Wave Remote Sensing System by GPS

Jian CUI *, Nobuyoshi KOUGUCHI*, Akihiro IKAWA*, Shigeyuki OKUDA** and Yasuo ARAI**
*Kobe University, Graduate School of Maritime Sciences
**Marine Technical College
5-1-1, Fukae-minami-machi, Higashinada-ku, Kobe, Hyogo, 658-0022, JAPAN

***Abstract*-It is well known that an observation of the long period gravity wave is very difficult to observe for its long period and small amplitude. In our recent research, an integrated wave remote sensing system utilizing multi-path GPS signals reflected from sea surface is proposed to measure accurate wavelength for long period gravity wave. The system is equipped with an arrayed GPS antenna that has a narrow fan beam directional pattern. It has a better performance to measure accurate wavelength than wide beam antenna in numerical simulation and it can acquire multi-path GPS signal reflected from specified sea surface in seaside experiments. In digital GPS signal processing, software GPS receiver is applied to estimate the relative time delays between multi-path GPS signals. In this paper, simulation results and seaside experiment results obtained by the wave remote sensing system are also presented.**

I. INTRODUCTION

It is really a hard and complicated task to measure information for long period gravity wave near a harbor, which has wave period from some ten seconds to some ten minutes and wave height less than 1 meter generally. Especially wavelength of long period gravity wave is just estimated with dispersion relation (wave period and height). In order to obtain more precise wavelength measurement, we propose an integrated wave remote sensing system that takes advantage of multi-path GPS signals reflected from specified sea surface.

In general, multi-path GPS signals are always considered as an error source in positioning by GPS. Because multi-path GPS signals occur in a complex environment and then they disturb Line-of-sight (LOS) signal that is used for positioning. Therefore multi-path GPS signal disturbance should be mitigated and eliminated in various positioning systems [1][2]. Contrarily, in our research we would like to take advantage of the multi-path GPS signals to measure wavelength for specified sea surface. Because multi-path GPS signals are delayed for their longer travel distances than LOS signal and the relative time delays among multi-path GPS signals are conditioned by wave characteristics, we consider that propagations of the multi-path GPS signals reflected from sea surface ought to contain wave information, especially the wavelength of long period gravity wave [3].

In our proposed integrated wave remote sensing system, we just utilize the relative time delays among some multi-path GPS signals to estimate precise wavelength for sea surface near a harbor.

The GPS signal receiving hardware segment of the wave remote sensing system includes two sets of antennae to receive LOS GPS signal and reflected multi-path GPS signals respectively. One is a RHCP antenna installed upwards normally to receive LOS GPS signal from satellites; the other is a LHCP arrayed GPS antenna installed obliquely downwards to receive multi-path GPS signals reflected from sea surface.

The arrayed GPS antenna is constructed by 16 elements of patch LHCP antenna and the interval of each antenna element is half wavelength of GPS radio wave. With the special design of arrayed configuration, the composite directional pattern of the GPS antenna array takes the shape of very narrow fan beam facing the front side of the arrayed GPS antenna.

Beside these two sets of antennae, the multi-path GPS signals received from sea surface by these two sets of GPS antennae are also processed by front-end IC and high-speed digitizer to generate digital GPS signals, which are analyzed by software GPS receiver. As the digital signal processing software segment, the software GPS receiver processes the digitalized multi-path GPS signals with general-purpose personal computer. In the software GPS receiver, especially the C/A autocorrelation computations for satellite acquisition are the most important processes to estimate accurate relative time delays for some reflected multi-path GPS signals from specified sea surface [4].

After successful construction of the prototyped arrayed GPS antenna and development of software GPS receiver, numerical simulation and some validation experiments were carried out [5][6]. After a series of experiments, we confirm that the constructed arrayed GPS antenna can receive multi-path GPS signals from specified sea surface and the software GPS receiver can find the relative time delays through the output of autocorrelation computations in a mass of digitalized multi-path GPS signal data. In this paper, firstly the proposed methodology to measure wave information by GPS is explained. Secondary, the system configuration of wave remote-sensing system ids described. Finally, some simulation and experimental results are shown to evaluate our system. From these results, our proposed system consequently has possibility to measure precise wave information.

