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Tsunami Wave Parameters Calculation before the Wave Approaches Coastal Line

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ABSTRACT

In this paper we provide a possible way to face the challenge of the tsunami wave height evaluation in real time after a seismic event. Our scenario is based on 2011 Japan Earthquake, in which case the wave traveling time after the seismic event to the nearest coast was close to 20 min. Three improvements to the existing data processing technique are proposed: sensor network optimization, fast determination of tsunami wave parameters at source, and to accelerate calculation of tsunami wave propagation. By applying these approaches it is possible to reduce the time required for wave height calculation to 12 minutes.

KEY WORDS: tsunami risk early warning, modern computer architecture.

INTRODUCTION

Friday, March 11, 2011 at 05:46:23 UTC, Japan was struck by an 8.9-magnitude earthquake near its Northeastern coast. This is one of the largest earthquakes that Japan has ever experienced. Tsunami waves swept away houses and cars and caused massive human losses. According to the CEDIM report, over 20,000 people died and about a million people lost their homes, due to earthquakes and their effects. More than one million buildings were damaged in Japan (http://earthsky.org/earth/economic-losses-from-earthquakes-and-natural-disasters-peaked-in-2011). Japan has lost considerable physical and human capital. Physical damage has been estimated to from $250 billion to as much as $309 billion.

Question arises is that possible to reduce human causalities and economy loss by timely warning about tsunami danger even in case of small traveling time from tsunami source to the coast. In other words, we are speaking about Tsunami Early Warning Systems (TEWS). Several of such systems exist over the world. In the sequel we will discuss possible improvements in TEWS built by NOAA (USA), which is based on deep ocean tsunami records, obtained at special buoys (DART). These data are processed to calculate wave parameters and inundation zones. Alternative approach was successfully implemented in Indonesia, see Lauterjung et al. (2010), Behrens et al. (2010) and Taubenböck et al. (2009). This is based on calibration of GPS sensors data. Perhaps, it is effective only at selected geo locations.

We propose a way to improve the quality of tsunami wave parameters prediction and to reduce time required for that. In that way we suggest to improve the quality of existing TEWS systems. Using new algorithms for data processing and facilities of modern computer architectures it is possible to calculate wave heights along the entire cost of Japan before the wave approaches the coastal line. This could be used for tsunami risk mitigation with the goal to reduce human loss by activating urgent evacuation measures in time.

There exists a well-developed system of deep ocean tsunami detectors operating across the Pacific (www.ndbc.noaa.gov/dart.shtml). Pressure sensors (DART buoys and other) provide direct measurements of tsunami-wave time series, which are immediately available for analysis through satellite channels. However, current tsunami-warning systems fail to predict basic parameters of tsunami waves on time. Among the reasons of that we note extended computational resources required for full scale modeling and lack of data for analysis right after a seismic event. In this paper we address both these aspects. In fact, modern computer architectures such as, GPU (graphic processing unit) and FPGA (field programmable gates array), can dramatically improve performance of data processing, which may enhance timely tsunami-warning prediction.

We propose to use three new techniques in the existing tsunami warning systems to achieve real-time calculation of tsunami wave parameters. Firstly, the measurement system (DART buoys location, e.g.) should be optimized (both in terms earlier detection of the arriving wave and in order to determine possibly the largest amplitude parameter). The corresponding software application is already developed and is ready for use (Astrakova, Bannikov, Cherny, and Lavrentiev, 2009). In application to the coastal line of Japan numerical tests show that optimal installation of only 4 DART buoys (accounting the existing sea bed cable) will reduce the tsunami wave detection time to only 10 min at most after an underwater earthquake.

According to typical scheme, the measured (or evaluated) data about tsunami wave parameters are recalculated in terms of initial sea bed (or sea surface, preferably) displacement. Then wave propagation is calculated with the MOST (method of splitting tsunami) software package (Titov and Synolakis, 1998) or any other tool.

Here we propose a new real time algorithm for tsunami source parameters determination by processing the time series obtained at DART or any other sensor system. The measured time series is approximated by a linear combination of synthetic marigrams calculated in advance. Coefficients of such linear combination are determined with the help of orthogonal decomposition algorithm, which is based on classical theorem from calculus.

