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Analysis of existing tsunami scenario databases for optimal design and efficient real-time event matching

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Abstract

Pre-computed tsunami scenario databases constitute a traditional basis to the production of tsunami forecasts in real time, achieved through a combination of properly selected Green's functions-like objects. The considered case-study database contains water elevation fields and waveform signals produced by an arrangement of evenly-spaced elementary seismic sources, covering fault areas relevant in determining the Portuguese tsunami hazard. This work proposes a novel real-time processing for the tsunami forecast production, aiming at the accuracy given by traditional methods but with less time cost. The study has been conducted on the Gorringe Bank fault (GBF), but has a general validity. First, the GBF database is analysed in detail, seeking for remarkable properties of the seismic sources, in terms of frequency content, cross-correlation and relative differences of the fields and waveform signals. Then, a reference forecast for a seismic event placed on the GBF is given, by using all the traditionally available subfaults. Furthermore, a novel processing algorithm is defined to produce approximate forecasts, through a strategic exploitation of the information obtainable by each of the seismic sources, taken in minor number. A further focus on sensible locations is provided. Remarkable results are obtained in terms of physical properties of the seismic sources and time-gain for the forecast production. Seismic sources at depth produce longwave dominated signals, allowing for an optimisation of the database content, in terms of sources required to properly represent seismogenic areas at certain depths. In terms of time cost, an overall improvement is obtained concerning the forecast production, since the proposed strategy gives highly accurate forecasts, using half of the seismic sources used by traditional forecasting methods, which reduces the required accesses to the database.

1 Introduction

Over the last 15 years tsunami events have been responsible for a high number of human losses. More than 200,000 people lost their life because of the Indian Ocean tsunami of 26th December 2004 (UNISDR, 2015) and other tsunami events have severely hit human communities in the following years, e.g. the 29th September 2009 event in the Samoa archipelago, the 27th February 2010 event in Chile, the 25th October 2012 event in the Mentawai islands and the 11th March 2011 event in Japan. The 26th December 2004 tsunami completely changed the attitude towards this kind of phenomena and revealed an urgent need for efficient Tsunami Early Warning Systems (TEWS).

Over the years following 2004, many initiatives and coordination groups have been established under the umbrella of the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) with the aim of improving and developing tsunami warning strategies worldwide. Among these, the ICG/NEAMTWS (see http://neamtic.ioc-unesco.org/) has been established, to develop monitoring and forecasting strategies within the North-Eastern Atlantic, Mediterranean and connected seas area (NEAM).

The NEAM area is characterised by a remarkable distribution of nearshore seismogenic areas, as shown in Figure 1.1, and widespread seismicity, shown in Figure 1.2. Therefore, the time window available for an efficient TEWS to react to hazards is limited to few minutes within this area (e.g. Omira et al., 2009; Tinti et al., 2012a). We stress here that the optimization of *time* is more than a crucial factor in tsunami early warning practices, which are constituted by hazard detection, impact forecasting, both decision-making and consequent alert dissemination, from local to regional and national level.