II. METHODOLOGY

When a GPS antenna is installed near seaside properly, it will not only receive LOS GPS signal but also multi-path GPS signals, which are reflected from sea surface and conditioned by the wave characteristics such as wavelength and wave height. It is easy to understand that a GPS signal transmitted

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by one certain satellite will reach the GPS antenna in different propagation paths of LOS signal and multi-path signals. Therefore, the GPS antenna will receive these GPS signals in different time. The LOS signal will reach the GPS antenna in the first moment, followed by multi-path signal. Figure 1 illustrates an antenna installed near sea surface receives GPS signal in different propagation paths.

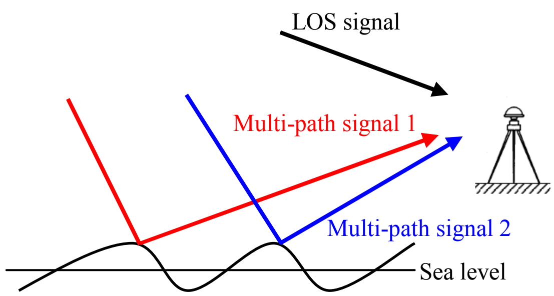

Fig. 1 Example of multi-path signals reflected from sea surface

The autocorrelation property of a C/A code can be explained that nearly no correlation except for zero leg. It means that a C/A code is nearly uncorrelated with itself, unless two identical C/A code are perfectly aligned [7]. Based on this property, if we compute the autocorrelation between arriving GPS signals and different code phase C/A code generated locally, the one of the autocorrelation outputs will indicate the code phase of C/A code contained in arriving GPS signals. Therefore, this autocorrelation property enables us find out the code phase of a C/A code to estimate the arrival time of GPS signals. The autocorrelation property can be expressed by the following autocorrelation function of one GPS C/A code sequence:

$$R(m)=\frac{1}{N}\sum_{l=0}^{N-1}C(l)C(l+m), \quad and \quad \begin{matrix} R(m) \approx 0, & |m|\geq 1 \\ R(m)=1, & m=0 \end{matrix}, \qquad (1)$$

where, $R(m)$ is the autocorrelation output, $C(l)$ is a C/A code, and N is a code length.

For the example showed in figure 1, the LOS signal arrives at GPS antenna at the first moment and multi-path signal 1 and 2 follow it and arrive at antenna in different time. If the C/A Code autocorrelation is calculated in order of 1023 code phases for the multi-path GPS signals, the autocorrelation output for LOS signal show a peak at the earliest time t1 (figure 2(a)) and the other two multi-path signals show two other peaks at t2 (figure 2(b)) and t3 (figure 2(c)). Therefore, the composite autocorrelation output of the multi-path GPS signal illustrated in figure 2(d) includes three peaks which indicate time t1, t2 and t3 respectively. In this figure, the black circle is the position of the arrival time of the LOS signal, the red circle means the position of the arrival time of the multi-path signal 1 and the blue circle indicates the position of the arrival time of reflected signal 2.

