Modern simulation tools for real time numerical simulation of ocean-related processes

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Abstract*—In this paper we focus on two particular ocean-related problems, valuable progress in which is expected due to extended facilities of the modern computer architectures. The first one concerns real time tsunami risk mitigation by using the advantages of such computer architectures as are Graphic Processing Units (GPU) and Field Programmable Gates Arrays (FPGA). Among many important aspects of tsunami simulation we study the time consumable calculation of the wave propagation over a given water area. A comparison of performances achieved at a range of architectures is given. Secondly, we discuss the coastal profile evolution. As it has been found relatively recently, behavior-oriented diffusion models reasonably describe the time evolution of the cross-shore position of coastal profiles. Two time-independent coefficients in the governing equation, which embody the relevant physical properties, are identified simultaneously. Earlier, the authors have validated and calibrated numerically the proposed model, processing two sets of real data, the first one being measured over 10 years at Duck, in North Carolina (USA), the second one obtained over 39 years measurements at Delfland (Holland). Here, the model dependence on the alongshore position of the observation point is studied. The coefficients of the model equation are determined by means of a certain iteration process. As it was observed, the achieved convergence is now better than when several separate observations along the coast are involved.

Keywords—real time measured data processing; modern computer architectures; tsunami risks mitigation; coastal profile evolution

I. INTRODUCTION

Mathematical modeling has achieved amazing progress in the recent years thanks to both a better description of physical processes and to the availability of new computer architectures. As analytic solutions are not available for such complex systems like trans-oceanic wave propagation, long-term evolution of coastal line and other, numerical experiments become a necessary part of any practically oriented study. Mathematical models of processes become nonlinear and complicated, so, numerical runs required extended computational resources. However, it is often necessary to complete the analysis fast in the real time. For example, an evaluation of the tsunami inundation zone should be done shortly after the underwater earthquake (within 20 minutes in the case of Japan). The authors propose both fast algorithms modeling tsunami wave propagation and coastal profile evolution as well as code acceleration by using advantages of modern computer architectures.

Even if the authors have developed several algorithms covering major aspects of tsunami risks mitigation, here we concentrate only on one of those – tsunami wave propagation. The numerical algorithm, used by the USA National Oceanic and Atmospheric Administration (NOAA), was optimized to achieve nearly real-time performance at the modern computer architectures like Graphic Processing Units (GPU) and Field Programmable Gates Arrays (FPGA). Performance of the NOAA tsunami simulation tool, the so-called Method Of Splitting Tsunami (MOST) software package [1], is nearly 100 times faster after optimization for NVIDIA GPU architecture. As a result, we expect to deliver calculated wave amplitudes (covering area compared to 1000*2000 km) within 12 minutes after the earthquake.

Erosion and accretion phenomena are responsible for modifications of the coastal environment, and thus have been a source of growing concern among coastal engineers. Taking into account human activities, a special study is needed to predict the impact of coastal zone management. The linear diffusion equation was proposed in [2] to describe a long-term evolution of coastal profiles, such as the cross-shore profile. This model was calibrated in [3] to describe the measured data of coastal profile evolution. Upon an appropriate choice of the two equation coefficients, modeled as piecewise constant functions depending on the distance from the shoreline, the depth profile evolution can be reasonably described on a rectangular region having the size of 3 km along the coast times about 1.5 km seaward [4]. As was also shown numerically, the model can even predict the depth profile evolution [3].

II. SIMULATION OF TSUNAMI WAVE PROPAGATION

Calculation domain for trans-oceanic tsunami wave propagation is not enormous for the modern high performance computing. So, for numerical experiment in the Pacific Ocean one needs 2500 by 2800 mesh points in case of 4 geography minutes between the calculation nodes. As it takes about 24 hours for the wave to travel from the shore of Chile to Japan, about 9000 time steps of 10 seconds each are needed. This problem size requires several hours of simulation of sequential MOST computer code. In case we are looking for a real time

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tsunami warning system, dramatic performance acceleration is needed. Several attempts to parallelize the existing simulation codes have been done in the recent years. Here we do not pretend to detailed historic review and refer the reader to [1,5].

MOST software allows making a forecast of the flood region in the real-time mode using tsunameters data. This package is mostly used in the USA for charting inundation maps [6]. An online version of MOST – comMIT – has also been created.