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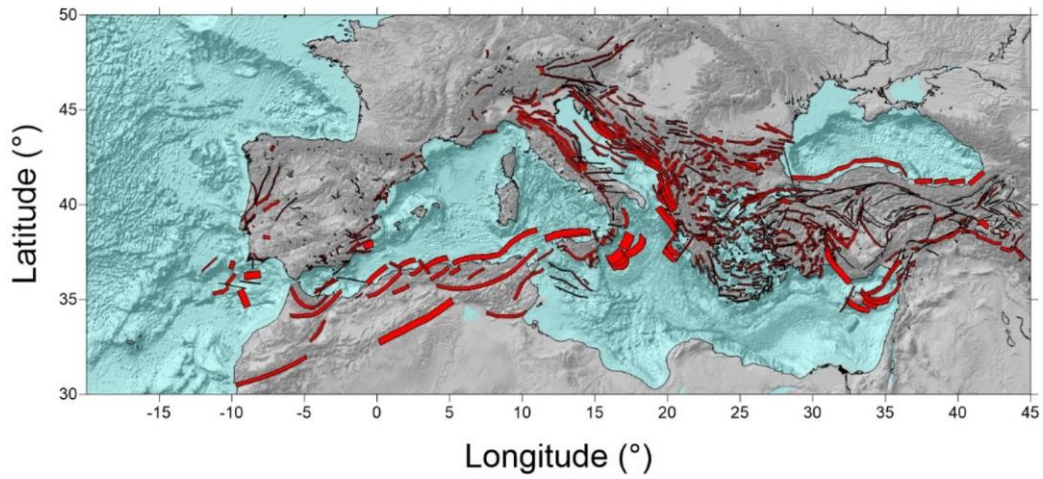*Figure 1.1: Map of the seismogenic areas of the NEAM region (red areas). The red-coloured polygons represent the seismogenic faults contained in the SHARE-EDSF database (Basili et al., 2013).*
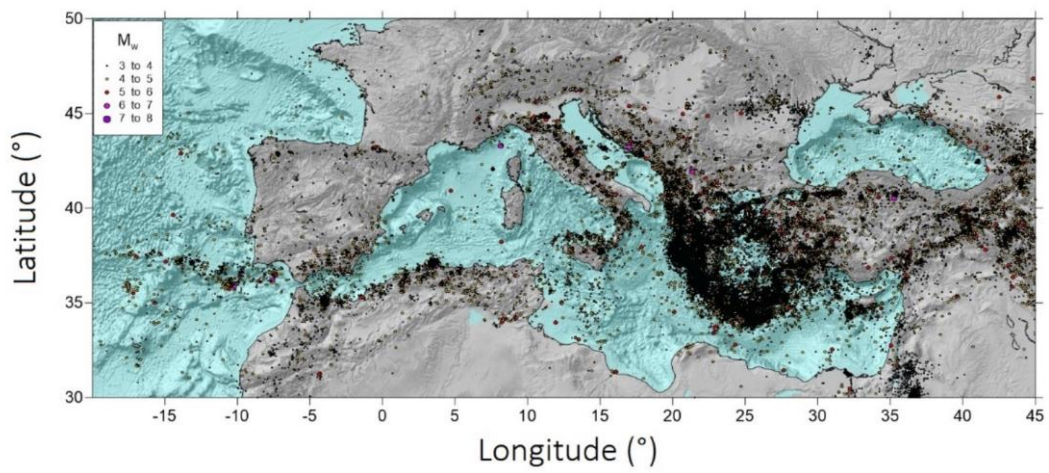

Figure 1.2: Seismicity in the southern portion of the NEAM area. The plotted events from the revised ISC Bulletin (http://www.isc.ac.uk,) cover the time period 1960-2016 and are shallower than 50 km.

In the early stages of ICG/NEAMTWS, the routinely adoption of the so-called Decision Matrix (DM) has been proposed and it is still used nowadays as a zero-order approximation in the tsunami hazard assessment. The DM is a simple tool, providing the relevant institutions with guidelines to follow in the occurrence of a tsunami hazard. It has the advantage of conveying almost instantaneous instructions, by only requiring the first physical parameters of the new seismic event and it can be used by non-experts in the tsunami-field, as a timely support for decision-making in the hazard occurrence. An example of DM for the NEAM area is given in Appendix A.

Nevertheless, the shortcomings of this approach have been pointed out in various occasions (Tinti et al., 2012b; Tinti et al., 2012c), as the DM approach does not take into consideration the focal mechanism of the earthquake, which strongly determines the tsunamigenic potential of the earthquake itself.

Novel techniques beyond the DM have been investigated over the last years, bringing remarkable improvements towards the production of tsunami forecasts.

A possible strategy relies on real-time simulations. This option foresees on-the-fly numerical tsunami simulations as soon as information is provided by the sensor network in the target area. The time needed by the simulations to run depend on a number of factors, roughly belonging to two distinct groups: the first is related to the available hardware and to the software implementation of the desired solving equations, the second has to do with the desired level of detail of the simulations. As for the first group, the continuous and fast improvement of processing units, including the graphical ones (GPUs) and of specific programming languages (e.g. Castro et al., 2015; Macias et al., 2016), the possibility to access small to large computer clusters (e.g. Blaise et al., 2013), are all factors that will allow a continuous reduction of the computation times. On the other hand, the level of detail required for the simulation results represent a key choice: for example, detailed inundation mapping over large coastal areas might request computation times incompatible with the tsunami early-warning needs even when super-computers are available.