Finally, we explore such modern computer architectures as GPU/FPGA to accelerate the execution of the MOST (method of splitting tsunami) code. The obtained performance gain is compared to 100 times (Lavrentiev and Romanenko, 2010a,b) versus the usual sequential program execution. Therefore, tsunami wave propagation over the area 2000*2000 km (wave propagation simulation: time step 10 sec, recording each 4th spatial point and 4th time step) could be calculated at:

- 3 sec with 4’ mesh
- 50 sec with 1’ mesh
- 5 min with 0.5’ mesh

Currently, version of algorithm to switch from coarse mesh to the fine grain one is under development. The algorithm is very fast and demonstrates good accuracy.

OPTIMIZATION OF DART BUOYS LOCATION

The problem of placing sensors optimally for the earliest detection of tsunami wave is considered as an optimization problem, well studied in mathematics. Accordingly, the “traveling time functional” was constructed, optimal value of which provides the minimal time of determination of disturbance from any point of possible wave origin (within the given subduction zone). Calculation of the wave traveling times from any source at subduction zone to all possible sensors locations is based on shallow water approximation similar to those, used in MOST software package. A version of the so-called genetic algorithm was applied to optimize sensor network location.

The developed software was first tested against several simple model cases, for which the desired solution is known analytically, see Figs.1~2. Thus, special depth profile is shown in Fig. 1. Area of buoys location is bounded by the black rectangle, exact analytical solution is displayed with black points.

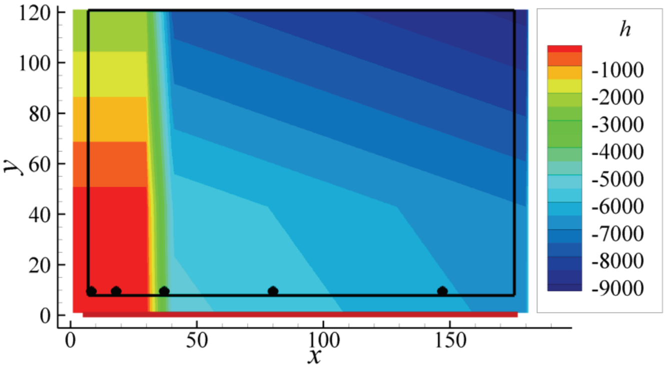


Fig.1.Special bathymetry, in which case the exact solution is known. Optimal location of 5 sensors is shown by black points.

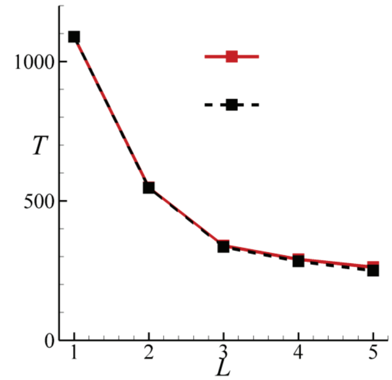


Fig.2. Time of the guaranteed tsunami wave detection versus number of sensors (L).

In Fig. 2 the exact solution is indicated with the dashed line and calculated solution – with the solid line. Lines are practically coincident, which proves the algorithm accuracy.

A version of software to solve two-objective optimization problem has been also developed. The second parameter corresponds to the amplitude parameter in order to improve the quality of entire warning system. In this case the solution is given as a Pareto graph or set.

During numerical tests we drive the possible tsunami source along the part of the Japan Trench, as is shown in Fig. 3.

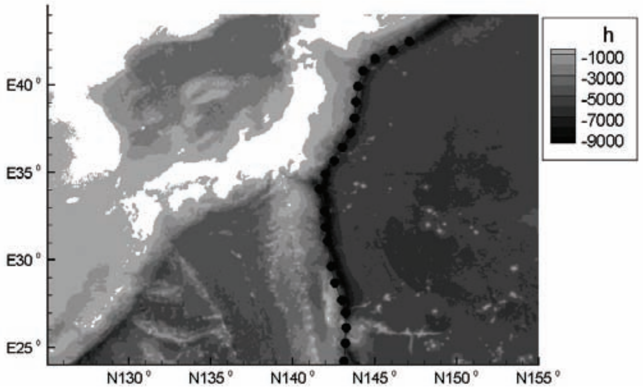


Fig.3. Various locations of the simulated tsunami sources along the Japan Trench are given with black points. These were used in numerically tests to calculate optimal location of DART buoys.

