Data Inversion for Tsunami Simulation*

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Abstract
Accurate prediction of tsunami wave parameters at certain coast locations is still among unsolved problems of tsunami hazard mitigation: for example, a country-wide tsunami alert in Japan after Chilean event of February 27, 2010. The expected wave height was largely overestimated: more than 3 meters expected versus 1.2 meters in reality. Thus, hundreds of thousands people were suggested to move out of coast line, hundreds of trains were delayed or canceled, which led to significant unjustified costs. In this paper we address the questions of quality prediction improvement and real time data inversion.

Key words: tsunami hazard mitigation, real time data inversion

1. Introduction

Friday, March 11, 2011 at 05:46:23 UTC Japan was struck by a magnitude 8.9 earthquake off its northeastern coast. This is one of the largest earthquakes that Japan has ever experienced. Tsunami waves swept away houses and cars in northern Japan and pushed ships aground. In order to predict tsunami wave parameters better and faster we propose to improve data inversion scheme and to achieve the performance gain of data processing.

One of the reasons of inaccurate predictions of tsunami parameters is that very little information about the initial disturbance of the sea bed at tsunami source is available. In this paper, we suggest a way to improve the quality of tsunami source parameters prediction. To have more stable results, we suggest a direct solution of inverse problem of source parameters identification in 1D (in space) hyperbolic equation (shallow water approximation) along the wave ray from source to DART buoy. As recently discovered, uniqueness theorems are available for such inverse problems.

So-called preliminary calculation approach is one of the most popular ways to determine tsunami parameters at source. This technique consists of several steps. First, the subduction zone is covered by the set of “unit sources”. Then, this zone typical shape of initial disturbance of unit amplitude is suggested at each unit source. Wave propagation from all these sources is calculated over the entire bathymetry, including the tsunameters locations (DART buoys). After real event time series obtained at DART are approximated as linear combinations of preliminary calculated time series from unit sources. V. Titov (University of Washington, Seattle) proposed and implemented this technique. This works rather well provided that a few unit sources cover the entire source area. However, there are a few constraints. Firstly, in case of an extended source area, too many CPU resources are needed. Secondly, real disturbance at source is approximated as a linear combination of only one selected shape, located at several unit sources.

We suggest the following improvements to the methodology by V. Titov. Smaller system of unit sources should be considered to approximate all typical shapes of initial disturbance by several suitable basis functions. To support this, performance of data analysis should be dramatically improved. This could be done by using signal orthogonalization procedure and calculation of Fourier coefficients of the measured time series with respect to orthogonal basis.

2. Available Data

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

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

(i) GPS data analysis. This method was developed after 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, Indonesia. This approach can hardly been used in other geo locations.

(ii) Satellite image analysis. The resolution of modern satellite images is really overwhelming. In the future correct data of sea surface displacement will probably be available in real time right after a tsunamigenic earthquake. At present this is just expectation.

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

(iv) Direct measurement of tsunami wave at deep water. At the time being, 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, see Fig. 1.

DART II has two-way communications between the BPR and the Tsunami Warning Center (TWC) using the Iridium commercial satellite communications system. The two-way communications allow the TWCs to set stations in event mode in anticipation of possible tsunamis or retrieve the high-resolution (15-s intervals) data in one-hour blocks for detailed analysis. DART II systems transmit standard mode data, containing twenty-four estimated sea-level height observations at 15-minute intervals.

Tsunami monitoring systems (see Fig. 2) have been strategically deployed near regions with a history of tsunami generation, to ensure measurement of the waves as they propagate towards coastal communities and to acquire data critical to real-time forecasts.

Taking into account that the number of DART-like buoys permanently increase, we believe that reliable inversion strategy could be based on these data.

A software application to optimize DART sensors system according to wave traveling time criteria exists [1]. All program modules have been written as FORTRAN code (genetic algorithm implementation and software application to calculate traveling time between any two given points of aquatoria). Typical time for optimization is close to 2 min on Pentium IV 3 GHz, compaq visual fortran 6.6 for 6 sensors. There is a parallel implementation of FORTRAN code for multi-computer systems. All communications are implemented using MPI. Preliminary test calculations show near linear speedup up to 64 processors. It is also possible to include the wave amplitude parameter into optimization process. Direct numerical experiments over the real bathymetry shows that in case of 3 existing DART buoys, their proper relocation can reduce tsunami detection time in half.