An alternative approach foresees the building of databases of pre-computed tsunami scenarios. In the emergency phase, suitable forecast algorithms oversee properly selecting and combining the relevant members of the databases in order to forecast the tsunami time evolution in terms of a set of pre-defined metrics. The largest part of the computation time is then shifted to the pre-emergency phase. Several examples of pre-computed databases exist worldwide, built upon different strategies. For instance, the NOAA Center for Tsunami Research has developed the so-called Forecast Propagation Database (http://nctr.pmel.noaa.gov/propagation-database.html), in which the known earthquake sources over the entire Pacific Basin, the Caribbean and the Indian Ocean have been discretised into unit sources, each consisting in 100-km long and 50-km wide faults with uniform 1 m slip over the fault plane (e.g. Gica et al., 2008). The focal mechanism is determined by the dominating tectonic regime of the area where the sources are found. A similar approach has been adopted by the Center for Australian Weather and Climate Research (Greenslade et al., 2009). A fault-based strategy was also adopted in the framework of the French tsunami warning centre (Gailler et al., 2013): the unit sources are 25-km long and 20-km wide, have 1-m uniform slip and their geometries and focal mechanism are tailored on the Mediterranean tectonic sources they discretise. A rather different approach is adopted by other authors (e.g. Molinari et al., 2016 and references therein). The idea is to discretise a given basin into a dense grid of regular cells, each containing an elementary tsunami source which can be Gaussian-shaped, a pyramid, a rectangular prism. In any case, the goal is to make no a-priori assumption about the seismic source geometry, while being able to reproduce any tsunami initial condition by properly combining the elementary cells.

Whichever the adopted source selection, the pre-computed databases consist in a number of products regarding different tsunami metrics, typically including water elevation/velocity fields at different times, fields of maximum/minimum water elevation/velocity, water elevation time series at several forecast points. Usually, linear shallow-water wave equations are implemented to compute the tsunami results.

The main objective of this thesis is to explore the content of a given database and to seek for its optimization, to minimise the time cost of the associated forecasting procedure, maintaining the accuracy of the forecast itself as high as possible.

The case study database has been developed within the European TRIDEC project framework and contains a wide number of pre-computed tsunami scenarios, concerning the North-eastern Atlantic and Western Iberian margin area, obtained by considering multiple elementary seismic sources.

In this case, we decided to focus on the only scenarios related to the well-known seismogenic Gorringe Bank area, located South-West with respect to the Portuguese coasts and presented within Chapter 2.

Together with the description of the focus area, Chapter 2 provides a detailed description of the database content, both in terms of water elevation fields and virtual tsunami waveform signals.

Within Chapter 3, a deep analysis of the properties of the available seismic sources is presented. 2D Fourier analysis is performed over the water elevation fields, while cross-correlation curves and relative differences are computed to the evaluate the similarity between waveform signals produced by different seismic sources.

Given the results of these analyses, a consequent strategy is defined within Chapter 4, to understand which aspects of the database can be optimised in terms of accuracy and time cost of the forecast production. Aiming at quantifying how much information can be extracted from a single seismic source, a seismic event of reference and the associated forecast are given.

Then, a *building* algorithm is strategically defined to produce approximated forecasts, using an increasing finite number of unitary sources, selected via different configurations and criteria. Our main purpose is to evaluate the degree of achievable accuracy in the forecast production, by using the smallest possible number of unitary seismic sources.

This kind of optimisation process has remarkable consequences on the time needed to produce a satisfying accurate forecast in real time.

In Chapter 5 a major focus on relevant stations, that produced extreme elevation values within the reference forecast, is discussed to further investigate the performances of the previously defined *building* strategy.

2 Case study database

The case study database, used in this thesis work, is named Matching Scenarios Database (MSDB) and was developed within the European FP7 TRIDEC project (see www.tridec-online.eu).

TRIDEC is a Collaborative project started in 01/09/2010 with a duration of 36 months and ended in 31/08/2013; see Löwe et al. (2013) for a detailed presentation of the project.

TRIDEC had multiple goals, concerning the intelligent management of information during evolving crises, arising both from natural and industrial hazards. It aimed at creating a system-of-services architecture to provide information, decision-making support and careful handling of the warning messages dissemination, with a strong focus also on Information and Communication Technologies (ITC) issues, see Wächter et al. (2012) for ITC aspects within TRIDEC.

Within this project, several efforts have been made towards the tsunami early warning practices and risk mitigation, focusing on certain geographical areas, among which the North-eastern Atlantic and the Western Iberian margin. In this framework, the Tsunami Research Team from University of Bologna developed MSDB as a pre-computed tsunami scenarios database.