Numerical test show that, accounting the existing underwater cable (offshore Japan), only 4 optimally positioned DART buoys are enough to reduce the largest wave detection time to only 600 sec after the event, see Figs. 4~5. In Fig. 4 the bathymetry at the cost of Japan is presented (picture is rotated anticlockwise). Black points, presenting the simulated tsunami sources, are located along the Japan Trench. Red points shows the calculated optimal positions of four (*L=4*) DART buoys. Red square shows approximate position of the existing underwater cable with sensors.

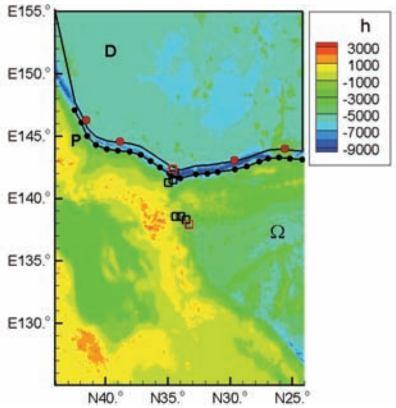


Fig.4. Optimal location of the four DART buoys (market with red points) and the existing underwater cable (red square) offshore Japan.

In Fig. 5 we plot time in seconds of the guaranteed tsunami wave registration after the seismic event at the optimized sensor system for different number of DART buoys *L* (dashed line). Solid line shows the same detection time in case the data of existing underwater cable are also accounting.

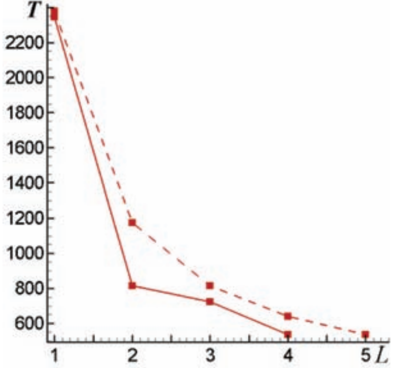


Fig.5. Largest time (in seconds) for tsunami wave to approach at least one DART buoy for different number of buoys (L): accounting the existing under-water cable (solid line) and just for DART buoys (dashed line)

REAL-TIME TSUNAMI SOURCE PARAMETERS DETERMINATION

To predict tsunami wave parameters better and faster, we propose to improve data inversion scheme and to achieve valuable performance gain for data processing. One of the reasons of inaccurate predictions of tsunami parameters is that a very little information is available about the initial disturbance of the sea bed at tsunami source. In this paper, we suggest a new way of improving the quality of tsunami source parameters prediction.

Modern computational technologies can accurately calculate tsunami wave propagation over the deep ocean provided that the initial displacement (perturbation of the sea bed at tsunami source) is known (Lavrentiev, Romanenko, Titov, Vazhenin, 2009). Direct geophysical measurements provide the location of an earthquake hypocenter and its magnitude (evaluation of the released energy). Among the methods of determination of the initial displacement the following ones should be considered:

(1) Direct numerical calculation through the known fault structure and available seismic information. This method is widely used and provides useful information. However, even if the exact knowledge about rock blocks shifts is given, recalculation in terms of sea bed displacement is needed. This results in a certain number of errors.

(2) GPS data analysis. This method was developed after the December 2004 event in the Indian Ocean. A good correlation between dry land based GPS sensors and tsunami wave parameters was observed in the particular case of the West coast of Sumatra island, Indonesia. Now the sea surface based GPS sensors are used. This approach is promising, but not yet well developed.

(3) Satellite image analysis. The resolution of modern satellite images has dramatically improved. In the future, correct data of sea surface displacement will probably be available in real time, right after a tsunamigenic earthquake. However, today this is not possible yet.

(4) Ground-based sea radars. This is an effective tool for direct measurement of the approaching tsunami wave. At the same time, the wave is measured at a rather narrow area in front of the radar and does not include information about neighboring parts of the wave.

(5) Direct measurement of tsunami wave at deep water (Borrero, Cho, Moore, Richardson, Synolakis, 2005). Today, this technology is certainly among the most useful and promising. The DART II® system consists of a seafloor bottom pressure recording (BPR) system, capable of detecting tsunamis as small as 1 cm, and a moored surface buoy for real-time communications. Details are given in Fig. 6.

