A new tsunami monitoring system using RTK-GPS

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Abstract. A new tsunami observation system has been developed which employs a real-time kinematic GPS technique to detect tsunamis in the open ocean before they reach coastal areas. The system consists of a GPS buoy, fixed GPS base station, data acquisition system, RTK data processing system, and a buoy position monitoring system. The new system utilizes a buoy equipped with an autonomous electrical power supply, tiltmeter, ultrasonic distance measurement system for draught line monitoring, ancillary data collection system, and a data telemetry system, as well as a GPS sensor. The buoy has been anchored approximately 2 km off the northeastern coast of Japan near the city of Ofunato since 23 January 2001. Every second GPS data from the buoy and base station are collected and processed using Reverse RTK processing software and the estimated position of the buoy is further transmitted to the city hall and the fire station of the city for real-time monitoring. Data can also be viewed and downloaded through a web page with a delay of about 30 min. The experiment will continue until January 2002 and various tests will be performed to determine the overall accuracy of the buoy positions, performance of the system using long-distance RTK, and the feasibility of detecting tsunamis.

1. Introduction

Detection and warning of a tsunami before its arrival at the coast may mitigate disasters due to its attack. A number of systems have been developed for this purpose such as pressure sensors (e.g., González *et al.*, 1999) and super sonic sensors (e.g., Hino *et al.*, 1998) placed at the sea bottom.

In the present study, we have developed a new tsunami observation system that employs the real-time kinematic (RTK)-GPS technique. The system presented in this study is the improved model from our prior ones that were successfully tested in the sea (Kato *et al.*, 2000). It is now deployed in the open ocean for a long-term experiment. This article briefly introduces the system and the experiment.

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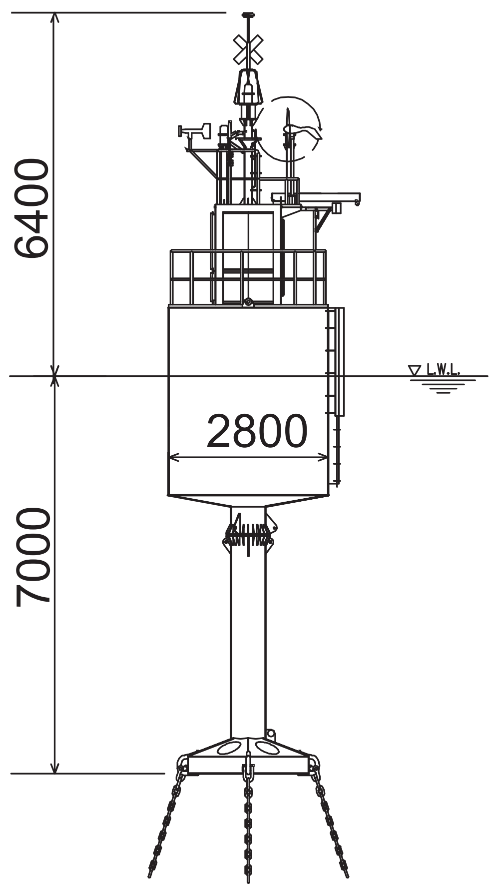

Figure 1: The design of the GPS buoy. GPS antenna is set at the top of the buoy. Unit: mm.

2. The System

The new tsunami monitoring system consists of a GPS equipped buoy and a GPS base station. The buoy is a self-contained GPS data collection station and is designed to be deployable as an autonomous platform. Electrical power is provided by a solar/wind/battery system and data from the buoy is transmitted to a base site by one-way radio transmission. Figure 1 shows the design of the buoy. The height of the buoy is more than 13 m and the weight is about 10 tons.

At the base station, the data from the buoy is combined with data collected by a fixed land-based GPS receiver in real time using RTK processing software. The resulting buoy positions are then transmitted by telephone modems to the Ofunato City office and fire department.

The positions generated by the current system relate to the position of the GPS antenna of the buoy, which is located at the top of the buoy. In order to study the relation of this position to the actual surface height of the ocean we have equipped the buoy with additional sensors: a vertical accelerometer to evaluate the vertical motion of the buoy, a tiltmeter to measure the buoy