The idea underlying this scenario approach (see Sabeur et al. (2013) for a further description) was to use the MSDB to produce real-time tsunami forecasts in terms of waveform signals, by suitably matching a new *unkown* event with the unitary sources of the database and combining them to produce a real-time forecast.

In the following paragraph of this chapter, the fundamental steps in the construction of this database and its content are presented.

2.1   The TRITSU Code

As a first step into the description of the Matching Scenarios Database (MSDB), the code used to compute the tsunami scenarios will be briefly presented.

TRITSU code was developed by the Tsunami Research Team of the University of Bologna and ws used to populate the tsunami scenarios database. TRITSU is a slightly modified version of the code called UBO-TSUFD, previously developed by the team and extensively used in several occasions to compute tsunami propagation and inundation, e.g. in the project TRANSFER (http://www.transferproject.eu/), in the project SCHEMA (http://www.schemaproject.org/) and in the study of the 2009 Samoa tsunami as described by Tonini et al., 2011. The main difference between the two codes lie in the fact that TRITSU has been updated to produce standard outputs with agreed format within the TRIDEC project framework.

Beyond this aspect, both codes can compute the solutions of nonlinear shallow-water (NSW) equations over a variable number of nested grids, with different resolutions, depending on the user's necessities and on the target areas. However, the physical assumptions underlying the implemented model and the numerical techniques used to solve the equations, remain the same in both cases. Hence, the interested reader could be referred to a more comprehensive view of the code development in the work by Tinti and Tonini, 2013.

2.2   Theory and implementation in brief

The code solves both linear and nonlinear shallow-water equations, which approximate the general Navier-Stokes equations. The NSWs are non-dispersive equations as the wave velocity does not depend on the frequency or wavelength but only on the square root of the ocean depth. These equations are obtained under the assumption of fluid incompressibility and pressure hydrostaticity, hence reducing the dimensionality of the problem. In fact, under these assumptions, the vertical component of the velocity becomes negligible and the horizontal

components of velocity represent an averaged value over the water column. The NSW equations can be written as:

$$u_t + uu_x + vu_y + g\eta_x + f_x = 0$$

$$v_t + uv_x + vv_y + g\eta_y + f_y = 0$$

$$\eta_t + \big(u(h + \eta)\big)_x + \big(v(h + \eta)\big)_y = 0,$$

with x and y representing the horizontal coordinates, u and v representing the horizontal components of velocity (averaged along the water column), h the unperturbed height of the water column, η the surface displacement from the equilibrium level and f_x and f_y the components of the bottom friction.

In these equations, the contribution of the Coriolis term is neglected and therefore their application is valid over spatial domains, whose extension is at most few hundred kilometres and over time domains of few hours of simulation. These conditions adequately suit the NEAM area for the TRIDEC application.

The solution is computed by means of a leapfrog finite-difference numerical scheme over staggered grids, which means that the solutions for velocity components are calculated over a computational grid that is shifted with respect to the computational grid used for sea level elevation. A proper discretization of spatial and time computational domains is essential to guarantee the stability of the leapfrog finite-difference method. The code UBO-TSUFD, which served as a basis for the development of TRITSU, has been tested against different benchmark cases that proved it to be efficient and performant (see Tinti and Tonini, 2013).

TRITSU can furnish the wave propagation solutions both in linear and nonlinear regime over a maximum of eight different nested grids, together with virtual tide gauge records in previously selected grid nodes.

For every run of the TRITSU code, the user should set:

- The number of nested grids for the elevation field solutions;

- The total number of time steps to compute, together with those to be printed as outputs;
- The initial condition (also External forcing or landslide sources can be taken into consideration);
- other options available, such as deciding whether a smoothing of the initial condition should be performed or not.

For each of the nested grids selected, the associated geographical coordinates must be furnished, together with the spatial and time discretization parameters to define the computational domain and the possible presence of bottom friction.

Eventually, a file indicating the locations at which virtual tide gauge records have to be computed should be included.

2.3 Database content

The parameters of the nested grids used for the MSDB scenarios are given in Table 2.1: Table showing the parameters of the nested grids used for the MSDB database.