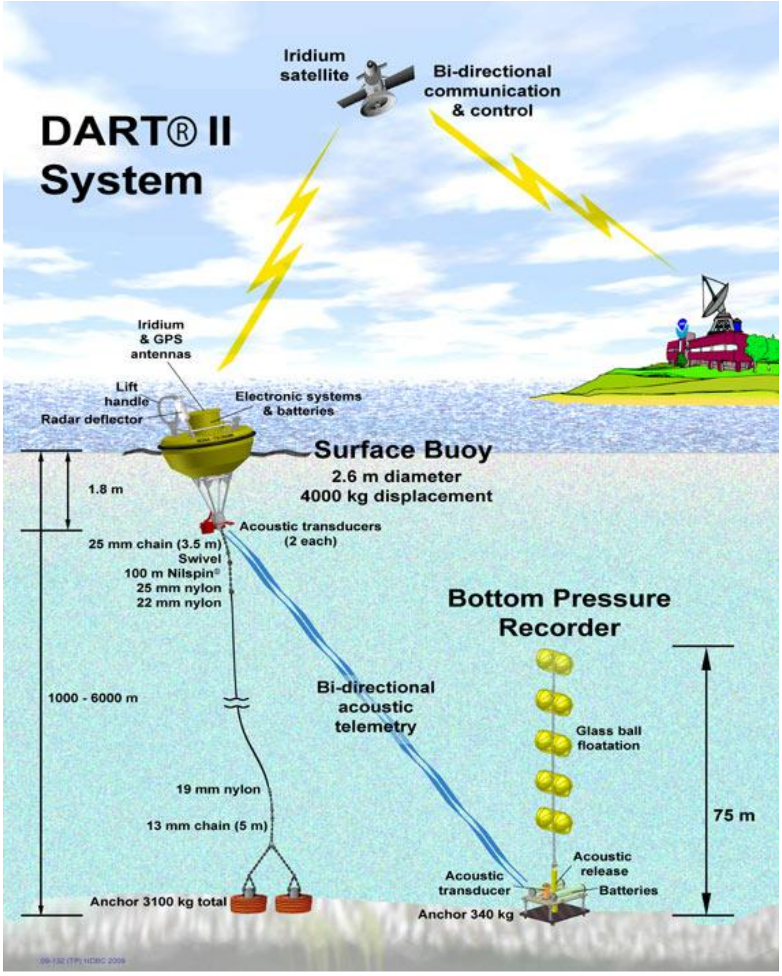

Fig.1. DART buoys operation scheme.

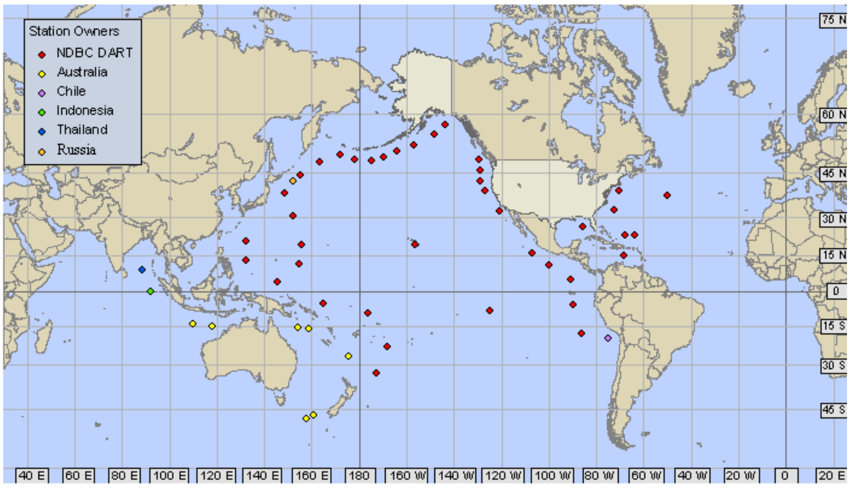

Fig. 2. Locations of NOAA's National Data Buoy Center (NDBC) DART stations comprising the operational network.

3. Data Inversion Scheme

In order to achieve reliable results it is reasonable to use all existing methods of data inversion simultaneously. The above mentioned "fault structure analysis" could be complemented by direct numerical solution of the source term determination inverse problem. The governing equations are linear and nonlinear approximations of the shallow water system. This is a hyperbolic system with two space variables, geo coordinates *x* and *y*. Generally, a solution to inverse problem with two space variables requires extended computer resources. As was shown by the authors, in this particular case of the source term identification (in contrast with the typical coefficient inverse problem), numerical inversion could be done practically in real time mode. However, necessary inversion data for such 2D inversion requires too many deep water buoys.

