Detecting Tsunami In The High Seas: How GPS Might Contribute To An Early Warning System

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BIOGRAPHY

Dr. Oscar L. Colombo works on applications of space geodesy, including gravity field mapping, spacecraft orbit determination, and precise positioning by space techniques. In recent years, he has developed and tested methods for very long baseline kinematic GPS, working with groups in Australia, Denmark, Holland, Spain, and the USA. He got his degree in Telecommunications Engineering from the National University of La Plata, Argentina, and his Ph.D in Electrical Engineering from the University of New South Wales, Australia.

ABSTRACT

Differential kinematic GPS with carrier phase data has been used successfully to position buoys at the sub-decimeter level in order to observe waves, tides, etc., mostly when the buoys are close enough to a coastal base station to resolve the carrier phase integer ambiguities.
With differential long-range methods proposed and tested in recent years, it should be possible to position just as accurately buoys, ships, and other surface craft in the high seas, at distances of thousands of kilometers from shore. The potential of one such long-range technique for the detection of possibly life-threatening tsunami (> 10 cm in height in the deep ocean), to give early warning to those at risk, is illustrated here with real-data results from a test conducted in Duck, North Carolina, in October of 1999.

INTRODUCTION

TSUNAMI waves are tidal waves generated by sudden movements of the ocean floor during earthquakes and volcanic explosions. In the deep ocean, they travel at speeds of about 700 km/h (~450 m.p.h.) as small, gentle changes in water level with periods of 10-30 minutes or longer, wavelengths of hundreds of kilometers, and heights from a few centimeters to more than one meter. (Potentially devastating ones are likely to exceed 10 cm).

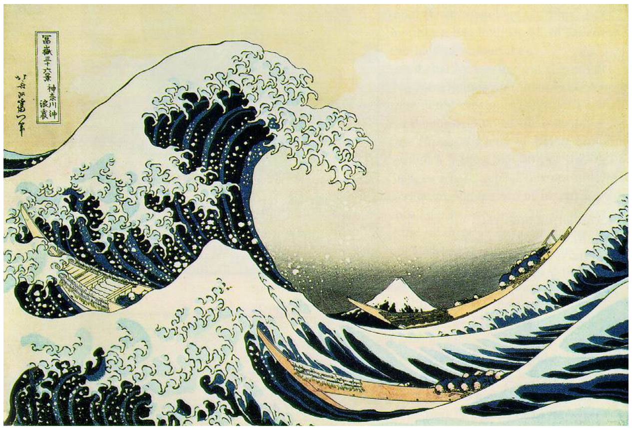

Figure 1. "The Great Wave off Kanagawa", print by Katsushika Hokusai (Japan, 1760 - 1849).

As they approach the coast, the waves become shorter and higher, as the ocean becomes less deep. Finally, they may run into the shore as successive walls of water many meters high, travelling at tremendous speed and causing catastrophic flooding. "Tsunami" means "harbor wave", because it only becomes noticeable in shallow waters, such as those of harbors.

Tsunami can devastate low-lying areas near the sea. In pre-Columbian times, huge earthquakes in the Cascadia region of North America sent tsunami waves across the Pacific, causing great destruction in populated parts of East Asia, notably in Japan. But tsunami may occur anywhere and at any time. A series of major volcanic explosions in the Aegean island of Santorini, around 1645 BC, that produced enormous tidal waves and rains of ash and molten rock, is thought to have precipitated the decline of Minoan civilization in Crete, and also to be the origin of the myth of Atlantis.

In very recent times, on the evening of Friday 17 July 1999, on the north coast of Papua New Guinea a magnitude 7.1 offshore earthquake was followed 15-20 minutes later by a catastrophic tsunami. The three waves of the tsunami completely destroyed three coastal villages causing 2200 dead and 1000 injured.

Tsunami Monitoring at Present

Tsunami waves are monitored with a combination of tide-gauges and seismometers. In the US, Federal and State government agencies cooperate in the National Tsunami Hazard Mitigation Program [1]. The monitoring devices are located at coastal sites. In order to provide a much earlier warning of an approaching tsunami, NOAA has under way its research project for Deep-ocean Assessment and Reporting of Tsunami (DART), using buoys in the high seas, acoustically linked to sea-floor pressure gauges [2]. In turn, the buoys would relay the sensor data to a central land site by satellite radio links. By deploying linear arrays of these buoys, the arrival times of the tsunami waves to the various buoys in the array would serve to infer their speed and direction.