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 basic wave parameters (propagation time period from the source to the recording device and wave amplitudes) rather accurately even for a fairly rough numerical bathymetry under the assumption that the initial displacement in the source is known.

The MOST software package uses numerical model of calculating wave propagation through the deep-water zone applying the so-called decomposition method for spatial variables. This method was initially developed in the Tsunami Laboratory, Computer Center of the Siberian Division of the USSR Academy of Sciences in Novosibirsk [7]. Later, the method was updated in the Pacific Marine Environmental Laboratory (NOAA, Seattle, USA) [8] and was adapted to the models and standards of data, accepted by tsunami watch services in the United States (as well as in other countries) and used in tsunami research works in many 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 the dry land (run-up and inundation). In this paper we only deal with the most CPU consuming second stage, deep-water tsunami wave propagation.

Up-to-date High Performance Computing (HPC) market suggests a broad variety of computing systems with different hardware architectures. Briefly, we could highlight regular clusters (distributed memory systems which can contain hundreds thousands processors), shared memory systems (characterizing with better performance but limited number of computation nodes), and hybrid systems. In the latter architecture each central processor (CPU) is accompanied with (several) GPUs, which serve as co-processors to a common general-purpose processor. In fact, different hardware architectures are also used as co-processors, namely Intel XeonPhi, FPGA, and others.

A GPU has a SIMD (Single Instruction Multiple Data) architecture according to Flynn's taxonomy (http://en.wikipedia.org/wiki/Flynn's_taxonomy), which supports up to several thousand parallel calculation streams. As the MOST algorithm calculates some parameters (the system invariants) in the parallel mode, such architecture was expected to be suitable for the case under study, as all the grid points of calculation domain are processed with the same algorithms. Generally, GPU architecture is considered 10 times more efficient (both in terms of performance and energy efficiency), compared to regular CPU [9]. The advantages of FPGA architecture are discussed below.

Modern architecture of re-configurable integral circuits FPGA supports parallel execution of up to hundred thousand streams having "on board" memory compared to tens Mb's. FPGAs are software configurable processors, that is logic connections among the calculation primitives and the inner memory are determined by the developer. Such arrangement makes it possible to construct calculation architecture, most suitable for the particular data processing algorithm (calculation scheme). Moreover, Virtex family of FPGA allows re-configuration by the use of specialized software tools. So, one hardware device could be adopted for solution of various particular problems. Such kind of special processor has been developed for stream video data processing [10]. The theoretical peak performance is evaluated as ~2200 mln points/sec.

Performance results to calculate tsunami wave propagation at the real bathymetry obtained with original and optimized codes for different architectures are presented in the table below (Table 1). Note that numerical precision were the same for all the architectures.

Most of our numerical experiments in Tab. 1 were completed in single precision. Because of comparatively large water depth variation (from 0 to 10 000 meters) and the required resolution, compared to centimeters, single precision is not enough in many practical applications. However, rows 1-5 and 7-8 in Table 1 represent calculations in single precision, observed to be correct in case of the used values of numerical parameters. Thus single precision could be used to perform modeling in a bay/gulf where the depth does not exceed several hundred meters. Row 6 shows the same performance (that was earlier achieved in single precision) in double precision available at the modern GPU platform Tesla K40. So, modern GPU architecture extends the limits to use this platform in practical applications. Use of FPGA based architecture results in

TABLE I. TARGET ARCHITECTURES AND ACHIEVED PERFORMANCE FOR THE ONE TIME STEP, 2580X2879 CALCULATION MESH.

	Performance at different architectures		
	Hardware architecture in use	***Before Optimization***	***After Optimization***
1.	Original code (sequential)	3000 ms	3000 ms
2.	AMD (6 cores)	1800 ms	420 ms
3.	Intel (8 cores)	300 ms	180 ms
4.	CELL BE (PS3)	5000 ms	60 ms
5.	GPU Tesla C1060	530 ms	20 ms
6.	GPU Tesla K40	-	20 ms (double precision)
7.	FPGA SLEDv7	-	7,85 ms
8.	FPGA VC709	-	3,9 ms
9.	FPGA VC709	7,85 ms	5,23 ms (double precision)

additional performance gain: 5 times acceleration in single precision and 4 times for double precision. Further performance optimization is also available.

The best up to date results were achieved at the advanced architecture of VC709 (two DDR-3 memory channels and FPGA xc6vsx315t), hardware details are described in [10]. The obtained performance of 5 ms in double precision makes it possible to use adaptive meshes for real time calculation of the inundation zones at different parts of the shore line. Obtained accuracy is agreed with the original sequential CPU code version.