Grid	Spatial resolution	Number of nodes	Rows	Cols
1	1 km	1342320	1190	1128
2	200 m	4883700	3345	1460
3	200 m	384200	565	680
4	40 m	65550	230	285
5	40 m	54990	234	235
6	40 m	28050	165	170
7	40 m	103750	250	415
8	40 m	60500	275	220

Table 2.1: Table showing the parameters of the nested grids used for the MSDB database.

The nested grids, shown in Table 2.1: Table showing the parameters of the nested grids used for the MSDB database. have been used to compute the elementary-source water elevation fields for the MSDB database. Grid 1 is the most extended grid with the lowest resolution available. Grid 2 and 3 respectively cover the largest part of the Portuguese coast and Madeira archipelago, with a 200 m resolution. The other 40 m resolution grids have been placed at five target sensible areas: respectively at Cascais, Sesimbra, Sines, Lagos and Funchal, as shown in Figure 2.1.
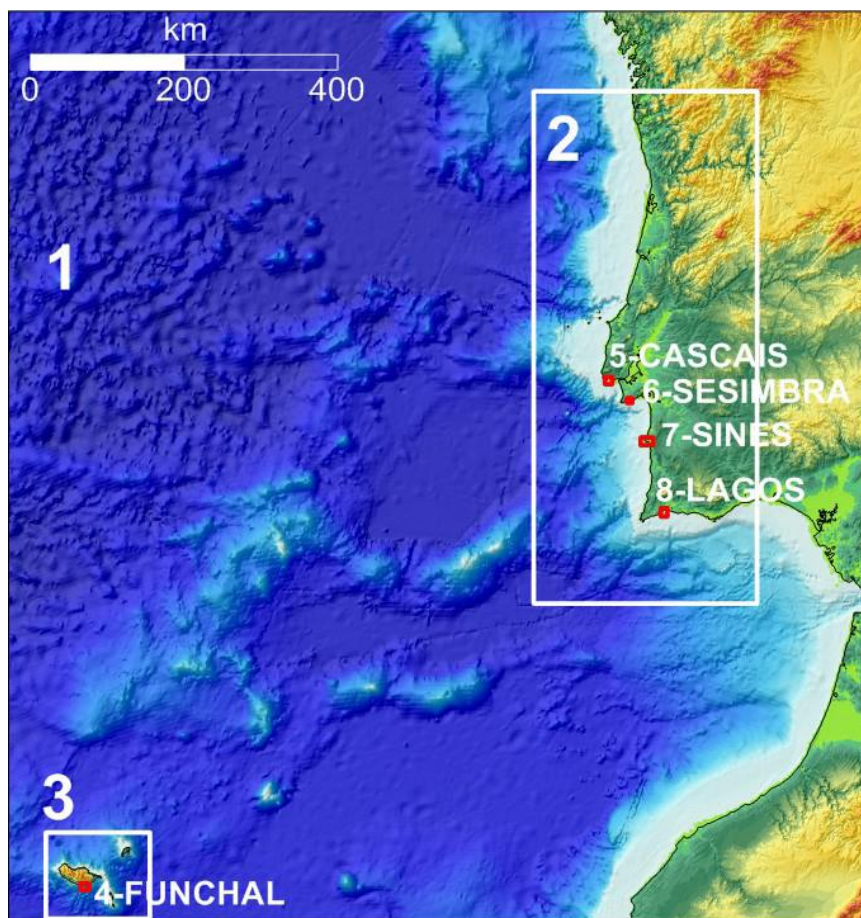
Figure 2.1: Location of the nested grids presented in Table 2.1.

Furthermore, for each scenario, 1760 virtual tide gauge records have been computed in widespread grid nodes, which we shall call *stations* from now on.