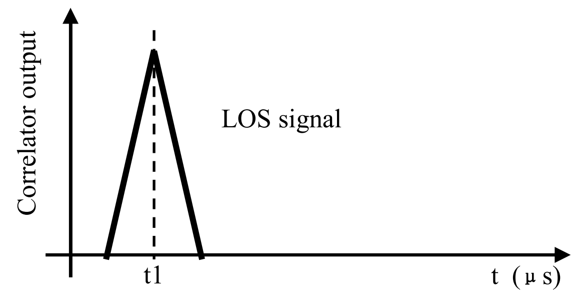

Fig. 2(a) Autocorrelation output for LOS signal

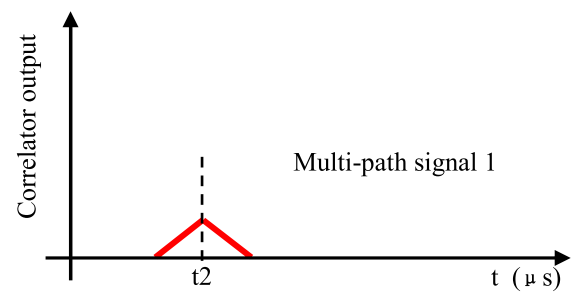

Fig. 2(b) Autocorrelation output for Multi-path signal 1

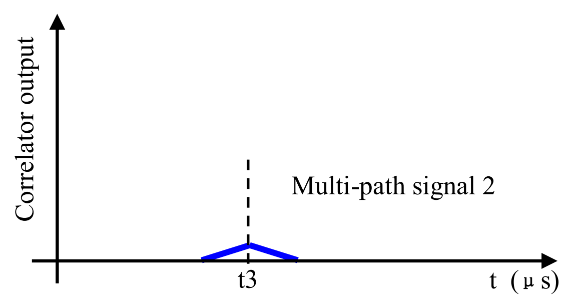

Fig. 2(c) Autocorrelation output for Multi-path signal 2

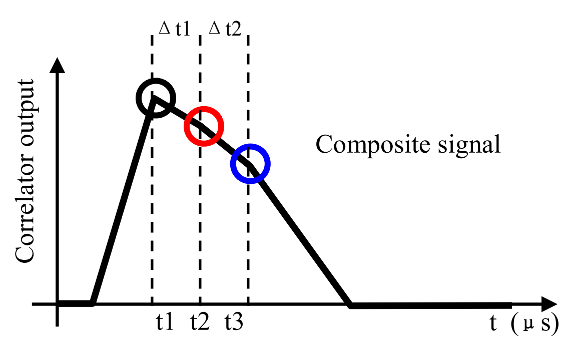

Fig. 2(d) Composite autocorrelation output

Furthermore, based on the composite autocorrelation output curve, the relative time delays $\Delta t1$ between LOS signal and reflected multi-path signal 1 and $\Delta t2$ between reflected multi-path signal 1 and 2 are easy to estimate. And they are all the most important parameters to estimate the wavelength of the sea area near the antenna.

III. SYSTEM

A. System Configuration

The integrated wave remote sensing system by GPS consists of three parts. The first part is the GPS satellites system which are transmitting GPS signals all the time. During experiments, one or two visible satellites are selected and it is assumed that the measurement sea area is exposed to GPS signals transmitted by them. The second part is the specified sea area. Usually, the area is the neighboring sea surface of one harbor where wave information of long period gravity wave is desired to keep mooring and anchoring security. The third one is the coral function part that processes multi-path GPS signals and estimates the wavelength for long period gravity wave. Figure 3 sketches the system configuration of wave remote sensing system.

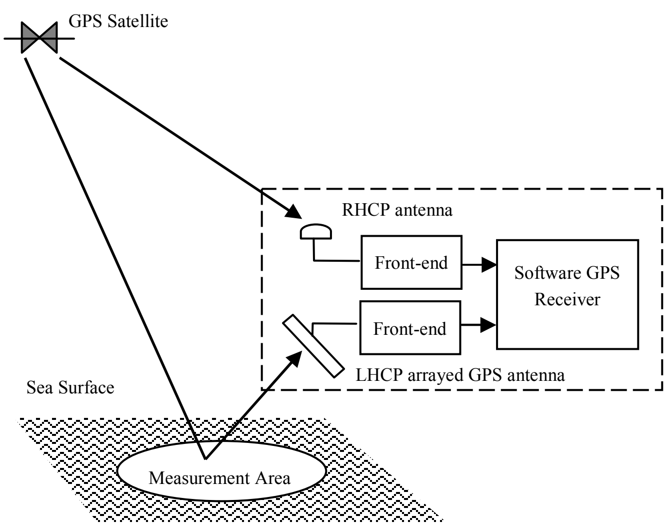

Fig.3 System configuration of wave remote sensing system by GPS

The third part is indicated in the dash line square. There are two sets of GPS antenna. The upper one is RHCP (Right Hand Circular Polarization) GPS antenna installed upwards to receive LOS GPS signal, and the lower one is LHCP (Left Hand Circular Polarization) GPS antenna installed obliquely downwards to receive multi-path GPS signals reflected from specified sea surface. The arrayed GPS antenna is designed and constructed specially to form a particular directional pattern of narrow fan beam which enable itself receive multi-path GPS signals from specified sea area and eliminate other multi-path signals reflected from side direction.

LOS GPS signal and multi-path GPS signals reflected from measurement sea area are received by these two sets of GPS antennas respectively. The outputs of these two sets of GPS antennae are weak UHF (Ultra High Frequency) band GPS signals. For the sake of processing GPS signals in general-purpose personal computer, the weak signals should be down-converted form UHF band into IF (Intermediate Frequency) band and amplified into appropriate amplitude value and then converted from analogue signals into digital signals. Two front-end units connected with antennae complete all the above tasks and the output of each front-end unit is the digital IF GPS signals.