III. Diffusion Model for the Coastal Profile Evolution

Following [2], we suppose that the long-term evolution of coastal lines, such as the cross-shore profile, is described by the diffusion equation

$$u_t(t,z) = D(z)u_{zz}(t,z) + B(z)u(t,z) + f(t) \qquad (1)$$

along with suitable Initial and Boundary Data. This model states that changes in the bathymetry, $u(t,z)$, (that is the elevation of the seafloor) rests on two space-dependent coefficients, $D(z)$ and $B(z)$, as well as on a time-dependent source-term, $f(t)$, the wave height.

Here $u(t,z) = p(t,z) - p(0,z)$, while $p(t,z)$ denotes the depth profile and thus $u(t,z)$ represents changes of the cross-shore profile. Concerning some general approaches to study the long-term coastal profile evolution, see [11-15]. The two functional coefficients, $D(z)$ and $B(z)$, which embody macroscopically all the relevant physical processes, are unknown, and it seems very hard to conceive any derivation of them from prime physical principles, or by means of purely physical measurements. The source term, $f(t)$, is associated with wave conditions, in fact it represents the average wave height. As was already mentioned, a validation of the considered model, proposed in [2], was obtained in [3]. As it was already observed, models like that in (1) reasonably describe depth profile evolution, that is the cross shore at a certain single point of the coast. Note that data sets measured at two geographic locations (in the USA and in Holland) and with essentially different structure, were considered. Moreover, the possibility of 1-2 years prediction of the depth profile evolution was demonstrated.

In this work, by using modern computer facilities, we include into consideration the along-shore dependence of the depth profiles. We apply the same model, where the coefficients, $D(z)$ and $B(z)$, only depend on the cross-shore distance, z, to describe the depth profile time-evolution on a certain interval along the shore line.

To recover the functions $D(z)$ and $B(z)$ in (1) optimization approach to minimize (by the proper choice of $D(z)$ and $B(z)$) the mean square difference between the measured changes of depth profile near the coastal line, $u^{mes}(t,0)$, and the numerically obtained depth profile variation according to (1), $u^{D,B}(t,0)$. For the problem statement details we refer the reader to [3,4]. The experimental data obtained at the Ameland Island (in Holland), over *36* years, from 1963 to 1998, have been used. In spite of [3] the full portion of the coast line located between the indicators *12.00* and *18.00* shown in the Fig. 1 were accounted.

At the so-selected part of the coast *30* observation points were located at the distance of *200 m* from each other. Measurements (depth versus distance from the given point at the coast) were taken once per a year. The number of points where the depth (cross shore) was measured varied from *70* to *150* opposite each point of the coast. Thus, an area of *3 km* along the coast times about *1,5 km* seaward was covered by measurements. The selected part of the coast is practically linear.

The coefficients, D and B, were supposed to be constant at each interval of *100 m*, that is they take on *15* values each:

$$D(z) = d_n,\ B(z) = b_n,\ 100n < z < 100\,(n+1),\ n = 0,1,\dots,14. \qquad (2)$$

This was supposed at three sets of observation points along the coast, consisting each of *10* observation points. That is, we suppose the coefficients $D_1(z)$ and $B_1(z)$ for the coast line located between the indicators *12.00* and *14.00* shown in the Fig. 1, $D_2(z)$ and $B_2(z)$ between the indicators *14.00* and *16.00*, and $D_3(z)$ and $B_3(z)$ between the indicators *16.00* and *18.00*. Each pair $D_i(z)$ and $B_i(z)$ supposed to have the form (2).

Such coefficients were numerically obtained and then (1) was solved with the so-obtained coefficients. The difference between the measured and the computed depth's variation at the coast is rather small and is given in Fig. 2. The corresponding related error does not exceed 25 cm practically in the entire calculation domain having several spikes, uniformly distributed, Fig. 3.

IV. Conclusion

A way to dramatically speedup modeling of trans-oceanic tsunami wave propagation is presented. The key point is to use advantages of modern computer architectures, namely GPU and FPGA. To use FPGA, a developer should be well acquainted with the digital circuit technology and fluently use special programming language. Computer code is created from the very beginning and the entire process may take several months.

