

# NUMERICAL SIMULATION OF LANTEX 2013 SCENARIO WITH HySEA MODEL. IMPACT ASSESSMENT ON PUERTO RICO COASTS

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## ABSTRACT

HySEA tsunami model is used to simulate the Caribbean LANTEX 2013 scenario. The numerical simulation of the propagation and inundation phases is performed with a single integrated model but using different mesh resolutions and nested meshes. Special emphasis is put on assessing the most exposed coastal areas at Puerto Rico affected by this event. Comparisons with MOST are made considering both time series at different locations, and inundation maps. Both models compare well for propagating tsunami waves in open sea, producing very similar results. The main discrepancies are observed in coastal areas, where maximum wave height provided by the propagation module of MOST is different from the one provided by HySEA. The main reason is that, while HySEA always compute inundation effects, MOST propagation does not include runup physics and locates an artificial numerical reflecting wall at a certain depth (typically 20 m). Henceforth, in nearshore shallow waters HySEA should be compared with the inundation version of MOST. Nevertheless the most striking difference resides in computational time; HySEA is coded using the advantages of GPU architecture, and can produce a 4 hour simulation in a 60 arc-sec resolution for the whole Caribbean Sea in less than 4 min with a single GPU and as fast as 11 seconds with 32 GPUs. When details about the inundation must be simulated, a 1 arc-sec (approximately 30 m) inundation resolution mesh covering all of Puerto Rico, an island with dimensions of 160 km east-west and 56 km north-south, is used, and a three level nested meshes technique implemented. In this case approximately 11 hours of wall clock time are needed for a 2 hour simulation in a single GPU. When domain decomposition techniques are finally implemented by breaking up the computational domain into sub-domains and assigning a GPU core to each sub-domain (multiGPU HySEA version), the wall clock time should decrease significantly, allowing high-resolution inundation modeling in just a few hours and at a modest hardware cost compared with present tsunami models.

Keywords: HySEA model, MOST model, tsunamis, numerical simulation, LANTEX 2013, Caribbean Sea, Puerto Rico.

## INTRODUCTION

The necessity of having a validated model that can run both fast and without requiring extremely expensive supercomputer resources is crucial in the tsunami simulation field, but such a model has not been developed yet. Nevertheless, the use of Graphics Processing Units (GPUs) allows increasing the computational potential at dramatically low cost. This new GPU technology together with well-adapted tsunami numerical models that exploit these capabilities will make it possible, for developing nations, to establish their own, in-house, tsunami flood mapping resources, a goal of many of the Intergovernmental Coordinating Groups (ICG's) that have been setup all over the planet.

The ever-increasing availability of high resolution topographic/bathymetric data makes it possible to perform high resolution flood mapping, allowing more accurate results. But this has to be tied in with the availability of affordable, and fast, hardware, and this requirement is, again, filled in by the use of GPUs and suitable numerical codes. At the same time, the numerical codes must be robust enough to deal with this kind of high resolution data with no need of smoothing topographic-bathymetric data, otherwise the effort of getting more precise results could be useless.

HySEA model, developed by the EDANYA Group (Diferential Equations, Numerical Analysis and Applications) at the University of Málaga, is a non-linear hydrostatic shallow-water model implemented in CUDA (NVIDIA® CUDA® is a parallel computing platform and programming model that enables dramatic increases in computing performance by harnessing the power of the graphics processing units (GPUs)), well adapted to be run in multi-GPU architectures. HySEA does not distinguish between propagation and inundation phases, and runs without any bathymetry smoothing, allowing for a more faithful simulation of what a real tsunami encounters. The reduction in computational time obtained by HySEA compared with other well-established tsunami models is major and the cost of the computational resources needed much less, thus encouraging us to propose HySEA as an efficient, fast and robust tsunami code.

In this work, testing of HySEA has been carried out in the Caribbean region by comparing with the widely-used MOST tsunami model, which runs in serial mode. This has been done in Puerto Rico, where MOST has been used since 2005. The latest inundation grids used by MOST in Puerto Rico have computational cells of 1 arc-second resolution (approximately 30 meters). Limitations in the MOST inundation software available at the University of Puerto Rico required breaking down the island of Puerto Rico (approximately 160 km east-west, by 56 km north-south) into three parts if it was desired to use that resolution in the inner (inundation) nested grid (Grid C in Fig. 1). Each part (West, Center, East) is run separately, each one in its own CPU, but all at the same time. This is something akin to the Domain Decomposition used in some parallel models, but with no feedbacks amongst the domains. But even on a high-performance 64-bits Linux box it takes around 10 days of wall-clock time to perform a 4-hour simulation (Mercado, 2014b) using the PGI Fortran with all optimization switches turned on.

