this paper is organized as follows. Section focuses the total procedures of the method. It discusses data and analysis process of data, principle of a GPS receiver, generation process of PWs and techniques of sea wind speed measurement. Section describes the analysis results of the experiment, i.e. power waveforms for data and model, estimated wind speed. Section describes the discussions of the results, achievements of this study, and limitations of the study and announces some ideas from this work in future.

2. Methodology

The reflected signal of GPS satellite data is used in this research. The research method is executed to obtain the final results of GPS raw data and GPS modeling. There are three parts of methodology. The first part is the power waveforms generation from GNSS-R raw data and second part is the power wave-forms from modelling and third part is the wind speed measurement from power waveforms (Hammond *et al*. 2020; Li *et al*. 2021; Guo *et al*. 2022) [10, 15, 9].

2.1 Data Collection

The GPS satellite data is collected from Bohai sea of Shandong Province, China. This campaign was arranged near the coast of Bohai sea and the aim is to acquire raw samples of direct and reflected GPS and BeiDou signals under different state conditions and the chosen site, whose latitude and longitude are 38.1541 and 119.0655 respectively, located at a wharf about 7 km from coastline in Bohai sea (Wang *et al*. 2016) [22]. The receiver is located at 40 meters up from mean sea level and LHCP antenna is positioned of 45 degrees slope with sea water level and 210 degrees of azimuth. Table 1 is presenting the information specification of collected GPS data.

Table 1: Specifications of data collection

Parameters	Unit	Values
RF frequency	MHz	1561.09
IF frequency	MHz	3.99
Sampling Rate	MHz	16.36
Quantization	MHz	2.0

2.2 Data Processing

The raw data is processed by a GNSS receiver. The basic configuration of the receiver includes antenna, radio frequency (RF) front end, analog-to-digital converter (ADC), acquisition and position calculation. Acquisition and tracking satellite are important task of a receiver. The purpose of acquisition is to determine visible satellites and coarse values of carrier frequency and code phase of the satellite signals (Borre *et al*. 2007) [4]. The main purpose of tracking is to refine these values, keep track, and demodulate the navigation data from the specific satellite (and provide an estimate of the pseudorange) (Borre *et al*. 2007; Kaplan 2005) [4, 12]. The open-source MATLAB programming-based software named 'GPS MATLAB Tools at Aalborg University by Kai Borre' (Borre *et al*. 2007) [4] is used for raw data processing. The source code of software receiver is modified according to the data format of the raw data. The raw data format has 8 data bits, first 2 data bits represent the direct signals and the next 2 data bits represent reflected signals and then the next 4 bits represent the next sample with the same data format. The raw signal characteristics are shown in Fig 1, including the time-domain plot, frequency-domain plot, and histogram of the GPS raw signal. These plots provide an overview of the temporal behavior, spectral characteristics, and sample distribution of the acquired signal before acquisition and tracking are performed.

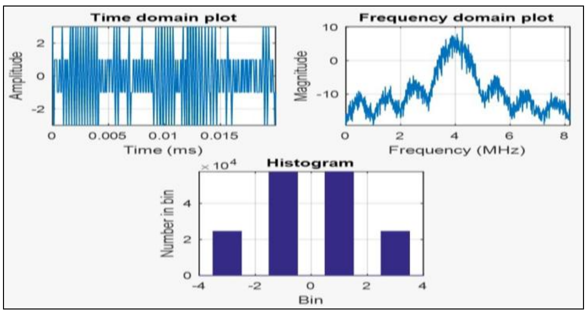

Fig 1: Raw GPS signal characteristics showing the time-domain plot, frequency-domain plot, and histogram of the acquired GPS signal

2.3 Acquisition and Tracking

Satellite acquisition and tracking are essential part for a receiver to get information from satellite. Moreover, tracking provides the I and Qs which is important to generate power waveforms. The result of acquisition of GPS satellite is shown in Fig 2. Here, the green bars are indicated the acquired satellites and blue bars represented not acquired satellites. The number of acquiring satellites are 02, 04, 05, 07, 08, 09, 10, 13, 26, 29 that means 10 (ten) satellites are visible in that moment. Tracking results is shown in Fig 3. This tracking results is performed for GPS satellite of PRN 29.