Possible Monitoring with GPS

Bottom pressure gauges are very sensitive, but expensive to deploy and operate. So the purpose of this work is to explore the possible use of GPS receivers on buoys, as a potentially cheaper way of *densifying* acoustic buoy arrays.

Differential, kinematic GPS has been used in the past to position buoys relative to nearby coastal stations.

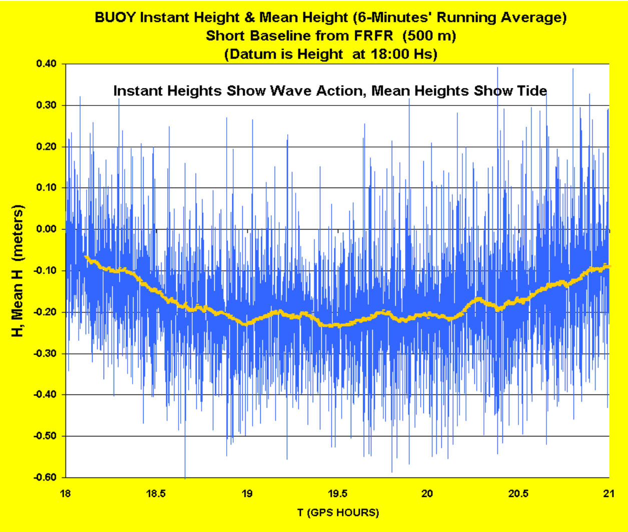

Figure 2. Waves and tide during test at Duck, North Carolina, as observed with GPS on a buoy. Short-baseline differential solution, with L1 and L2 carrier phase ambiguities resolved.

As shown in Figure 2, a running average of the observed instantaneous buoy height, with a window of 5 or 6 minutes duration, largely eliminates the short-term fluctuations due to ordinary waves (with periods of 5 to 30 seconds). This reveals more gradual changes in water level, such as a tsunami [3]. The accuracy is a few centimeters, so one should be able to detect a tsunami of 10 cm or more in height. Such accuracy is possible because the differential effect of the ionosphere on the data cancels itself out on the short baselines used (less than 10 km), making it possible to resolve exactly the carrier phase ambiguities.

To detect a tsunami well in advance of its arrival in coastal areas, the buoys must be placed in the high seas, at distances of hundreds and even thousands of kilometers from the nearest land site. The author has been developing methods for sub-decimeter kinematic positioning over just such long baselines [4], [5], [6].

BUOY TEST AT DUCK, NORTH CAROLINA

The buoy test took place on 26 October 1999, at the initiative and under the direction of Dr. Alan G. Evans, of the Naval Surface Warfare Center, Dahlgren Division (NSWCDD), at the Army Corps of Engineers Field Research Facility (FRF) in Duck, North Carolina. GPS dual-frequency receiver data were collected at a buoy (site "BUOY") anchored at the seaward end of the very long FRF pier, and at a reference site atop a building ("FRFR"), 500 m away, near the pier's landing. The observing rate was 2 Hz. Aspects of the local test setup are shown in Figures 4, 5, and 6.

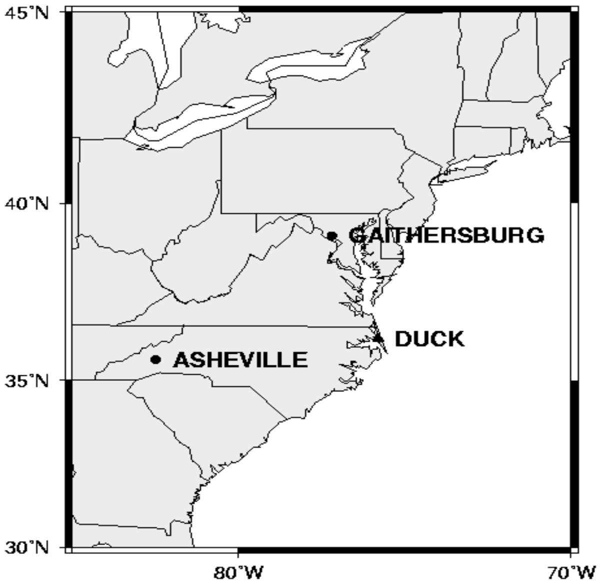

Figure 3. Duck and the distant C.O.R.S. GPS sites. Duck is 352 km from Gaithersburg, 617 km from Asheville. (Using reference receivers far across land, instead of far across water, should not affect the results of the test.)