Besides, MOST is very sensitive to abrupt depth changes, typical of tropical islands surrounded by reefs, offshore mangrove islands, very steep bathymetry, and often times the model crashes, sometimes after more of a week of wall-clock time. This implies going back to do additional bathymetric smoothing and starting all over again. Finally, sometimes the amount of smoothing leads one to be concerned about the changes being introduced into the model bathymetry.

This study intends to take advantage of capabilities of the HySEA model in terms of robustness, reliability and time-efficiency by comparing results of LANTEX 2013 (LANTEX is the acronym for Large Atlantic Tsunami Exercise, which is carried out annually) experiment with the MOST tsunami model. The HySEA model has been extensively tested and validated for tsunami simulation purposes. In this process, analytical solutions, laboratory experiments and complex simulations have been reproduced as can be found in a series of works compiling HySEA model progress and evolution (before the name of HySEA was adopted), as in Castro et al. (2005), Castro et al. (2006), Gallardo et al. (2007), Castro et al. (2008), de la Asunción et al. (2013), among others. In particular all the benchmarks on Synolakis et al. (2008) have been successfully passed (EDANYA Group, 2014) including the Monai Valley test case (Macías et al., 2013) and Tohoku 2011 (González-Vida et al, 2014).

## **SOURCE DEFINITION**

The tsunami scenario for the CARIBBEAN WAVE/LANTEX 13 simulates a tsunami generated by a magnitude 8.5 earthquake occurring 57 miles north of Oranjestad, Aruba, in the Caribbean Sea (IOC, 2012). This scenario is based on tsunami sources included in the NOAA/Pacific Marine Environmental Laboratory SIFT database for the Caribbean. In 2008, ten Brink et al. (2008), as part of their evaluation of tsunami sources with the potential to impact the US Atlantic and Gulf Coasts, considered this Southern Caribbean convergence zone.

Table 1 shows the parameters defining the tsunami source for the LANTEX 2013 scenario. The initial deformation is depicted in Fig. 2.

## **TOPOGRAPHIC/BATHYMETRIC DATA**

Several bathymetric data with different grid resolutions are used. There is no need to smooth bathymetric data prior to running HySEA (which attests to its robustness), nevertheless the data provided were already smoothed since it was the same one used by MOST in Mercado (2014b). The global bathymetric grid covers the area extending in longitude from -89.997778624 to -55.002214376 and latitude from 6.0022206643 to 24.997783336 (Fig. 1). The spatial resolution of the global bathymetric grid is 60 arc-second (approx. 1800 m) and composed of 2,397,241 cells (2101 by 1141 grid points in lat - lon).

For the inundation grid, the data were obtained from the National Geophysical Data Center Digital Elevation Model for Puerto Rico, with 1 arc-second resolution (approximately 30 m). This includes near shore bathymetry. This mesh extends from -67.4388607031 to -65.1845245512 in longitude and from 17.8164537959 to 18.5795201181 in latitude. This grid coincides with Grid C in Fig. 1. For MOST inundation this grid is split in three parts due to array size limitations (3000x3000) in the MOST source code available at UPR (East, Central and West grids), while for HySEA a single mesh encompassing these three is used.

## COMPUTATIONAL MESHES

### Propagation Mesh

For testing the propagation features of HySEA code has been run in three different computational meshes covering the whole domain (that coincides with the global bathymetric grid and is shown in Fig. 1). This is done in order to assess mesh refinement influence on the tsunami wave simulated, convergence of the refined solutions and for assessing computational time requirements. The complete computational domain extends from -90.0 to -55.0 longitude and from 6.0 to 25.0 in latitude. The coarser mesh is a 60 arc-sec one composed by  $2,101 \times 1,141 = 2,397,241$  cells. The global intermediate mesh has a 16 arc-sec resolution and  $7,878 \times 4,278 = 33,702,084$  cells. Finally, a 8 arc-sec resolution propagation global mesh composed of  $15,757 \times 8,557 = 134,832,649$  cells is considered. MOST is run just in the coarser mesh.