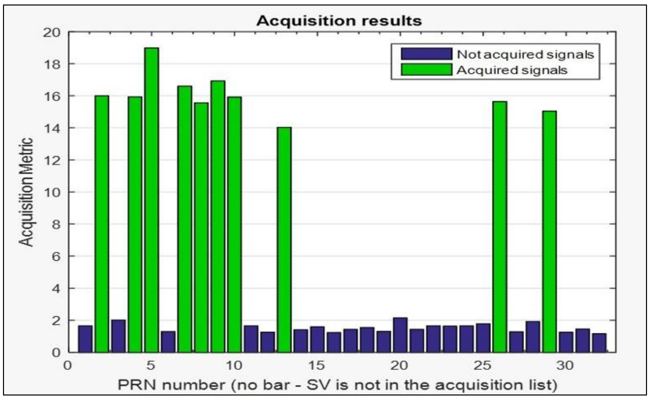

Fig 2: Satellite acquisition results

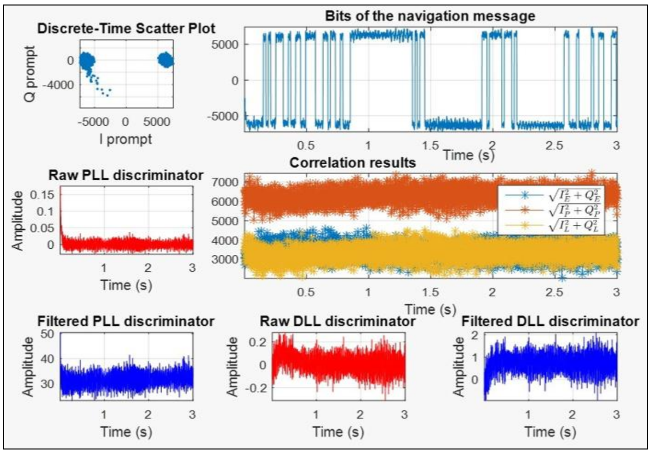

Fig 3: Tracking results of GPS for PRN 29

2.4 The Generation Process of Power Waveforms

For GPS raw data, a geographical user interface (GUI) is designed by MATLAB programming for generation of power waveforms from reflected signals. The operation procedure of the GUI is given by some steps of action. 1. It has to load the tracking data file by MATLAB, 2. the algorithm of GUI can be read information of tracking and displayed the tracking results i.e. Doppler frequency and code phase, 3. the user has to select the signal type and coherent time button of the GUI, 4. Lastly, the user has to select just 'press' button to simulate the waveform and after then power waveforms are displayed on screen. The procedure has to repeat for next set of sample data.

For model, the reflected power waveforms are generated by using some models. Actually, two models are utilized in this paper. At first, wave spectrum model which is used to represent sea surface slopes. Wind speeds and satellite elevation angles are collected along with raw data and these are used it as the input to wave spectrum model. This model is provided the up and cross variances as output. Then Z-V scattering model is used for generation of power waveforms using up and cross variances as input of this model (Zavorotny and Voronovich 2000; Guo *et al*. 2021, 2022) [25, 8, 9].

The scattering model can simulate the Delay Doppler Map (DDM). Three main steps are highly mentioned for whole technique as: 1. determination of the location of specular point (SP) and the glistening zone in the Earth-Centered, Earth- Fixed (ECEF) coordinate system. The glistening zone is usually close to the SP, 2. obtaining the coordinates of the grid elements in the glistening zone. Coordinates transformation is essential for grid elements for sea surface. At first, it is transformed the receiver's and transmitter's locations & velocities from the ECEF coordinate system to the X-Z Incidence (ECXI) system. Then it is conducted a coordinate calculating process for grid elements in ECXI system. 3. Finally, mapping the power which is reflected from glistening zone into the Delay Doppler (DD) domain.

2.5 The Technique of Wind Speed Estimation

To understand the ocean state or ocean roughness the power waveforms are analyzed according to different wind speed and compared the amplitudes and shapes of the waveforms. The comparison is performed for raw data and model so that it can understand the state of the sea surface according to amplitudes of waveforms (Hammond *et al*. 2020; Li *et al*. 2021; Asgarimehr *et al*. 2022) [10, 15, 2] Linear regression method is used to estimate the sea wind speed. This method can model a relation-ship between an independent variable and a dependent variable by fitting a linear equation to the data. The equation is simple linear equation, $Y = KX + C$, where X is independent variable, Y is dependent variable, K is a constant and C is intersection of X and Y.

In this research, it is found that there is a relationship between known variables (amplitude of waveforms) and dependent variables (wind speed). The waveforms are fitted with real wind speeds which collected from data collection site. Finally, it is disclosed an inversely relationship between waveforms and wind speeds by linear regression method. The sea wind speed is estimated using this established relation.

3. Results Analysis

3.1 Power Waveforms for Raw Data

Here is displayed the power waveforms for GPS raw data in Fig 4. The result is performed the pattern (amplitude & shape) of the waveforms for different wind speeds (i.e. 2.6 ms−1, 2.8 ms−1, 3.0 ms−1 & 3.2 ms−1). From Fig 4, it is disclosed that the amplitude of the power waveforms is enhanced according to decreasing of wind speed. It is also disclosed that when wind speed is going to zero by decreasing, the amplitude of the waveforms is increasing and the shape is going to auto correlation function (ACF) gradually. So, there is an inversely relationship between wind speed and waveforms amplitudes.