These stations have been distributed along the coastal areas of western Portugal and Gulf of Cadiz, along the north-western coastlines of Morocco and among the coasts of the Madeira archipelago. A few stations have been also deployed in open ocean. The location of the whole set of stations is shown in Figure 2.2.
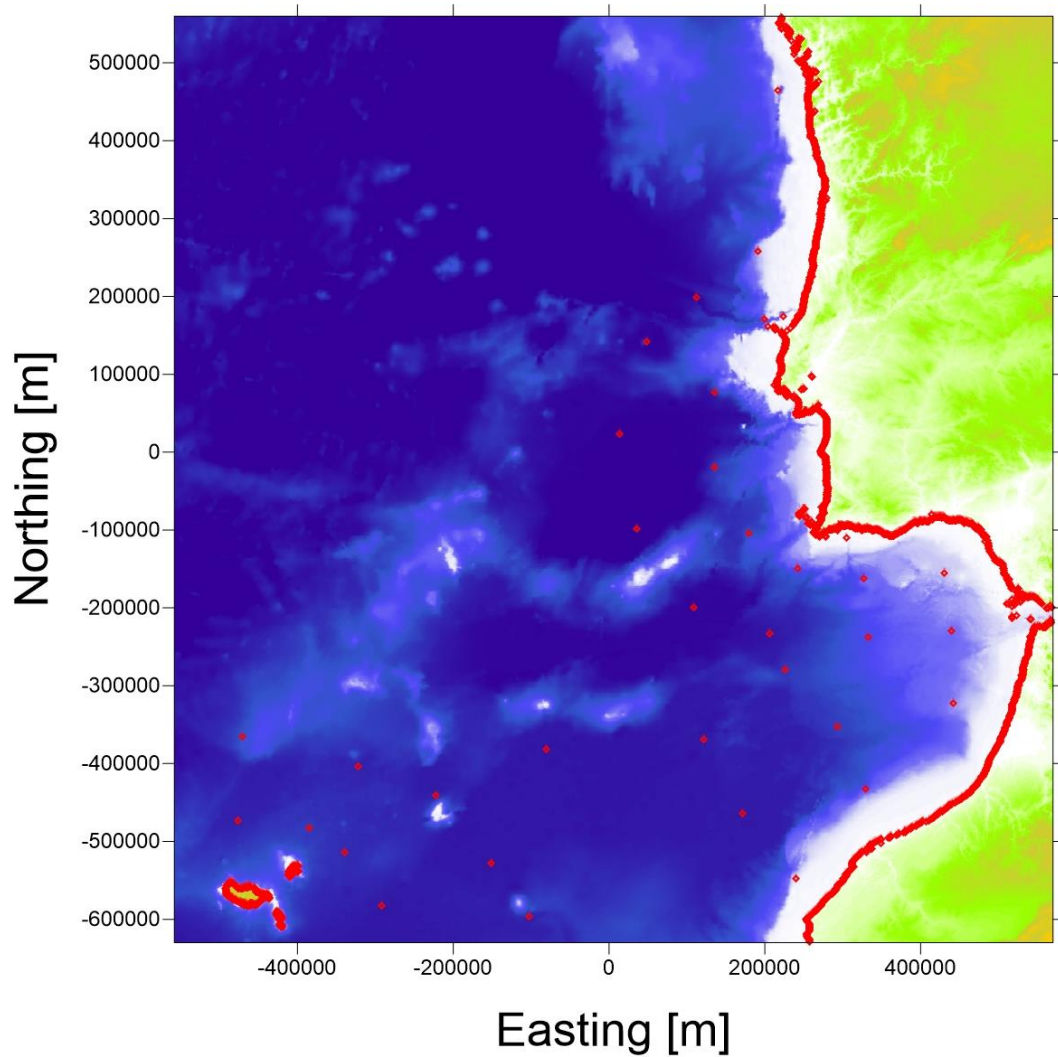
Figure 2.2: The red dots shown in figure, represent the stations at which virtual tide gauge records have been computed for each scenario within the MSDB database.

2.4 MSDB Content

MSDB contains a total amount of 1332 scenarios, each of which has been computed by means of the TRITSU code, within the <u>linear approximation</u> regime of shallow-water equations. Both water field elevations and tide gauge records have been computed for each one of the scenarios.

Using the linear approximation privileged the aspects regarding open-ocean wave propagation over coastal inundation and run-up, where the nonlinearity would have become a leading factor of the descriptive equations.

Within this framework, five seismogenic areas have been defined, based on a previous work by Omira et al. (2009), within which five credible seismic faults have been proposed for the North-eastern Atlantic and Western Iberia region.

The idea, underlying the creation of MSDB, was to use these five seismic faults and their geometry, i.e. strike, dip and rake angles, to define wider planar seismogenic areas, within which tsunamigenic shocks could occur.

Once that the seismogenic areas have been defined, a "tessellation" process has been carried on for each of them. Each area has been divided in a finite number of elementary regular *subfaults,* with the same geometry of the associated area.