We focus our research on improving the later method, method of calculation in advance (MOCIA), based on the direct measurement of tsunami wave at deep water. We suggest the new way to analyze DART data, modifying the “calculation in advance” methodology originally proposed in (Titov and Synolakis, 1998). It was proposed to cover the given subduction zone with a set of model tsunami sources – unit sources. These are 50x100 km rectangles, corresponding to typical area of sea bed disturbance for 7.5M earthquake. Initial disturbance of the suggested shape, characteristic to the subduction zone under study and normalized with respect to the amplitude, is placed to each unit source. Direct numerical simulation provides the database of the wave heights from all these unit sources in the entire water area. The real measures signal (wave profile, detected at sensor) is approximated as a linear combination of the model profiles, calculated in advance at the same point. Details and pictures are given below in this section.

As was observed, see Tang et al. (2010), the MOCIA method provides good agreement with tidal gage observations even far from the tsunami source. However, to use it in the real time forecast systems, performance of data analysis should be dramatically improved. This could be done by using an orthogonalization procedure for model signals, obtained from the considered system of unit sources and calculation of Fourier coefficients of the measured time series with respect to orthogonal basis.

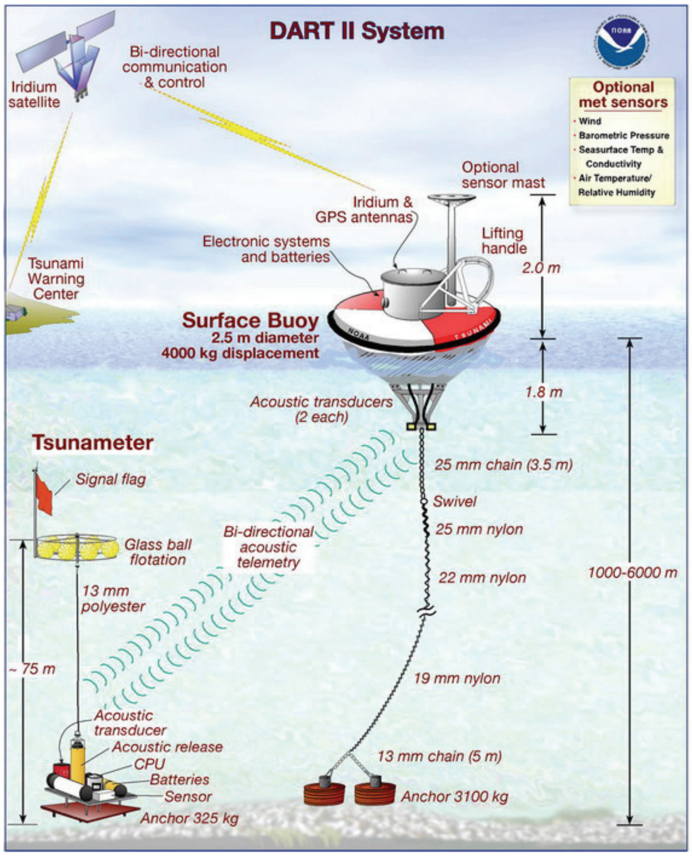


Fig.6. Operation scheme of the DART bottom pressure recorder.

The corresponding algorithm was proposed and realized as the software application. Software application was first tested against synthetic data. Simplified bathymetry for model numerical tests is given in Fig. 7. This is keeping characteristic features of typical subduction zone. Sensors (deep water tsunameters, underwater cables, GPS, or so) were displaced along 11 lines (parallel to the shore line), distance between the lines – 50 km. First line – 50 km from shore line, last – 550 km from the shore. Each line contains eight sensors, located 50 km from each other.