The digital IF band GPS signals are saved in computer as data files, input and processed by software GPS receiver. The software GPS receiver is developed on the platform of general-purpose personal computer. It can process digital IF band GPS signals to estimate relative time delays between multi-path GPS signals as well as provide the navigation information.

B. Arrayed GPS Antenna

The figure 4(a) and figure 4(b) show the front side and back side of the arrayed GPS antenna. From the front side, it can be seen that the arrayed GPS antenna is constructed by 16 elements of LHCP patch antenna in horizontal direction in series.

Fig. 4(a) Arrayed GPS antenna (front side)

Fig. 4(b) Arrayed GPS antenna (back side)

Interval of each patch antenna is half of wavelengths of GPS L1 signal frequency. The arrayed GPS antenna is also equipped pre-amplifier in back side. Because usually arrayed GPS antenna is far from the front-end units so that a long cable is used to transmit GPS signals to front-end, which will attenuate GPS signals before the signals reach front-end units.

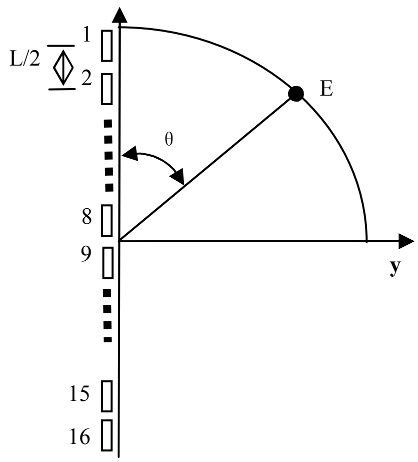

Fig. 5 Coordinate system of electric field intensity

We designed the GPS antenna as an arrayed configuration, because the arrayed design can achieved a special directional pattern that makes the arrayed GPS antenna only receive GPS signal in range of 10 degree from its front side. The directional pattern of the arrayed GPS antenna can be calculated as cross dipole for each element with the arrayed design. In the coordinate system for electric field intensity shown in figure 5, electric field intensity at angle θ is calculated as following equation.

$$E = \frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta} \times \frac{\sin\left(8\pi\sin\theta\right)}{\sin\left(\frac{\pi}{2}\sin\theta\right)} \tag{2}$$

According to the above equation, if the electric field intensity is calculated in the range of θ from 0 to 180 degrees, the directional pattern of the arrayed GPS antenna can be described and it has been shown in figure 6. It is obvious that the directional pattern of the arrayed GPS antenna takes the shape of very narrow fan beam facing the front side ($\theta = 0$ deg.) of the arrayed GPS antenna as mentioned before. The beam width of this prototype arrayed GPS antenna is 10 degrees. Therefore, it is become possible that the arrayed GPS antenna only receives GPS signals incoming from front side and eliminates the effect of side signals, and in the wave remote sensing system, it is confirmed that the arrayed GPS antenna has the ability to receive multi-path GPS signal from specified sea area.

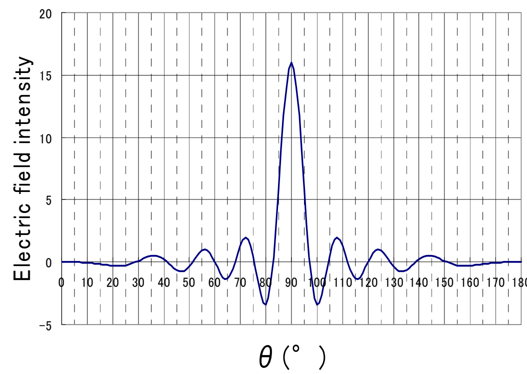

Fig. 6 Directional pattern of arrayed GPA antenna

C. *Software GPS Receiver*

In the wave remote sensing system, two sets of GPS antennae receive LOS signal and reflected multi-path signals and then the composite multi-path signal is amplified, down-converted, filtered, and analog-to-digital converted to digital IF GPS signals saved in computer as data files. It is the task of the software GPS receiver to process digital IF GPS signals to estimate relative time delays between multi-path GPS signals and present wavelength information.