Since the nature of what lies between receivers hardly affects GPS results, instead of distant sites across the sea, it was just as valid to test the idea using readily available reference receivers installed far *inland.*

So additional GPS observations, collected at a 0.2 Hz rate, were downloaded over the Internet from the National

Oceanic and Atmospheric Administration (NOAA) Continuously Operating Reference Stations (C.O.R.S) sites at Gaithersburg ("GAIT"), Maryland, and Asheville ("ASHE"), North Carolina. These were situated 352 km and 617 km away from Duck, respectively (Figure 3). All three land sites were put in the same reference frame by a precise static solution where the coordinates of the C.O.R.S. sites were kept fixed to their published values. A total of four hours of data were collected, but only the last three hours of data were used, because of reception problems in the first hour.Those distant sites were used as base stations in a long-range kinematic solution for the buoy, which was then compared to a short-range solution relative to FRFR, near the pier's landing. The short-range solution had the L1 and L2 carrier phase integer ambiguities resolved on the fly. To get the highest accuracy possible, only the resulting unambiguous L1 phase was used to position the buoy. The differences in short and long-range positions were regarded as being mostly the errors in the long-range solution.

Figure 4. The Duck FRF pier seen from a nearby tower.

Figure 5. The buoy deployed near the end of the pier.

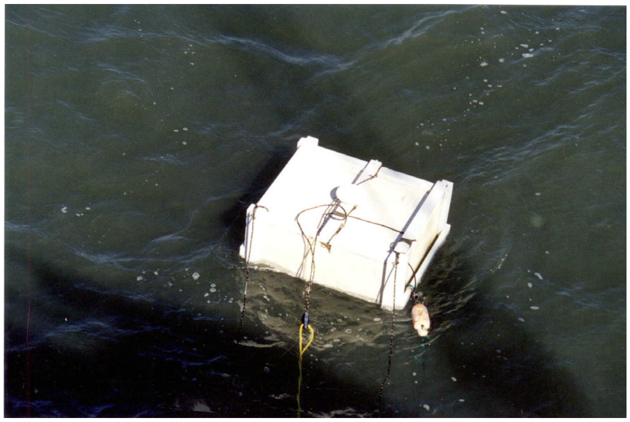

Figure 6. Close-up of the buoy showing the small, round GPS antenna on top. (Dimensions: 4' x 4' x 2')

KINEMATIC DATA ANALYSIS

The results shown in this paper were obtained in sequential post-processing of phase and pseudo-range, using both a Kalman filter and a smoother procedure.
The 2-Hz, short-baseline solution was obtained as already explained. For the 0.2 Hz, long-baseline solution, the data were the ionosphere-free linear combinations of L1 and L2 carrier phase, or Lc, and the corresponding combination of P1 and P2 pseudo-ranges. The Lc biases (the linear combination of the L1 and L2 ambiguities) were "floated", estimated as real numbers. This is the standard procedure for long-baseline GPS solutions.
(Recently, there have been successful attempts at resolving the L1 and L2 ambiguities with roving receivers hundreds of kilometers away from any base station, using computed ionospheric tomography to model and then correct the effect of the ionosphere on the GPS data [7].)
The unknowns were: (a) the buoy kinematic position ("white noise" states, 100 m a priori precision (sigma) per coordinate); (b) the biases in the Lc (ionosphere-free) combination of the L1 and L2 phases (10 m a priori sigma, each); (c) troposphere refraction correction errors (a small constant plus a slow random walk per site); (d) GPS orbit errors (analytical partials, a priori sigmas according to the IGS SP3). At least the rover and two reference sites are needed to solve quickly for the three-dimensional orbit error. This is why ASHE and GAIT were used simultaneously in the long-range solution.
The author used his own long-range GPS software, which runs under UNIX, LINUX, Windows 95, 98, and NT, and made the calculations in the same 266 MHz-Pentium II laptop used to write this paper.

GPS-DERIVED BUOY HEIGHT AND LOCAL TIDE

Since 1978, the National Ocean Service (NOS) of NOAA has operated a primary tide station (No. 865-1370) at the seaward end of the FRF pier. A NOS acoustic tide gauge (Next Generation Water Level Measurement System, NGWLMS) provided water level data every 6 minutes.