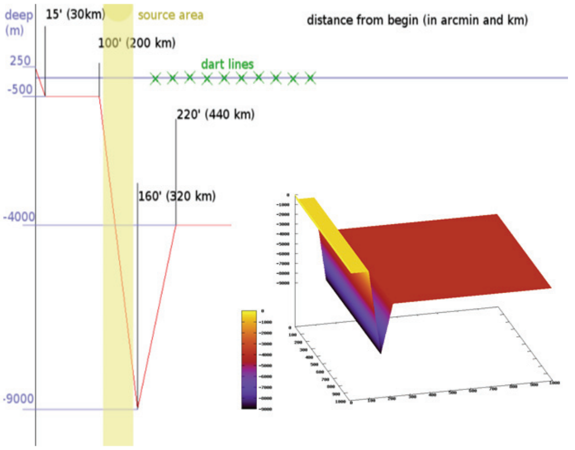
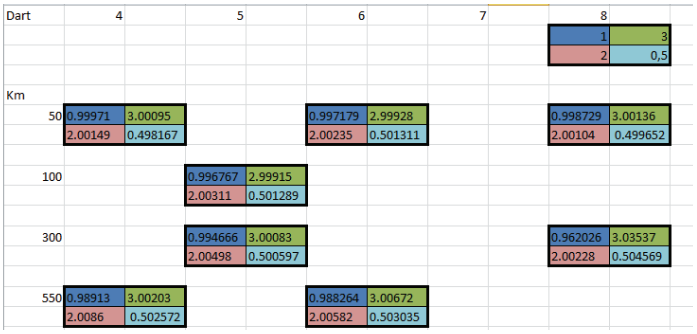


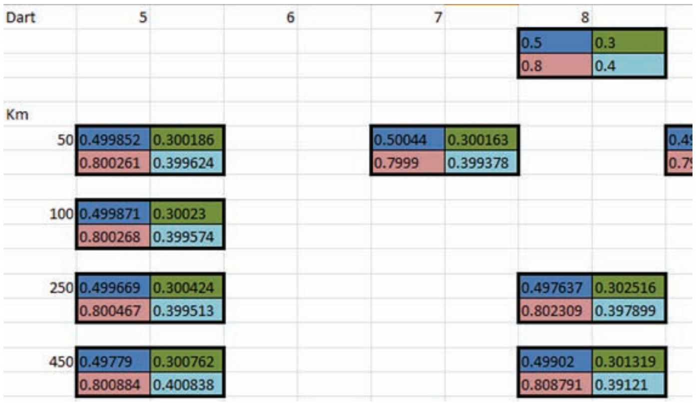
Fig. 7. Cross-section (orthogonal to the shore line) of synthetic profile is given. Source zone is indicated with yellow, sensors are given in green.

In Fig. 7 we show a vertical cross-section of synthetic bathymetry, the direction is orthogonal to the shore line. Typical depth profile is not changed along the shore, a 3D image is presented. The picture includes a tsunami source zone (indicated with yellow color) and sensors (depicted by green crosses). Initial sea bed displacement was composed as a linear combination of four unit sources with several sets of coefficients. The proposed algorithm calculates amplification coefficients of the unit sources. Numerical tests show very good agreement with the model data and practically real time performance. The results of numerical test (large variety in the values of coefficients) are given in Fig. 8. The tsunami source was approximated as a linear combination of the four model sources with the coefficients 1, 3, 2, 0.5, respectively, as is shown in the right upper corner, Fig.8. The algorithm reconstructs these coefficients using only one synthetic marigram, obtained at the selected sensor. For all sensors, the values of the above coefficients were determined with fairly good precision, the relative error does not exceed 1%. Each rectangle in Fig.8 shows reconstructed values of the above coefficients for the corresponding sensor.



Dart	4		5		6		7		8	
									1	3
									2	0,5
Km										
50	0.99971	3.00095			0.997179	2.99928			0.998729	3.00136
	2.00149	0.498167			2.00235	0.501311			2.00104	0.499652
100			0.996767	2.99915						
			2.00311	0.501289						
300			0.994666	3.00083					0.962026	3.03537
			2.00498	0.500597					2.00228	0.504569
550	0.98913	3.00203			0.988264	3.00672				
	2.0086	0.502572			2.00582	0.503035				

Fig. 8. Reconstruction of tsunami source parameters by orthogonal decomposition method. Data from any point are suitable for inversion.



Dart	5		6		7		8		
							0.5	0.3	
							0.8	0.4	
Km									
50	0.499852	0.300186			0.50044	0.300163			0.4
	0.800261	0.399624			0.7999	0.399378			0.7
100	0.499871	0.30023							
	0.800268	0.399574							
250	0.499669	0.300424					0.497637	0.302516	
	0.800467	0.399513					0.802309	0.397899	
450	0.49779	0.300762					0.49902	0.301319	
	0.800884	0.400838					0.808791	0.39121	

Fig. 9. Reconstruction of tsunami source parameters, case of small variations in amplification coefficients.