### Inundation Mesh

When a detailed description of the inundated coastal areas is required, an enhanced coastal resolution is needed. In that case tsunami-HySEA has been run in a three level nested mesh, with an enhanced resolution of 8 times when moving from one level to the next one. The spatial extension of each one of these three submesh levels can be found in Fig. 1. Therefore, for HySEA the submesh resolutions are 64, 8, and 1 arc-sec. Mesh A, with a 64 arc-sec resolution is much smaller than the global propagation mesh where bathymetric data were given, extending from -73.00 to -65.02 in longitude and from 10.00 to 19.99 in latitude, with  $450 \times 563 = 253,350$  cells. Mesh B with an 8 arc-sec resolution is composed by  $1,344 \times 896 = 1,204,224$  cells. And finally, Mesh C with a 1 arc-sec resolution extends from 67.4388607031 to -65.1845245512 in longitude and from 17.8164537959 to 18.5795201181 in latitude (i.e. same extension as the topo-bathymetric inundation grid described in previous section) and is composed of  $8,112 \times 2,736 = 22,194,432$  cells. Therefore, in the case of propagation with inundation, the size of the whole computational mesh is 23,652,006 cells, most of them corresponding to the finer inundation grid. In this case we did not run the MOST inundation code due to the computational time required for a single simulation (the numerical results for this simulation can be found in Mercado (2014b)).

## NUMERICAL RESULTS AND COMMENTS

According to Mercado (2014a and b) a constant Manning coefficient of 0.03 was used.

### Propagation buoys

In order to compare the propagation phase of both codes, HySEA and MOST, eight propagation buoys have been located between the epicenter and the South offshore virtual gauge defined below, i.e. a total of 10 control points. The geographical coordinates of these points are gathered in Table 2 and depicted in Fig. 3. In the propagation phase both codes are compared using the same MOST base resolution of 60 arc-seconds used in Puerto Rico, but for HySEA two additional resolutions of 16 and 8 arc-sec were also considered. These time series are presented in Figs. 4 and 5. It can be

observed that maximal amplitude and arrival times agree for both models. As the tsunami wave gets away from the source it can be noted that the maximum amplitude decreases from 1.3 m to 0.9 m for buoy 3 and below 0.5 m for buoy 4. It can be observed that when the tsunami wave approaches the coast (buoy 9) the amplitudes increases back (compare buoys 7, 8 and 9). Observing the behavior of these time series for HySEA as resolution increases, a certain convergent trend can be noticed.

### **Offshore tide gauges**

In order to have an idea of the strength of the tsunami signal reaching the island of Puerto Rico, and its duration, four virtual gauges were placed offshore of each one of the four coasts (as in Mercado, 2014a and b) at a sufficient water depth so that nonlinear effects, although present, were not predominant. The location of each gauge can be found in Table 3 and it is shown in Fig. 3.

Fig. 6 shows the sea surface elevation time series for the 4 offshore gauges comparing HySEA in the three available resolutions and MOST in the coarser 60 arc-sec mesh. Arrival times and first wave amplitudes agree for both models. At locations where the tsunami wave has a direct impact, agreement between HySEA and MOST models is larger (South and West buoys). Main discrepancies appear at North and East buoys, where the tsunami wave impact is not direct, and suffers larger nonlinear interactions before arriving to these locations. It can be observed a kind of convergence of the numerical solutions for the two finer resolutions of 16 and 8 arc-sec.

### **Maximum Sea Surface Elevation**

Fig. 7 upper panel, shows the maximum sea surface elevation along the 4 hour simulation for the HySEA model. It can be observed that the largest impact is on the northern coast of Venezuela and Colombia close to Aruba, representing the closer coastal area to the source. In Fig. 7 lower panel the same field is depicted for MOST. Figure 8 shows the difference between HySEA and MOST maximum sea surface elevation for the 4 hour simulation. It should be stated that the MOST propagation code imposes a standard numerical reflecting wall at 20 m depth (this value is an input variable).

It can be observed that the main discrepancies are found just northward of the shallow waters found at the entrance of the Gulf of Venezuela, which could be due to different numerics, (like the reflecting numerical wall in MOST for propagation purposes). A correct comparison would be between HySEA and the inundation version of MOST. It must be understood that MOST simulations were carried with the island of Puerto Rico in mind, not the north coast of Venezuela. Northward of the island of Aruba no discernible differences can be found at the scale of Fig. 8.

### **Coastal gauges**

Eighteen additional coastal gauges, at shallow waters and close to coast have been considered for analyzing the tsunami wave features at its arrival to the coast, prior to inundation. Figs. 11, 12 and 13 show the location for the west, central and east coastal gauges, respectively. The geographical coordinates of these gauges are compiled in Table 4. Figs 14, 15, and 16 depict the tsunami wave time series at these locations separated by zones.