Software GPS receiver is designed and developed according to theories of real hardware GPS receiver. The software GPS receiver processes GPS signal as it is processed on hardware GPS receiver chipset. Figure 7 shows a flow chart of digital channel of software GPS receiver. The acquisition processing aims to detect the existence of GPS signals and acquires the coarse value of frequency and code phase of every visible satellite signal. The acquisition processing must ensure the signal is acquired at the correct code phase and carrier frequency [8]. In this software GPS receiver, parallel code phase search algorithm is adopted to acquire the visible satellites for its high efficiency. The tracking processing consists of code tracking and carrier frequency/phase tracking. It will refine the coarse values of frequency and code phase. And the output of tracking is precise carrier frequency and code phase.

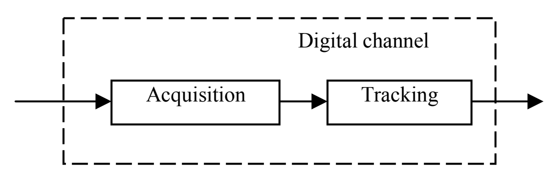

Fig. 7 One digital channel of software GPS receiver

For the software GPS receiver, the most interesting processing is highly efficient autocorrelation computation for multi-path GPS signals and its graphic representation for autocorrelation results. It will be very easy to identify relative time delays between multi-path GPS signals. Figure 8 illustrates an example of autocorrelation output generated by software GPS receiver for composite multi-path GPS signals. In this figure, three obvious peaks are contained in the autocorrelation output curve. the relative time delays Δt1 and Δt2 between multi-path signals can be obtained on this figure easily.

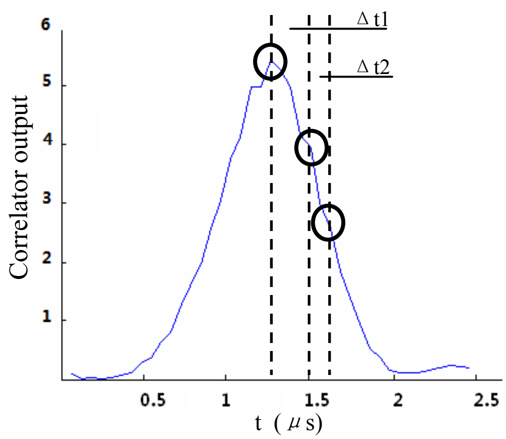

Fig. 8 Example of autocorrelation output of software GPS receiver

And moreover, digital filtering is necessary to be developed in the software GPS receiver to improve the quality of the input signal. And for long-term wave observations and measurements, software GPS receiver should be able to analyze autocorrelation results to estimate relative time delays and compute wavelength for long period gravity wave.

IV. Simulation and Experiment

A. Simulation

Since the directional pattern of the arrayed GPS antenna is known, the numerical simulation can be conducted definitely. The purpose of the simulation is to validate whether the arrayed GPS antenna can receive reflected multi-path GPS signals from specified direction in enough signal strength and whether it has a better performance to identify multi-path GPS signals than broad beam width GPS antenna. In table I, the simulation conditions are listed.

The above conditions were selected because the wave peak interval was easy to measure without correlation confusion. Because the received satellite signal power varies with user antenna gain, satellite elevation angle [9].

Table I
Simulation conditions

Wave length (m)	10.0
Wave height (m)	1.0
Antenna height (m)	2.5
Satellite elevation angle (deg)	60.0

In the simulation, two kinds of GPS antennae were tested. One was wide beam width antenna and the other was the arrayed antenna with narrow beam width. And antenna conditions are listed in table II.

Table II
Antenna conditions

Antenna	Polarization	Beam width (deg.)
Wide beam width	LHCP	40
Arrayed antenna	LHCP	10

These two sets of antenna were all LHCP antennae to receive reflected GPS signals from sea surface which size was determined by beam width, height of antenna and the satellite elevation angle.