In the second test values of the desired coefficients were similar, namely 0.5, 0.3, 0.8, 0.4 (see rectangle in the upper right corner of Fig. 9). Again, all these values were reconstructed well, regardless of the distance from the source, as is shown in Fig. 9.

The proposed method was also tested on real bathymetry and compared to earlier results obtained by the “manual” complete enumeration technique, available for the (small) Andreanov event of 1996. As was proposed in (Titov and Synolakis, 1998) the Alaska Aleutian subduction zone was covered with the set of 50x100 km rectangles – model tsunami sources, see Fig. 10. These “unit sources” are arranged in two lines and marked as A and B with the corresponding number.

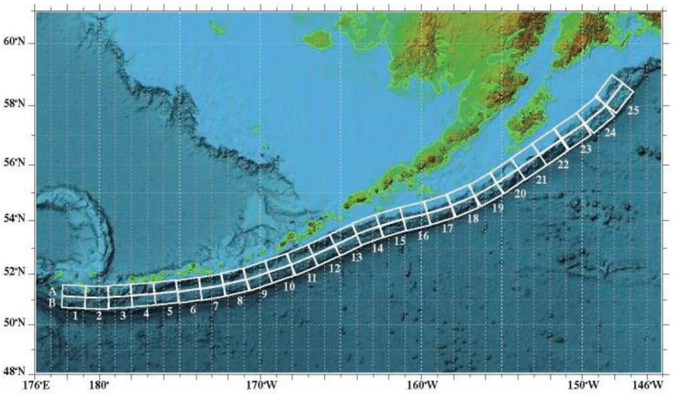


Fig. 10. Location of the unit sources along the Alaska Aleutian subduction zone.

In the late 90-s of XX century technical facility of precise deep ocean registration of tsunami waves appears. This makes it possible to obtain tsunami marigrams free of noise and disturbances from the near coastline phenomenon. Experimental positions of the five deep water registration stations, which have been arranged in 1996, are given in Fig. 11. No telemetric facilities – records of waves from the rather week Andreanov tsunami have been decoded after few months (earthquake epicenter is indicated with the yellow point, left part of the picture). The idea to reconstruct the true source parameters was realized by MOCIA method for the first time. Main tool – the database of time series of the calculated waves initiated by tsunami "unit sources" typical for the given subduction zone.

Fig 11. Location of measures sensors and the Andreanov event epicenter.

Based on the initial displacement at source, typical to the Alaska Aleutian subduction zone, the tsunami wave propagation at all the north-eastern part of Pacific ocean have been calculated from each of the unit source. Collection of all these calculated time series has been arranged as the FACTS database. In particular, synthetic marigrams have been obtained at all the mesh nodes, closest to the real positions of the above mentioned record stations. Based on the FACTS database, the first version of Andreanov tsunami source has been determined. By manual varying of weight (in fact, amplitudes) coefficients of the selected unit sources (selection of these sources have been made on the basis of the first arrival times analysis), the set of amplitudes at four unit sources have been obtained.

Signals, measured at Ak70, Ak71, Ak72, Ak73 sensors (see Fig. 12), were approximated as linear combinations of wave profiles, obtained as calculated signals from the proposed unit sources: A4, A5, B4, B5 (see Fig. 10). Amplification coefficients were first obtained by V.Titov experimentally (in manual mode). Later, a similar result was achieved by automated software by the use of "brute force" (complete enumeration) approach.

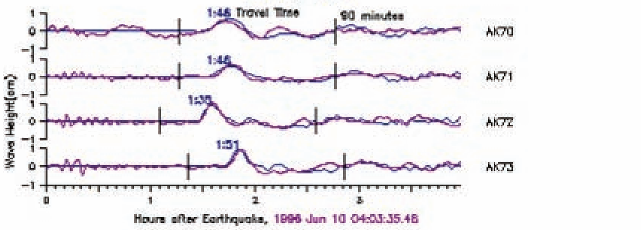


Fig. 12. Measures wave profiles (purple), and approximation of the measured wave profile by linear combination of four model sources (blue) at different sensors.

Recently, the authors have used the same data for verification of the proposed orthogonal decomposition method.

Table 1. Comparison of results obtained by V.Titov (Brute Force approach) and the proposed method of orthogonal decomposition.