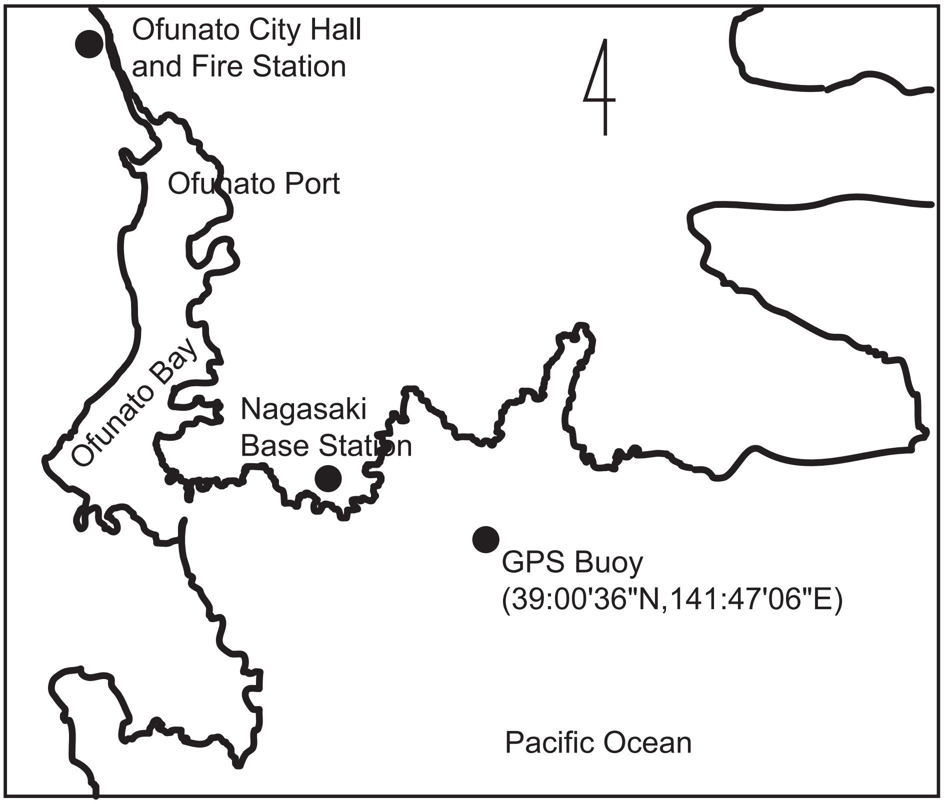

Figure 2: Location map of the GPS tsunami monitoring system.

inclination and an ultrasonic distance measurement system to monitor the draught line, and finally a meteorological sensor to detect wind direction and velocity.

A radio transmission system of small electric power consumption is used for data transmission. Since the transmission rate is limited to 4800 bps, only GPS data is transmitted to the base station, while other data are stored in the data logger equipped in the buoy.

In the last buoy system (Kato *et al.*, 2000), we used dual buoys, one a spar type about 8 m long equipped with only a GPS antenna, and the other a larger buoy containing the GPS receiver, lead batteries, solar panels, etc. on board. These buoys were tethered with a cable. However, the system was thought to be too complicated to keep stable in the open ocean for the long term. So, in the present model, we decided to use a single buoy, which embarks all necessary equipment for operation on board.

3. Experiment

The buoy has been anchored at (39°00′36″N, 141°47′06″E), which is about 2 km away from the coast of Ofunato city, along the Sanriku coast, northeastern Japan, since 23 January 2001 (Fig. 2). The water depth at the buoy is about 50 m and the buoy is anchored with tri-directional anchors with an

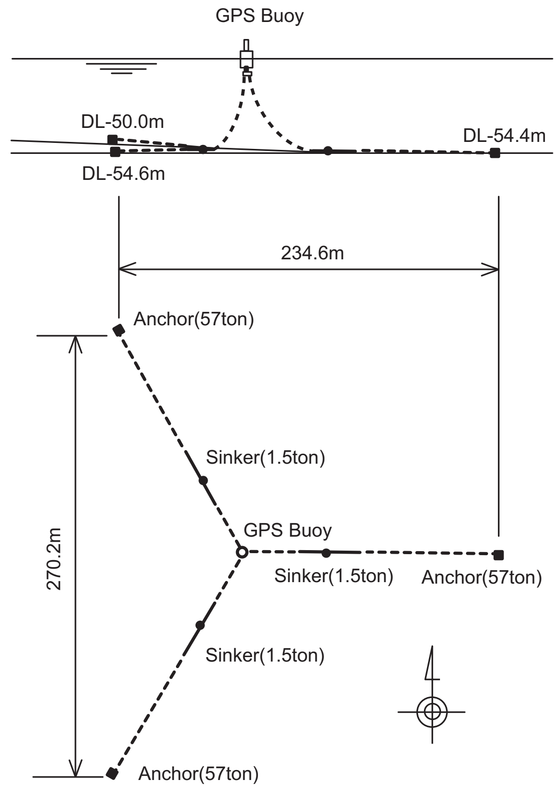

Figure 3: Layout of the buoy anchoring system.

intermittent depth sinker (Fig. 3). The horizontal movement of the buoy is thus limited to within the circle of about 20 m of diameter. Numerical simulation of the buoy's ability to track vertical displacements of the sea surface long wave shows that almost any possible sea surface displacement will be reflected by the vertical position of the buoy. Therefore, the buoy may move sufficiently freely to detect a considerable tsunami, though a small correction may have to be made for accurate estimation of wave height changes.