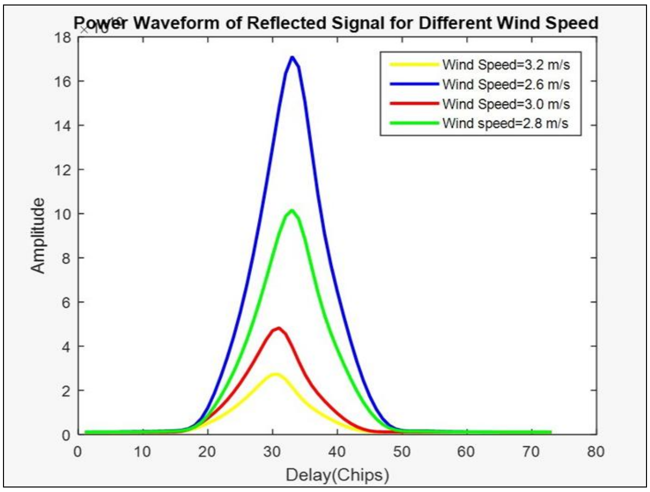

Fig 4: Power waveforms of reflected signals for different wind speed

3.2 Power Waveforms for Model

The wave spectrum model and scattering model are used to produce the power waveforms for reflected GPS signals. Firstly, the wave spectrum model is used to retrieve the ocean surface and the scattering model is used to generate the waveforms from these surface slopes. The power waveforms of model are also tested according to different wind speeds.

In Fig 5, it is displayed the results of the power waveforms for model. It is performed the waveforms of 5 different wind speeds of 5.0 ms−1, 10.0 ms−1, 15.0 ms−1, 20.0 ms−1 & 25.0 ms−1. It is also observed that the result is similar of raw data. So, for model, there is also an inversely relationship between wind speed and waveforms amplitudes.

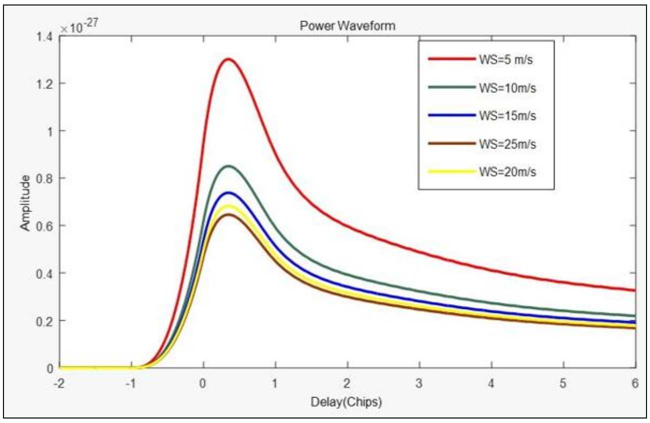

Fig 5: Model power waveforms of different wind speeds

3.3 Estimation of Sea Wind Speed

It is established that shape and magnitude of waveforms is directly related to the glistering zone(s) of the sea surface and this glistering zone(s) depends sea roughness conditions and one of the seasons of this roughness is surface wind speed. For this reason, amplitudes of the waveforms are tested according to different wind speed. The linear regression is used to establish a relation between wind speed and amplitudes of waveforms.

From regression, it is also found that the amplitude of power waveforms depends on wind speed inversely and obtained a specific a relation between amplitude and wind speed for selected dataset. The results of wind speed versus amplitude of reflected signal is shown in Fig 6.

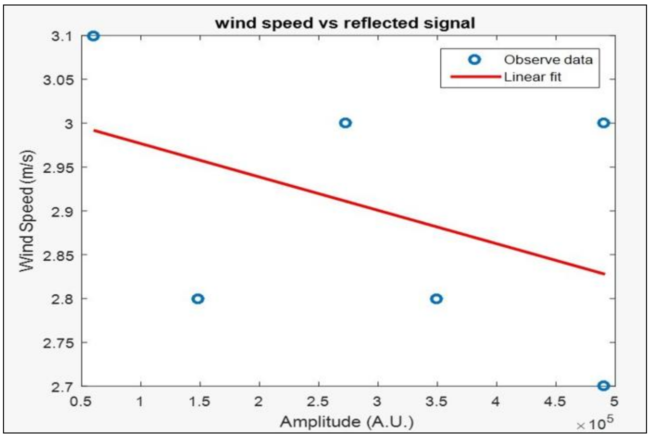

Fig 6: Wind speed versus amplitude of reflected power

From the equation of linear regression, it is obtained the intersection and slope, i.e. intersection, c = 3.01 and slope, m = -0.041. The amplitude of reflected power waveforms is linearly fitted with real wind speed. The established relation is used to find sea wind speed. It is also found the second and third order fitted results to get more accurate results. It is obtained that third order fitted wind speed is closer to real wind speed compare to results of second and first order.