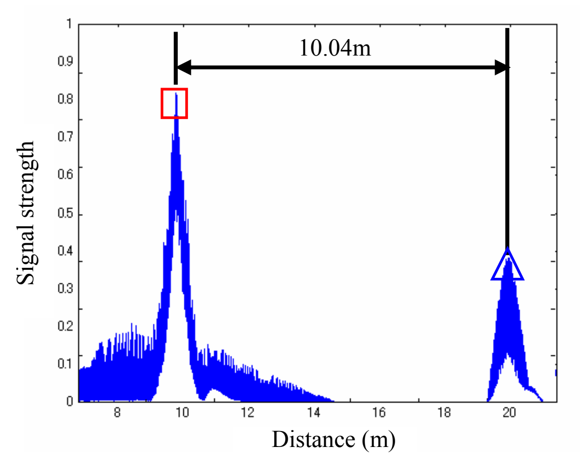

Fig. 9 Received signal strength with arrayed antenna

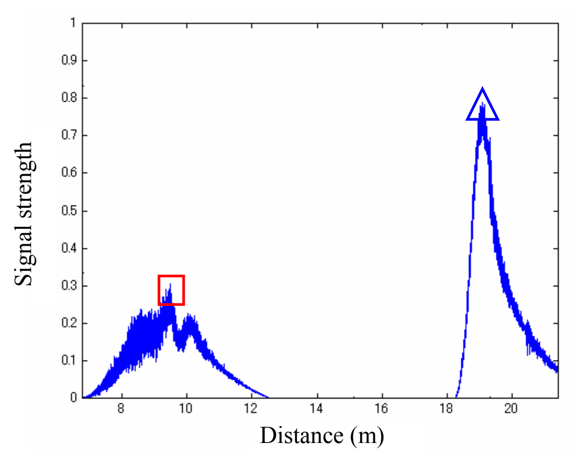

Fig. 10 Received signal strength with wide beam width antenna

Figure 9 and Figure 10 show the received signal strength with each antenna. In these two figures, the horizontal axis means distance conversion from radio wave propagation time, which is equivalent to sea surface reflection point [3]. And the vertical axis means correlation output, which is equivalent to received signal intensity. The smooth peak of the received signal strength can be considered as a peak of the autocorrelation output, because a real autocorrelation output ($O(m)$) can be computed with convolution operation between the ideal autocorrelation output (triangle form: $R(m)$) and the received signal strength ($S(m)$).

$$O(m) = \sum_{n} S(n) R(m-n) \tag{3}$$

According to the simulation results showed in figure 9 and figure 10, the arrayed GPS antenna has obvious comparative advantage. Because the arrayed GPS antenna has a very narrow fan beam directional pattern, it can eliminate most of disturbing multi-path signals incoming from side directions. Therefore, these two peaks around 10 meters and 20 meters can be identified definitely. In figure 9, the peak interval is about 10.04 meters and approximates to the wavelength of 10-meter generated wave. Contrarily, the wide beam width antenna received numerous redundant multi-path signals from wider reflection sea area, the peak of signal strength around 10 meters point cannot be distinguished easily in figure 10. Therefore wavelength measurement accuracy is worse than arrayed GPS antenna. Consequently, it can be confirmed that the arrayed GPS antenna is a better choice to estimate wavelength information in high measurement accuracy.

B. *Experiment*

On 23rd February 2010, a wave remote sensing experiment was conducted near the seaside of Japanese Sea area of Kyotango, Kyoto, Japan. Figure 11 shows the sea surface condition. In this experiment, the direction of the arrayed GPS antenna was 325 degrees, and because the location of the GPS antenna is little far away from sea area, depression angel was adjusted to 10 degree facing sea surface to receive multi-path GPS signals.