The observed tidal heights were used as "ground truth", comparing them to a 6-minutes' running average (to reduce the effect of waves) of the GPS-determined ellipsoidal height of the buoy, corrected for the Earth body tide (but not for ocean loading). Tide-gauge water level and GPS height were each on a different datum (buoy height at 18:00 hours GPS time, taken from the short-baseline solution, versus the NGVD datum). Only their temporal changes could be compared (Figure 7). The difference in water level according to short and long baseline solutions is shown in Figure 8.

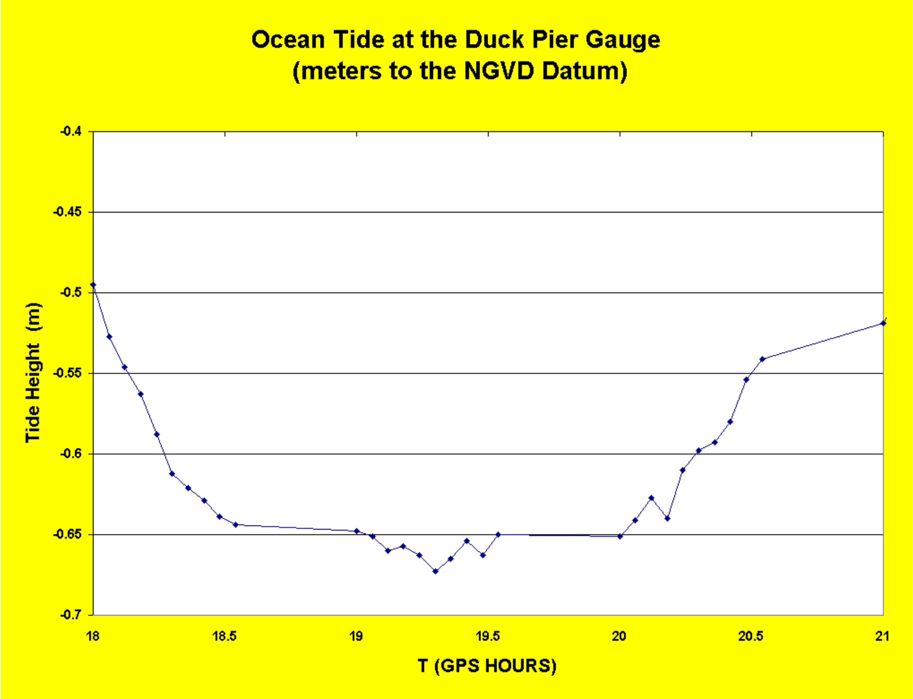

Figure 7. The change in water level during the test, recorded at the local tidal station.

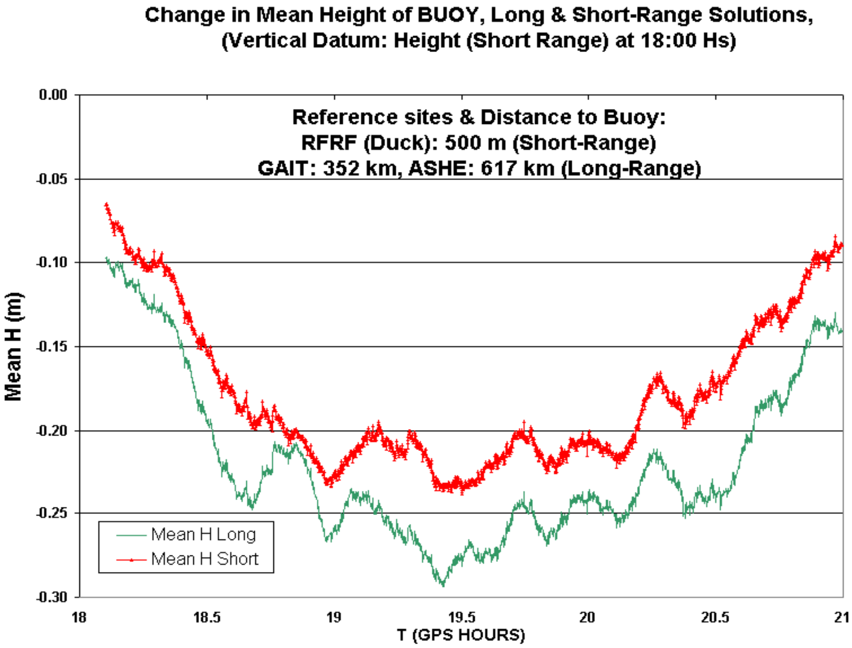

Figure 8. Change in buoy height from short- and long- baseline kinematic solutions.