For practical use, we propose a numerical solution of the following 1D inverse problem. Consider equation

$$\frac{\partial^2 u(x,y,t)}{\partial t^2} = div(D(x,y)\nabla u) + \frac{\partial^2 f(x,y,t)}{\partial t^2}$$

where *u(x,y,t)* represents the desirable sea depth and *D(x,y)* stands for the depth profile (bathymetry).

Inverse problem: Find the source term in the form

$$f(x,y,t) = \theta(t)\varphi(x,y)$$

provided that the several traces of solution (measurements obtained at DART buoys) are known at given locations

$$\eta_i(t) = u(x_i, y_i, t)$$

The 1D version of this inverse problem is rather simple both for numerical treatment and theoretical analysis. Thus, uniqueness results, recently obtained by Prof. V. Romanov, are available. To obtain useful information about tsunami source through solution of this 1D inverse problem we propose to perform inversion along the wave ray between tsunami source and each measurement buoy. Solutions to these 1D inverse problems will provide additional information about initial displacement of sea surface at tsunami source.

The proposed inversion scheme is as follows.

(i) Draw wave route (trace) between source and each DART buoy. Real time software application is ready.

(ii) Solve numerically 1D inverse problem to obtain "section" of 2D tsunami source. Shape of such section is calculated based on direct measurement of the wave at given buoy.

(iii) Correct the wave amplitude "dissipation coefficient" along the wave trace under consideration is calculated.

Preliminary numerical tests show that the information obtained this way is in a good correlation with alternative inversion methods in use.

4. Performance Optimization

There are several software packages for tsunami simulation, which include stages of wave generation, trans-oceanic propagation, and inundation at dry land. Here we discuss a part of MOST (Method of Splitting Tsunami) software package, which has been adopted by the USA National Ocean and Atmosphere Administration as the basic tool to calculate tsunami wave propagation and evaluation of inundation parameters. MOST [2-3], developed at Pacific Marine Environmental Laboratory (NOAA, Seattle, USA), allows real time tsunami inundation forecasting by incorporating real-time data from detection buoys. The MOST model is also used in the United States for developing inundation maps as well as for Tsunami Inundation

Modeling [4]. The new web enabled interface for MOST is released with the name ComMIT.

In this paper, we only discuss the trans-ocean propagation part. To cover the Pacific Ocean area, the calculation domain is 2581x2879 points (for 4' grid). All initial data required could be stored in 120MB. The number of time steps necessary to simulate tsunami wave propagation during 24 hours period is of the order of 8600. One time step requires approximately 110x2581x2879 ~ 109 elementary math operations (+, -, *, /). One time step takes about 3 seconds (for the original sequential program execution) at P4 2.8GHz hardware. Therefore, it takes 3 sec * 8600 = ~ 7 hours for total tsunami propagation modeling. These numbers make it impossible to use the package for real time modeling.

That is why an acceleration of the executable code of the MOST package should provide additional time for tsunami hazard reduction.

Direct attempt to use cluster systems with distributed memory access results in approximately 2 times performance gain, regardless of the number of computational nodes used.

After code transfer to C++ language and computational platform optimization, the average computation time was reduced by 16 times at 16-cores system with shared memory access SMP 4 x Intel Xeon CPU X7350, 2.93GHz.

The best results were obtained using Tesla C2050 graphic processing unit (see some details in [5, 6]). The original time for one time step of 3 seconds was reduced to 20 ms, that is 150 times performance gain. This result was achieved after deep analysis of code execution and a number of optimizations.

5. Conclusion

Based on the last results in the theory of inverse problems, numerical methods of data inversion, and facilities of modern computer architectures, it is possible to improve tsunami warning system both in terms of reliability and performance.

We suggest the following original directions of theoretical and applied studies to be conducted by international teams.

Pre-event:

(i) Energy based precursors analysis for advance alert of the warning system;
(ii) Measurement system optimization according to various criteria;
(iii) Preliminary calculation of different scenarios.

After seismic event:

(i) Initial displacement determination using all existing methods (multi-method approach);
(ii) Real time calculation of worse, best, and realistic scenarios, repeated after any data updates.

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