Reverse RTK processing for 1-s sampling data is conducted at the base station and the estimated position of the buoy is further transmitted to the city hall and the fire station of the city for real-time viewing. Data can also be monitored and downloaded through a web page (http://tsunami.ekankyo21.com/) with about 30 min of delay. An example snapshot of a page is shown in Fig. 4.

Our ultimate goal is to be able to detect a tsunami in the open ocean to provide as much warning time as possible. The current experimental buoy is located only 2 km off the shore and would provide little warning time. In future deployments will require the buoy to be located much further from the coast, which will require longer kinematic baselines to be processed. We plan to operate temporary base stations located as far as 100 km from the buoy in order to test the performance of the system for long baselines.

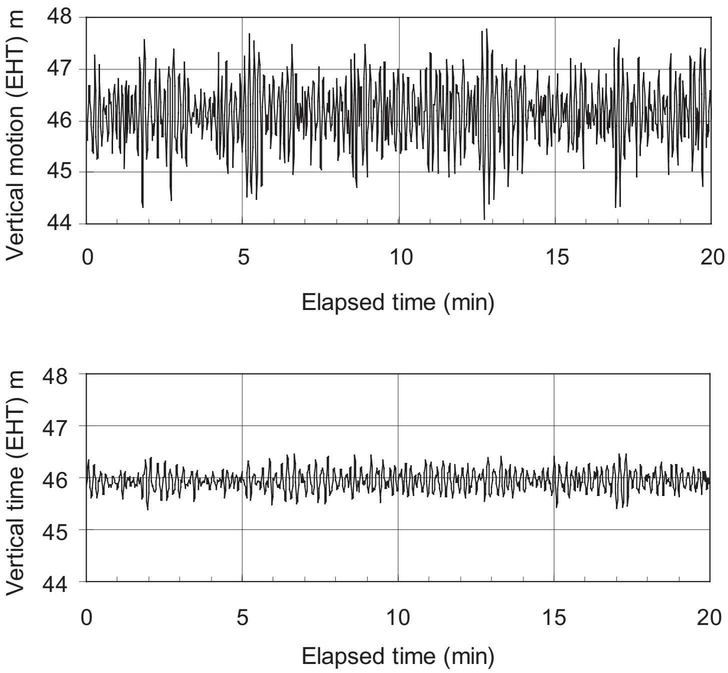

Figure 4: Samples of vertical motion of the buoy in the case of a rough sea (top), and in the case of a calm sea (bottom).

3.1 Discussion and Remarks

So far the system is running without any serious trouble except intermittent losses of fix of the RTK-processing and data transmission errors. When the software fails to fix ambiguities, it outputs DGPS solution. We examined 1-day data at 16 March 2001, and found that more than 97% of data is normally analyzed and only less than 3% of data suffered from miss-fixing ambiguity. Data transmission errors have occurred intermittently, probably because of the problems of modem and telephone line, both of which are not essential for the buoy system.

Since the buoy is floating in the open ocean, its integrity and reliability is very important for a long-term operation. Moreover, it is important to place the buoy far enough from the coast, say, at least 10 km, so that an effective tsunami warning can be made before its arrival at the coast. In order to realize this, three key factors must be considered: 1) long distance RTK GPS with a few centimeter accuracy, 2) a cost effective data transmission system, and 3) long-term operability of the buoy at the deep ocean.

The present system uses a single frequency RTK so that the feasible baseline distance is only several kilometers from the coast. Highly accurate long-distance kinematic processing is necessary. Such an application is already studied by a number of researchers as an off-line non-real-time processing (e.g., Tsujii *et al.*, 1998; Colombo, 2000; Isshiki *et al.*, 2000a, 2000b, 2001). Such an algorithm may have to be implemented in the real-time operational mode.

Second, the present radio transmission system allows for a maximum distance of 5 or 6 km between the buoy and base station. A much stronger radio system or satellite telemetry should be considered. Although technological developments should solve these problems in the near future, cost effectiveness will have to be considered among available techniques.

Third, the buoy has to be placed and moored at a particular location in the sea for long-term monitoring. A more reliable and robust buoy system may have to be designed for this purpose. Our 1-year experiment will clarify problems to be solved.

In addition to these problems, we will have to develop an effective algorithm for detecting the arrival of a tsunami automatically. So far, we have applied a moving average algorithm of long-term (300 s) and short-term (30 s) periods to sections of the height data. Significant departure of the averaged height for these long- and short-term averages may allow us to detect tsunamis. More extensive simulations and tests using real tsunami records are clearly needed.

None of these problems are principally difficult to solve. Thus, overcoming these problems, we will be able to deploy operational tsunami monitoring system (or, more generally, wave monitoring system for wider applications) in the near future. An array of such tsunami monitoring systems along the coast will significantly contribute to the mitigation of tsunami disasters.

Acknowledgments. The authors would like to express their sincere gratitude for the assistance provided by the people in Ofunato City, Iwate, Japan. The present research was conducted under the Grant-in-Aid of the Ministry of Education, Culture, Sports, Science, and Technology (#11792031).

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