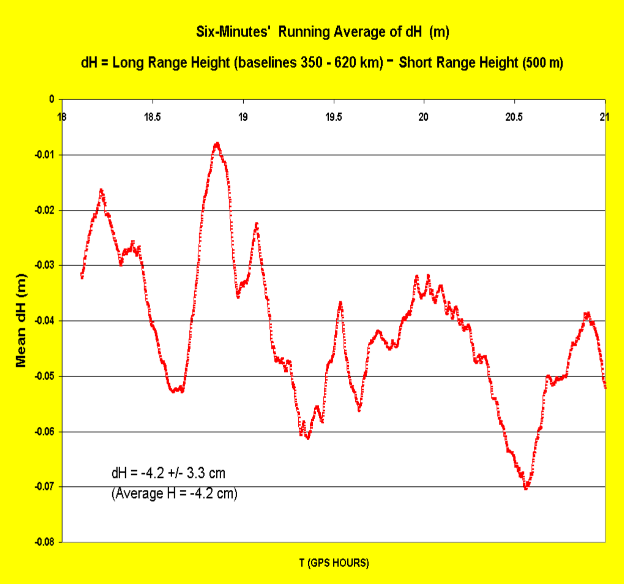

Figure 9. Discrepancies between estimated water level variation from short- and long-baseline solutions.

The water level[1] change according to both long- and short-baseline solutions (Figure 8) does agree with a nearby tide-gauge within 5 cm. (Part of the differences with the locally observed tide reflect the imperfect earth tide correction, and the neglect of ocean loading.)

During a total of three hours, the 6-minutes averaged GPS water levels obtained relative to: (a) the nearby reference site (500 m away), and (b) the distant ones (at 352 km and 617 km), are offset from each other by 4.2 cm (irrelevant to tsunami detection, it should be *less* in longer runs), and their differences fluctuate ± 3.3 cm about this offset (Figure 9). So if a potentially damaging tsunami of 10 cm or more can be detected with the short-baseline solution, it can also be detected with the long-baseline solution.

SPEEDING UP KALMAN FILTER CONVERGENCE FOR REAL-TIME USE

The post-processed results shown above correspond to a fully converged Kalman filter. The filter needs to assimilate enough data to *converge* to a precise solution. The time needed to obtain those many data should be as short as possible, since a tsunami could pass unnoticed while the calculated height of the buoy is not precise enough to detect it. The use of a slow-varying water level constraint can shorten the convergence transient. In normal kinematic GPS (e.g., the solutions in previous sections, Figs. 2, 8, and 9), no assumption is made concerning the dynamics of the vehicle (in this case, a buoy), which is often too poorly known. In the case of a buoy, the running average of the height approximates the wave-filtered, time-varying water level that would be measured at a tide-gauge, and which changes gradually and predictably most of the time.

By coincidence, the long-range kinematic technique, as implemented by the author, uses *data compression* (averaging) to speed up calculations and economize other computer resources, such as hard disk space for scratch files [5]. This procedure requires solving for the mean position of the vehicle over the compression interval, as well as for the instantaneous position. And so the mean height on that interval is already one of the estimated quantities (converted to sea surface height by correcting for the antenna, if so desired). It is quite simple to create, and assimilate in the filter, along with the GPS data, pseudo-observations of the form:

water level(local model) = water level(unknown)
+ constant + random walk + noise.

The "local model" is the known value of the time-varying water level at the location of the buoy. It is the sum of long-term mean sea level, geocentric tide (ocean tide + solid earth tide + ocean loading), inverted-barometer correction, and other calculable effects. (The model can be improved, over time, using the record of GPS-determined buoy heights.) For this study, the "model" was simply a constant height, set equal to the first 6-minute height average of the unconstrained, short-range solution. The "constant" term represents the error in the model's water level at the start of the run. The "random walk" represents the model's error in the change in water level from the same epoch. The "noise" is the residual wave action after averaging.