In Fig.14 it can be observed that in West Puerto Rico, Peñuelas, in the South, receiving the most direct impact from the source, presents the highest amplitude of the five points in this area, while Arecibo, in the North, the weakest impact. The highest wave not always is the first one. In several locations (Arecibo in the North, Mayagüez in the West, and Peñuelas in the South) does appear a second or third wave with higher amplitude than the initial one. Similar situations can be found in Fig. 15 (Central Puerto Rico), where the same is observed for the four locations in the South (Ponce, Salinas, Port of Yabucoa and Lobos Bay) and the three locations in the North (Balneario Vega Baja, Punta Miquillo and San Juan). In Fig. 16 for East Puerto Rico, Vieques South is the location that receives the highest impact with several waves with over 1 m amplitude. On the other side, North-West location points, as Fajardo and Ceiba, receive longer waves with lower amplitudes.

As we did not perform the simulation with MOST inundation, the coastal time series considered here must be compared with those in Mercado (2014b). Nevertheless, in the former study, the epicenter is slightly displaced to the North relative to LANTEX 2013 location used here. This makes that arrival times for the simulated tsunami waves are not equal, but the shape, amplitude and qualitative behavior of them is similar.

## **Coastal Inundation**

Fig. 17 presents the global coastal inundation map for LANTEX 2013 as simulated by HySEA. In Figs. 18, 19 and 20 selected location at East, Central and West areas are shown. As could be expected, the more affected coastal areas are those located both in the South and East of Puerto Rico. The Cabo Rojo coastal area is the first one hit by the tsunami. Bahía Salinas and Bahía Sucia in the Southwest are widely inundated. More to the East, the Bosque Estatal de Boquerón is another flat area largely inundated. Several populated areas are affected by the inundation in the South of the island: Ponce, Ensenada or Guanica. Important effects are also presented in the Eastern area. In fact the maximum amplitude point is located in Punta Moja Casabe in the South West of this area. Several populated areas are affected along the Western coast including Alturas de Mayagüez, although this city is not located where inundation effects are more significative.

From Punta Higuero (in the Northwest area of the island) and all over the North coast, inundation effects are neatly lower as the tsunami waves impact along this coast is not direct. Finally, there are some areas more affected by inundation in the Eastern area: Punta Santiago and Roosevelt Roads are the more inundated zones. Finally, Vieques Island and Isla de Culebra are also affected especially in Southern areas where the tsunami waves impact is more direct.

As was mentioned in previous section, we compared inundation maps with those obtained in Mercado (2014b). Both the areas affected by inundation and the extension of the inundated areas are in good agreement with the ones provided by MOST along all the Puerto Rico coasts.

## **Computational Times**

Several tests for evaluating computational performance have been undertaken for the propagation phase alone and for the propagation/inundation phases both together. For the propagation tests we have used two different GPU clusters. The first one is the PICASSO cluster (at the Supercomputing Center for BioInformatics, SCBI, University of Malaga) composed of 32 nVidia Tesla M2075

GPUs (each one has 448 cores and 6,144 Mb). For assessing scalability, 6 tests with increasing number of GPUs have been performed. The computational times obtained for the 60 arc-sec resolution mesh are shown in Table 7. The resulting speedup graphic is shown in Fig. 21. The second cluster (Laboratory of Numerical Methods -University of Malaga-) is composed by 8 GPUs nVidia GeForce GTX TITAN Black (each one has 2880 cores and 6,144 Mb) and was used for assessing convergence as resolution is increased. We had to take into account that, when doubling mesh resolution, the number of cells is multiplied by four, but due the CFL restriction, the time-step is reduced approximately to a half. Consequently, when doubling the resolution the increased computational cost comes out of the order of 16 times larger. The newer GeForce GTX TITAN is faster than the Tesla M2075, but while the PICASSO cluster has 32 GPUs, our Laboratory of Numerical Methods has only 8 homogeneous GPUs available. This is the reason why the scalability tests were also performed in PICASSO. Table 8 shows the wall clock times for 1, 2, 4 and 8 GeForce GPUs in the three resolution meshes where HySEA was run (60, 16 and 8 arc-sec) for a 4 hour simulation in the global computational domain. It should be noted that the finer resolution problem, with nearly 135 million of cells, cannot be solved in a single GPU, at least two are required.