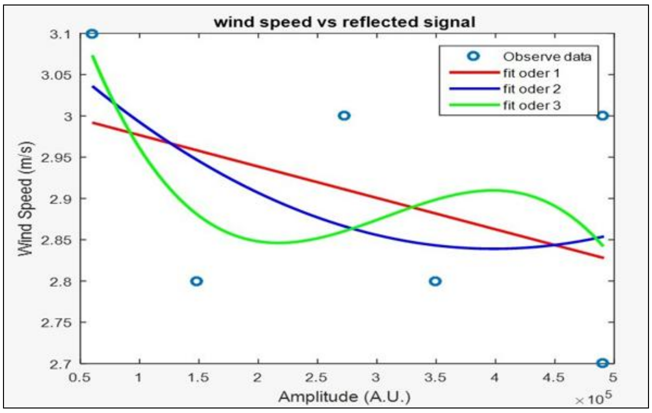

Fig 7: Wind speed versus amplitude in different order fitting

It is performed the wind speed according to different samples by Fig 8. In order to retrieve the more accurate outputs of wind speed estimation, the real wind speed is fitted according to sample of data.

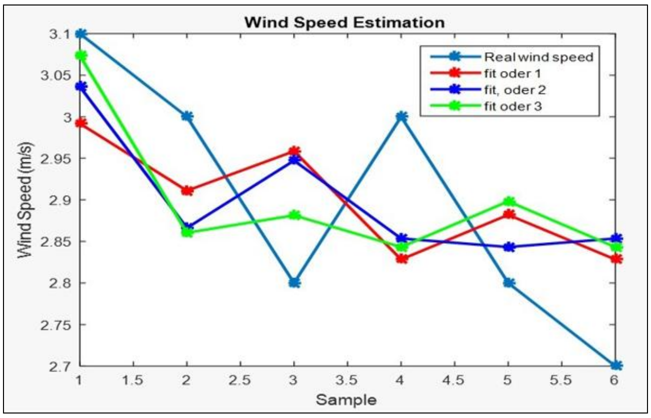

Fig 8: Wind speed estimation with different fitting order

The estimated wind speed for different time of data set is shown in Table 2.

Table 2: Estimated wind speed by regression method

Date	Time	Amplitude of PWs in AU ($\times 10^4$)	Slope $m = y/x$	Intersection c	Estimated WS (m/s) $y = mx + c$	Real WS (m/s)
2015_09_03	15_23_48	2.7	-0.041	3.01	2.90	3.0
2015_09_03	15_07_16	4.8	-0.041	3.01	2.81	2.6
2015_09_04	09_23_44	10.4	-0.041	3.01	2.58	2.8
2015_09_04	10_02_00	12.2	-0.041	3.01	2.51	3.0
2015_09_04	10_10_16	3.8	-0.041	3.01	2.86	3.4
2015_09_04	10_18_32	17.4	-0.041	3.01	2.40	3.4
2015_09_04	10_26_48	Error	-0.041	3.01	——-	3.6
2015_09_04	10_35_04	9.6	-0.041	3.01	2.62	3.0
2015_09_04	10_43_20	12.8	-0.041	3.01	1.96	3.5

4. Conclusion

The proposed concept in this paper provides an effective technique for estimation of sea wind speed. It is also a new idea to measure sea wind speed from power waveforms of reflected signals directly. This new idea is executed by some process i.e. 1. GPS raw data analysis for power waveforms, 2. modelling for power waveforms and 3. understanding the waveforms for sea wind estimation. Finally, the estimated wind speeds are the outputs of the total process. Since, the obtained wind speeds are underestimated compare to real wind speeds but the results are closely matched with it. The process is sharp and easy to estimate sea wind speed only measuring by amplitudes of the reflected power waveforms. There is a limitation of frequency of GPS reflected data. If it is possible to get the time continuous frequency data, it would be performed better results in this method. This work can help to measure sea wind in advance by using the reflected signals from sea surface before applying other existing method. In case of disaster periods i.e. during tropical cyclones, depressions, storm surge and others, this work can play significant rule for sea weather forecasting especially sea wind forecasting. In future, it is possible the sea wind measurement during typhoon period as further research after this research.

5. Acknowledgements

The authors gratefully acknowledge the support and academic environment provided by the Hangzhou International Innovation Institute of Beihang University, Hangzhou, China. The authors also acknowledge the Bangladesh Space Research and Remote Sensing Organization (SPARRSO), Dhaka, Bangladesh, for its institutional support and encouragement related to this study.

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