	Unit-sources			
Station	A4	A5	B4	B5
	Method of Orthogonal Decomposition			
Ak70	0	0.578	3.732	0
Ak72	0.408	0.210	4.650	0
Ak73	0.955	0.240	2.761	0.188
	Brute Force Approach			
Ak70	0	0.6	3.6	0
Ak72	0.4	0.2	4.6	0
Ak73	1	0.2	2.6	0.2

The first column in Table 1 shows measuring sensors, see Fig. 11. Each row provides amplitude amplification coefficients for the selected unit sources A4, A5, B4, B5, obtained by one of the described methods. Linear combination of calculated wave profiles (model wave initiated by artificial disturbance at the given unit source) with these given values of coefficients provides the best approximation of the real wave, measured at the corresponding sensor Ak70, Ak72, or Ak73.

Data from the Table 1 shows a very good agreement of the values of amplification coefficients, obtained by suggested method with results of the previous studies. Both software applications were used at Intel (R) Core(TM) 2 Duo, CPU T6600 2.2GHz, 4GB RAM. Execution time for the new method of orthogonal decomposition was less than 1 second that is by several orders faster, compared to implementation of the Brute Force method.

SPEEDING UP TSUNAMI WAVE PROPAGATION MODELING

The approximations of shallow-water theory (both lineal and non-lineal) are used as the basic models for describing wave propagation throughout the ocean. These models reflect rather accurately the basic wave parameters (propagation time period from the source to the recording device and wave amplitudes) even for a fairly rough numerical bathymetry in the assumption that initial displacement in the source is unknown. There are several software packages for modeling wave propagation throughout the ocean and the run-up heights. The most well-known packages are MOST and TUNAMI.

MOST (Method of Splitting Tsunami), proposed in (Titov, and Synolakis, 1998) allows to make a forecast of the flood region in real-time mode using tsunameters' data. This package is mostly used in USA for charting inundation maps (http://nctr.pmel.noaa.gov/inundation_mapping.html). Online version of MOST – comMIT – has also been created. TUNAMI N2 package for the Tsunami Inundation Modeling Exchange (TIME) program was worked out by Imamura in 1993. The registered copyright holders for this package are professors Imamura, Yalziner, and Synolakis. TUNAMI N2 has been successfully used for analyzing some tsunami (Shuto, Goto, Imamura, 1990). All speculations hereafter will refer to the MOST software package only.

The MOST software package uses numerical model of calculating wave propagation through deep water zone applying decomposition method for spatial variables. This method was initially developed in the Tsunami Laboratory, Computer Center of the Siberian Division, Academy of Sciences of USSR in Novosibirsk. Then the method was updated in the Pacific Marine Environmental Laboratory (NOAA, Seattle, USA) and was adapted to the models and standards of data accepted by tsunami watch services in the United States as well as other countries and used in tsunami research works in most countries. MOST is used to numerically simulate three processes of tsunami evolution: the estimation of residual displacement area resulting from an earthquake and tsunami production, transoceanic propagation through deep water zones, and contact with land (run-up and inundation). The given research work is concerned with the second stage – deep water wave propagation.

Nonlinear approximation of shallow water system is used for numerical calculation of tsunami wave propagation in the following form (http://nctr.pmel.noaa.gov/most-pubs.html):

$$H_t + (uH)_x + (vH)_y = 0,$$
$$u_t + uu_x + vu_y + gH_x = gD_x,$$
$$v_t + uv_x + vv_y + gH_y = gD_y,$$

where *H(x, y, t) = h(x, y, t) + D(x, y, t), h(x,y,t)* - stands for the height of the wave calculated from unperturbed level, *D(x,y,t)* – the function delineating bottom configuration (digital bathymetry), *u(x,y,t), v(x,y,t)* – velocity vector components along x and y directions, respectively, and *g* – acceleration of gravity.

The adduced shallow water model soundly describes the process of tsunami wave transoceanic propagation providing that the horizontal dimension of ocean floor surge by an order exceeds the ocean depth at that point.

The above system could be turned to canonical form and solved with a method based on spatial decomposition along axis directions. For the final system, it was suggested to make an explicit difference scheme on a four-point stencil with quadric approximation order regarding spatial variables and first order approximation with respect to time.

As a result we have fine-grain system which is well-suited, for example, for shared memory systems and GPUs. We successfully adopted modelling of transoceanic propagation of tsunami waves to different computer systems. Our conclusion is that GPUs provide the best performance for this task.