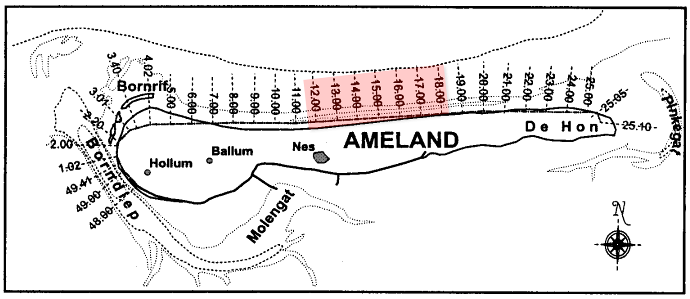

Fig. 1. Schematic map of the Ameland Island (above). The part of the coastline where the depth profiles have been used in the numerical experiments, is given in pink.

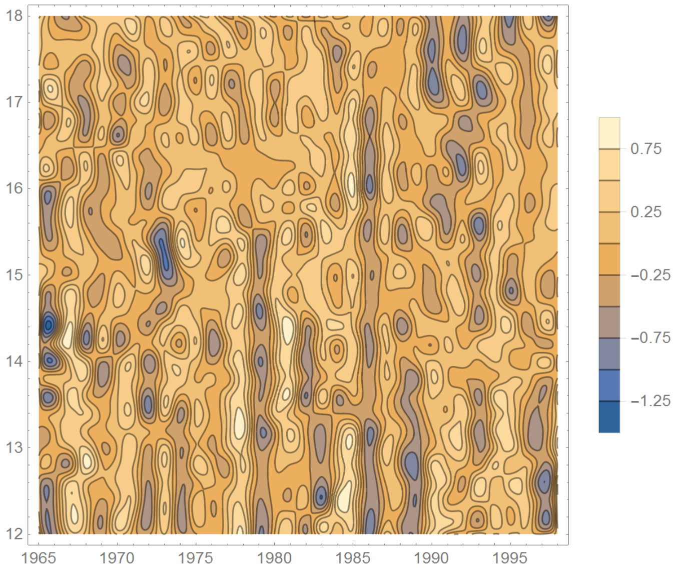

Fig. 2. Difference between the measured and the computed depth's variation close to the coast, contour plot.

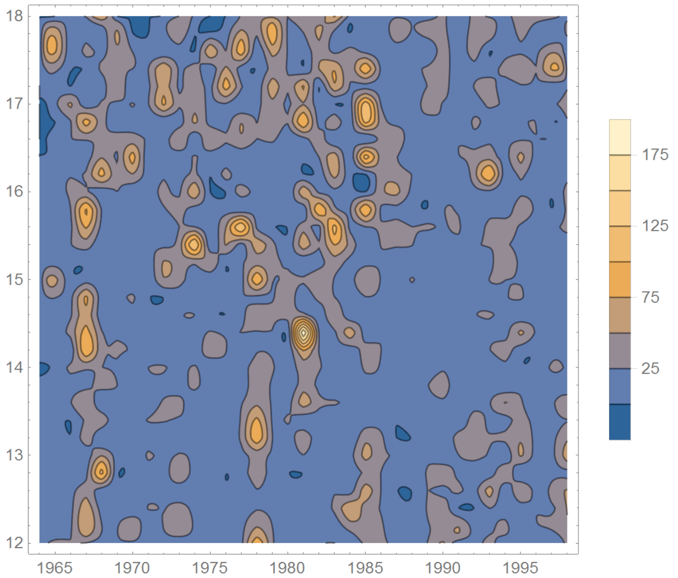

Fig. 3. Contour plot for the related error for the numerically obtained depth profile variations.

The obtained performance of the selected part of MOST code raises the question of the real time tsunami risk mitigation. It seems that finer meshes could be also used in the real time mode for evaluation of inundation zone. Directly after a potentially dangerous seismic event, it is now possible to check many alternative scenarios to provide better grounds for evacuation decisions.

The diffusion model (1) was used to describe the measured data of coastal profile evolution. Upon an appropriate choice of the two space-dependent coefficients, *B(z)* and *D(z),* modeled as piecewise constant functions, the depth profile evolution can be reasonable described on a rectangular region having the size of *3 km* along the coast times about *1,5 km* seaward. The model (1) exploits data up to the so-called depth of closure, that is the distance from the shore where depth changes virtually end. Even though the available measured data does not possess this property, the numerical relative errors are rather small over the entire area of observation.

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