The simulation performed with HySEA in which the detailed inundation was computed was done in a computational grid composed of three nested meshes with increased resolutions of 64 arc-sec, 8 arc-sec and 1 arc-sec. As the tsunami-HySEA multi-GPU code in nested meshes has not been implemented yet, computing times presented for nested-meshes are for tests run in just one GPU card. The multiGPU programming of HySEA code including nesting meshes is currently in progress. The wall clock time for a 2 hour simulation, including propagation plus inundation phases, came out to be 11 h, 21 min, 37 sec in a single GeForce GTX TITAN Black graphic card.

## CONCLUSIONS

The HySEA model provides fast reliable simulations for tsunami wave studies and coastal risk assessment. This model, developed by the EDANYA Group at the University of Málaga, enables dramatic increases in computing performance by harnessing the power of the graphics processing units (GPUs), and has been implemented to be run in multi-GPU architectures too. HySEA is a non-linear integrated model that does not distinguish between propagation and inundation phases. That is, in a single run it goes from generation to propagation and inundation, and runs without any bathymetry smoothing, allowing for a more faithful simulation of what a real tsunami encounters. The reduction in computational time obtained by HySEA compared with other well-established tsunami models is major and the cost of the computational resources needed much less, thus encouraging us to propose HySEA as an efficient, fast and robust tsunami code.

When used with low resolution meshes the HySEA model can be used as a code for Tsunami Early Warning Systems, computing tsunami propagation in real time. This will start at INGV (Italy) in pre-operational mode in October 2014. When inundation maps are desired, then high resolution meshes with nesting capabilities can be used for accurate and faster computations. A version of tsunami-HySEA code is available upon request at [hysea@uma.es](mailto:hysea@uma.es).

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## REFERENCES

- de la Asunción, M., Castro, M.J., Fernández-Nieto, E.D., Mantas, J.M., Ortega, S., González-Vida, J.M. (2013). Efficient GPU implementation of a two waves TVD-WAF method for the two-dimensional one layer shallow water system on structured meshes. *Computers & Fluids*, 80, 441-452.
- ten Brink, U., Twichell D., Geist E., Chaytor J., Locat J., Lee H., Buczkowski B., Barkan R., Solow A., Andrews B., Parsons T., Lynett P., Lin J. and Sansoucy M. (2008). Evaluation of tsunami sources with the potential to impact the U.S. Atlantic and Gulf coasts: An Updated Report to the Nuclear Regulatory Commission. U.S. Geological Survey Administrative Report.
- Castro, M.J., Chacón, T., Fernández-Nieto, E.D., González-Vida, J.M., Parés, C. (2008). Well-balanced finite volume schemes for 2D non-homogeneous hyperbolic systems. Applications to the dam break of Aznalcóllar. *Computer Methods in Applied Mechanics and Engineering* 197 (45), 3932-3950.
- Castro, M.J., Ferreiro, A., García, J.A., González, J.M., Macías, J., Parés, C. and Vázquez, M.E. (2005). On the numerical treatment of wet/dry fronts in shallow flows: Applications to one-layer and two-layer systems. *Math. Comp. Model.* 42 (3-4): 419-439.
- Castro, M.J., González, J.M. and Parés, C. (2006). Numerical treatment of wet/dry fronts in shallow flows with a modified Roe scheme. *Math. Mod. Meth. App. Sci.* Vol. 16, No. 6, 897-931.
- EDANYA Group (2014). Validation and verification of HySEA tsunami model. *In preparation.*
- Gallardo, J.M., Parés, C. and Castro, M.J. (2007). On a well-balanced high-order finite volume scheme for shallow water equations with topography and dry areas. *J. Comput. Phys.* 227: 574-601.
- González-Vida, J.M., Ortega, S., Castro, M.J., Macías, J., (2014). Modelling propagation and inundation of March 2011 Tohoku tsunami with the tsunami-HySEA model. *In preparation.*

Intergovernmental Oceanographic Commission. Exercise Caribe Wave/LANTEX 13. A Caribbean Tsunami Warning Exercise, 20 March 2013. Volume 1: Participant Handbook. IOC Technical Series No. 101. Paris, UNESCO, 2012.

Macías, J., Castro, M.J., González-Vida, J.M., Ortega, S. (2013). Non-linear Shallow Water Models for coastal run-up simulations. EGU 2013.

Mercado, A. (2014a). Report on Puerto Rico tsunami flood maps for local events. Submitted to the Puerto Rico Seismic Network. 55 pages.