The first attempts to speed-up the algorithm were performed in 2008. We archived 60x speedup on CELL BE processor compared to single core of CPU. Later, in 2009 we moved the algorithm to GPU with 170x speedup (Lavrentiev and Romanenko, 2010a,b). Testing the algorithm on real data leads us to understanding that storing data in single precision data types is not suited for transoceanic modeling. The surface of the ocean became unstable due to insufficient accuracy of float data type. The ratio of the wave height to the ocean depth is on the edge of float point precision. Thus we requested for the newer version of MOST software package and apply our knowledge and experience to moving it on GPU. Now we have no unstable ocean surface and our results agreed with NOAA PMEL modeling results. Accuracy is less than 10^-3 cm.

Some numbers worth to be provided.

Original program	3 sec/iteration
Tesla C2050	0.06 sec/iteration
Tesla K40	0.02 sec/iteration

In terms of wave propagation modelling the achieved performance means that computational time for the entire Pacific water area (4' mash computational grid) decreases from 7 hours for original program to just 3 minutes for Tesla K40 GPU.

SCENARIO

The natural way to protect people living at shoreline from catastrophic tsunami wave is to provide in time (prior to the wave arrival) the accurate calculated estimation of expected tsunami wave parameters, namely the wave height. To date, there exist several original algorithms which bring us closer to real time tsunami risk mitigation. Here below we present the desired timeline scenario of the developing decision support system to be used by the corresponding public services.

- tracking (monitoring) seismic activities (for example at http://earthquake.usgs.gov) in semi-automated mode;
- in case of potentially dangerous seismic event:
  a) estimate tsunami traveling time from epicenter to populated areas and tsunami measuring network (DART stations, e.g.) - original real time algorithm is ready to use (Marchuk 2008). Moreover, software application to optimize DART stations network is available as well (Astrakova, Bannikov, Cherny, and Lavrentiev, 2009);
  b) read an appropriate data from the nearest DART stations (http://www.ndbc.noaa.gov/dart.shtml) - usually before tsunami wave approaches the coast line;
  c) filter tide waves out (real time);
  d) calculate the amplitude parameter at tsunami source by processing the measured data. Real time original algorithm is proposed and preliminary tested;
  e) perform tsunami wave propagation modeling. Currently, MOST code have been accelerated dramatically (from 16 to 150 times performance gain depending of the available hardware platform);
- Deliver the expected tsunami parameters to public/governmental services.

Table 2. Time line of executing selected component of the proposed tsunami warning system.

	What happens after a seismic event	Time line
1	Wave traveling time to the nearest sensor (DART, e.g.) after optimization	10 min
2	Source parameters determination by orthogonal decomposition method	1 min

3	Calculation of wave propagation, GPU use, 1' mesh, 2 000 * 2 000 km area	1 min
4	Total time (after the event) for wave height calculation	12 min
5	Wave traveling time to the nearest point at coast	20 min
6	Time reserve for warning issue and evacuation measures	8 min +

Table 2 summarizes the results of the implementation of three proposed components to tsunami warning system. Even in case of only 20 min wave traveling time to the nearest shore, there will be some time for decision making, warning of population, and other activities within risk mitigation framework.

CONCLUSION

In this paper we have presented recent research results that allow improving the quality and reducing the time for tsunami danger evaluation. In particular, the questions of sensor system optimization, of reconstruction of initial sea surface displacement at tsunami source, and of acceleration of the wave propagation process have been studied.

Several algorithms, both original ones and those used in existing software packages, have been optimized for modern hardware platforms. This allows the user to make all the necessary calculations in a few minutes (or even seconds) after the tsunami wave approaching the nearest measuring station (we refer to the DART buoys first of all). Data from the other DART stations (approached by the wave later) will be used to refine the first evaluation of tsunami wave parameters.

Applying three proposed components to the existing tsunami warning system should dramatically reduce the time to correct evaluation of tsunami danger. In particular, for Japan, wave height evaluation will be available within 12-14 minutes after the earthquake. That is even before the wave approaches the nearest shore point (which usually takes about 20 minutes).

In the future we are going to improve the precision of the simulation in the near shore area by using the adaptive calculation grids and to develop semi-automated system for seismic activity monitoring.

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