For a simple box-window average T_a seconds long, approximately sinusoidal waves of dominant period T_w and peak-to-null amplitude A_w, and a data rate high enough to keep aliasing small, the r.m.s. value N_w of the residual wave-effect, or "noise" is:

$$N_w \leq T_w / (2^{3/2} \pi T_a) \; A_w$$

To be conservative, "≤" is replaced with "=". Choosing: T_a = 120 seconds (a good compression interval for the solution, not for averaging waves), A_w ~ 2 m (peak-to-null, or half peak-to-through), and T_w ~ 20 seconds, then N_w ~ 4 cm (r.m.s.). Waves at the time of the test were much smaller, but this choice of amplitude was judged more realistic for open waters. The other (one sigma) uncertainties were chosen as follows: unknown constant, 10 cm (mean sea surface and tides, from satellite altimetry); random walk system noise, 3 cm(min)$^{-1/2}$ (i.e., a change of ~12 cm in 15 minutes.)

The effect of the water level constraint on the convergence of the Kalman filter can be seen in Figure 10. This figure shows the (one sigma) precision of the estimated *instantaneous* buoy height as a function of time (in meters): (1) for a purely kinematic (unconstrained) solution, and (2) for a height-constrained solution. The convergence for height clearly improves with the

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[1] "Water level" here means "the observed sea height filtered to eliminate the effect of sea waves".

constraint. (Not shown here, the convergence in *horizontal* precision also improves markedly). Since the filter is supposed to be operating in real-time, the GPS satellite orbits have been given a priori uncertainties of 1 m in each initial coordinate (although precise SP3 orbits were used throughout). This assumes the availability of reasonably good predicted nominal orbits, and that the errors in those orbits are also estimated in the filter (to reduce their adverse effect). Such orbits may be calculated at the central monitoring site, using the data from its own stations, or else might be obtained from some international service, such as the one now being discussed within the International GPS Service (IGS). In either case, solving for orbit errors simultaneously with the position of the buoy is essential to achieving sub-decimeter precision and, therefore, for tsunami detection.

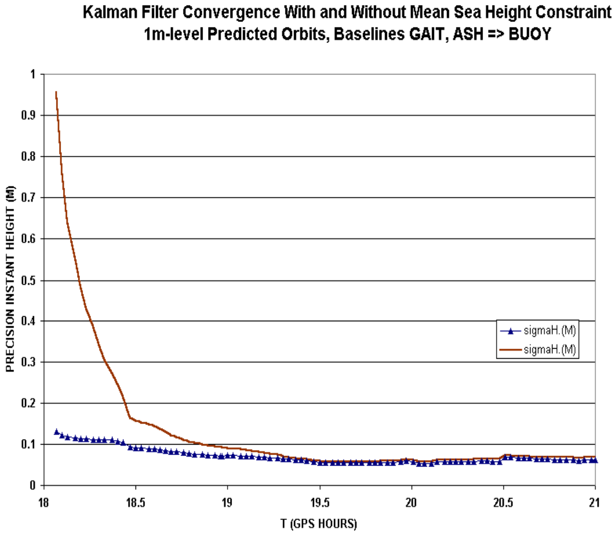

Figure 10. Convergence of the Kalman filter solution with and without the proposed water level constraint. (Vertical precision, in meters.)

To see to what extent the use of the height constraint biases the solution, long-range constrained, post-processed results (filtered and smoothed) were compared to the unconstrained ones of earlier sections. Their differences in estimated heights, over the three-hour run, had a mean of 1 cm, plus a variation of ±7 mm r.m.s.

DISCUSSION

The early results look encouraging. However, they have been obtained by post-processing the GPS data. Tsunami detection must be done quickly, reliably, and in real time. How to process GPS data from arrays of buoys in this way, fusing them with other significant information, such as seismic and tide gauge measurements, remains to be investigated.

Latency due to the kinematic calculations themselves is probably not an issue. Less than 30 seconds were needed to process all the data for the full three-hour solution, using a "starter" Pentium II laptop. In the open sea, tsunami waves travel at most 20 km in 30 seconds. The time needed to update the filter from one epoch to the next should be much less than that. The main delay would be in the procedure used to filter out the waves (e.g., half the length of a running-average window.) Correlating results from several buoys with tidal, seismic and other data should speed up detection, as well as sharpen it.

Another issue to consider is how to best sample and compress the GPS data to reduce the bandwidth needed to send them from the buoy to a processing site in real time.

ACKNOWLEDGEMENTS

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