Mercado, A. (2014b). Report on Puerto Rico tsunami flood maps for regional events. Submitted to the Puerto Rico Seismic Network. 141 pages.

Synolakis, C.E., Bernard, E.N., Titov, V.V., Kânoğlu, U., González, F.I. (2008). Validation and Verification of Tsunami Numerical Models. *J. Pure and Applied Geophysics*, 165 (11-12): 2197-2228.

## TABLES

Table 1. Parameters defining the source (\* in km).

Longitude	Latitude	Strike	Dip	Rake	Depth *	Length *	Width *	Slip (m)
-69.95°	13.35°	90.0°	17.0°	90.0°	10	300	100	5.26

Table 2. UTM coordinates for the location of the propagations buoys in Fig. 3.

	Epicenter	1	2	3	4
Longitude	-69.95	-69.5648	-69.1796	-68.7944	-68.4092
Latitude	13.35	13.85	14.35	14.85	15.35

	5	6	7	8	9
Longitude	-68.0241	-67.6389	-67.2537	-66.8685	-66.4833
Latitude	15.85	16.35	16.85	17.35	17.85

Table 3. Location of offshore virtual tide gauges. Shown in Fig. 4.

Gauge	Longitude	Latitude	Water Depth (m)
North coast	-66.48332863	18.500000263	224
West coast	-67.24999545	18.2000002568421	150
South coast	-66.48332863	17.850002494	50
East coast	-65.44999509	18.300002589474	31

Table 4. Selected (virtual) tide gauges for the West of Puerto Rico. Depicted in Fig. 5.

Location Name	Longitude	Latitude	Depth (m)
Arecibo	-66.70238	18.4812	3.73207
Aguadilla	-67.163333	18.456667	0.860237
Mayaguez	-67.161245	18.217361	0.567165
Lajas	-67.0466	17.9716	0.947873
Peñuelas	-66.76302	17.98035	8.68585
Ponce	-66.6268155348	17.9700213196	10.0638

Table 5. Selected (virtual) tide gauges for Central Puerto Rico coasts. Depicted in Fig. 6.

Location Name	Longitude	Latitude	Depth (m)
San Juan	-66.11624998493	18.45819445611	9.63465
Punta Miquillo	65.791614418	18.4253079103	2.04614
Balneario Vega Baja	-66.40124998721	18.49069445637	3.26424
Playa Salinas	-66.30513887533	17.96236111881	2.94167
Jobos Bay	-66.214027762851	17.954583343967	1.73197
Port of Yabucoa	-65.83402776098	18.05263889992	15.6709

Table 6. Selected (virtual) tide gauges for the East of Puerto Rico. Depicted in Fig. 7.

Location Name	Longitude	Latitude	Depth (m)
Fajardo	-65.62958	18.3338	0.969195
Ceiba	-65.6193055377	18.222361122883	14.5356
Vieques South	-65.471527759195	18.093750011211	1.53988
Vieques North	-65.44374998128	18.152361122578	2.34908
Culebra	-65.303	18.3016	0.9637
Humacao	-65.74180553	18.16430556487	1.73014

Table 7. Speed-up for 1 to 32 Tesla M2075 graphic cards for 4 hours of simulation on the 60 arc second resolution global mesh composed of 2,397,241 cells. #FTRT for number of times faster than the real time is the numerical simulation.

	Real Time	#FTRT
1 GPU	3 min 55 sec	61.15
2 GPUs	2 min	119.49
4 GPUs	1 min 3 sec	226.68
8 GPUs	32 sec	437.99
16 GPUs	18 sec	783.85
32 GPUs	11 sec	1245.23

Table 8. Speed-up for 1 to 10 GeForce GTX TITAN Black graphic cards for 4 hours of simulation in three mesh resolutions (60, 16 and 8 arc-sec). (\*) Due the size of the problem it cannot be computed in a single GPU card.

	60 arc-sec		16 arc-sec		8 arc-sec	
	Real Time	#FTRT	Real Time	#FTRT	Real Time	#FTRT
1 GPU	2 min 7 sec	112.64	2 h 31 min 37 sec	1.58	(*)	(*)
2 GPUs	1 min 8 sec	210.95	1 h 22 min 5 sec	2.92	10 h 26 min 36 sec	0.38
4 GPUs	36 sec	393.99	46 min 49 sec	5.13	3 h 3 min 13 sec	1.31
8 GPUs	28 sec	507.24	24 min 26 sec	9.82	1 h 42 min 7 sec	2.35