Fig. 11 Sea surface condition

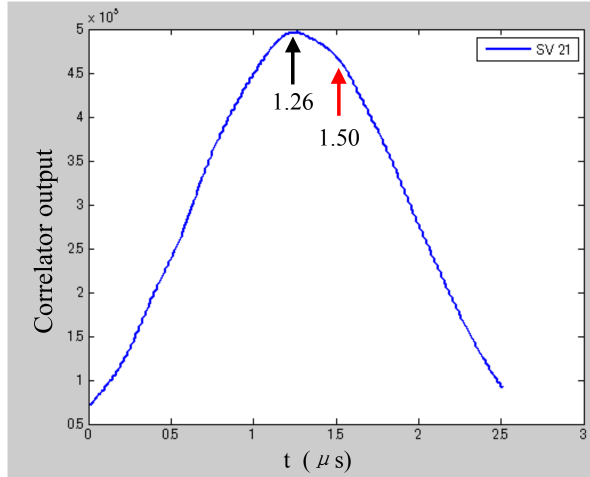

Fig. 13(a) Composite autocorrelation output for SV 21

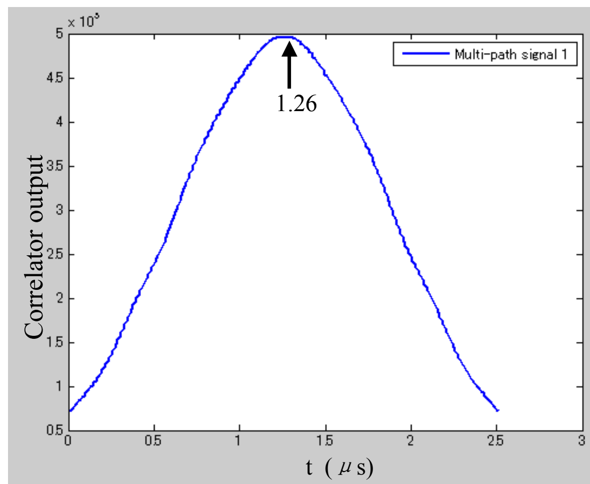

Fig. 13(b) Autocorrelation output of multi-path signal 1 for SV 21

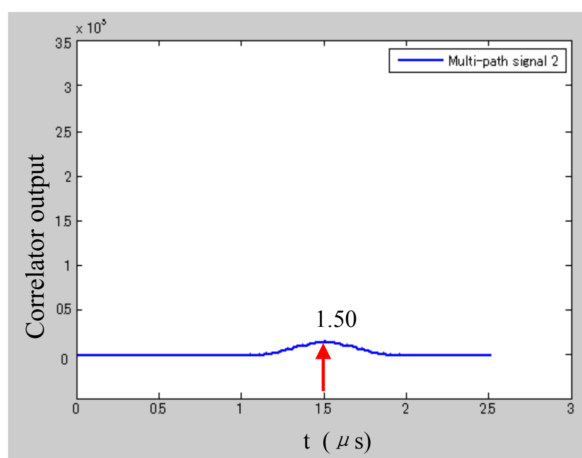

Fig. 13(c) Autocorrelation output of multi-path signal 2 for SV 21

Software GPS receiver processes the digitalized multi-path GPS signals, and the autocorrelation output for SV 21 is generated in the processing of acquisition. In figure 12(a), the composite autocorrelation output is shown, and two obvious peaks are indicated in points of 1.26 μ s and 1.50 μ s. It can be confirmed that the relative time delay between multi-path signal 1 and 2 is about 0.24 μ s. It is a very important parameter to estimate the wavelength in the measurement sea area. Figure 12(b) and figure 12(c) show the autocorrelation output of multi-path signal 1 and 2 transmitted by SV 21 respectively. Consequently, our proposed system can measure the wavelength in direction of 325 degree.

In this experiment, the correlator output signal was seemed to be smooth, because we had to use the narrow band amplifier compared with this signal bandwidth, We will be able to have more sharp variation of the correlator output signal, and indicate more accurate position of the multipath signals from the ocean waves by use of more adequate amplifier bandwidth.

V. Conclusion

In order to acquire precise wavelength information for long period gravity wave, a wave remote sensing system has been designed and developed. In the system, the arrayed GPS antenna has also been constructed, and its composite directional pattern of the arrayed GPS antenna takes a shape of very narrow fan beam facing the front side. This fan beam directional pattern has only 10 degrees beam width. In numerical simulation, it had a better performance to estimate wavelength under a certain designed condition than wide beam width antenna. In experiment near sea area, the arrayed GPS antenna was able to receive multi-path GPS signal reflected from specified sea area and estimate the relative time delays between them.

Beside the arrayed GPS antenna, software GPS receiver has been developed according to the theories of GPS receiver and GPS signal processing. As an important part of wave remote sensing system, it can process the digitalized multi-path GPS signals and generate autocorrelation output for estimation of relative time delays between multi-path GPS signals.

In future, more seaside experiments with the wave remote sensing system will be conducted to validate its performance of wavelength measurement by use of more adequate amplifier bandwidth, and based on the availability of one system, two sets of the wave remote sensing systems will be utilized to obtain precise wavelength information. If the two systems work well, we will carry out enough experiments with the wave remote sensing system on sea surface to measure the precise wavelength.

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