The number of subfaults, used to cover a certain seismogenic area, has been fixed by seeking for a compromise between two aspects:

- Using numerous subfaults with smaller and smaller dimensions, allows to achieve a higher detail in describing the properties and the behaviour of the target area;
- Using a small number of subfaults, hence bigger in dimensions, limits the computational costs required to populate the MSDB database, which becomes smaller in dimensions too. Nevertheless, a too small number of subfaults conveys poor detail in describing the target area.

Based on the magnitude-seismic moment relations by Hanks and Kanamori (1979), designing 20 km long and 10 km wide elementary sources have been regarded as a satisfactory choice. In fact, by assigning an average uniform slip 1.05 over the subfault area and by assuming a rigidity modulus of 30 GPa, each single subfault is comparable to a source of a Mw 6.4 earthquake, which has been considered as a suitable unitary event for the study areas. Given the seismogenic areas of interest and the tessellation parameters, a second tessellation has been defined for every area, by shifting the first one by 10 km along the strike direction. Hence, we have two tessellations for each seismogenic area of interest.

The tessellations are shown in Figure 2.3 and their parameters are given in Table 2.2.

MMSFs	Number of subfaults	Subfaults along the length	Subfaults along the width	Strike (°)	Dip (°)	Rake (°)
GBF1 & GBF2	108	9	12	53	35	90
HSF1 & HSF2	120	12	10	42.1	35	90
MPF1 & MPF2	108	12	9	20	35	90
PBF1 & PBF2	80	10	8	266.3	24	90
CWF1 & CWF2	250	25	10	349	5	90

Table 2.2: Geometrical parameters for each tessellation in terms of strike, dip and rake angles. The number of subfaults along the length and the width of each tessellation are provided.

Having said that, each subfault has been associated with an initial seafloor vertical displacement, (see Okada,1992), that has been used as initial water elevation field for the TRITSU code.
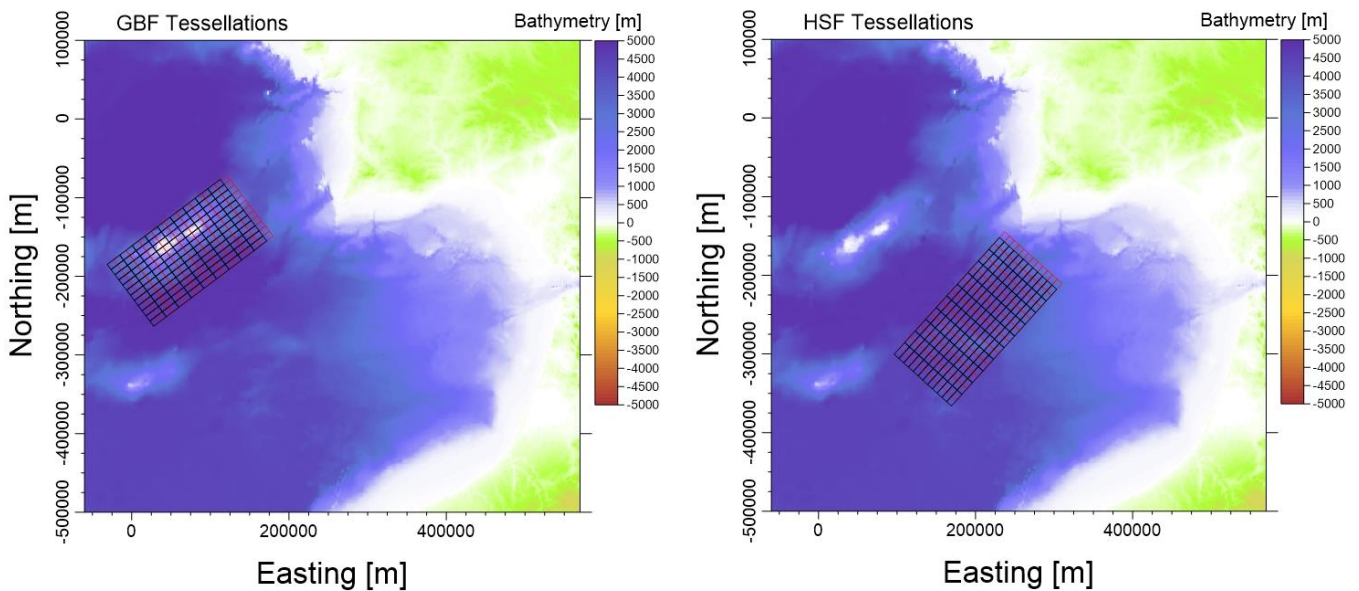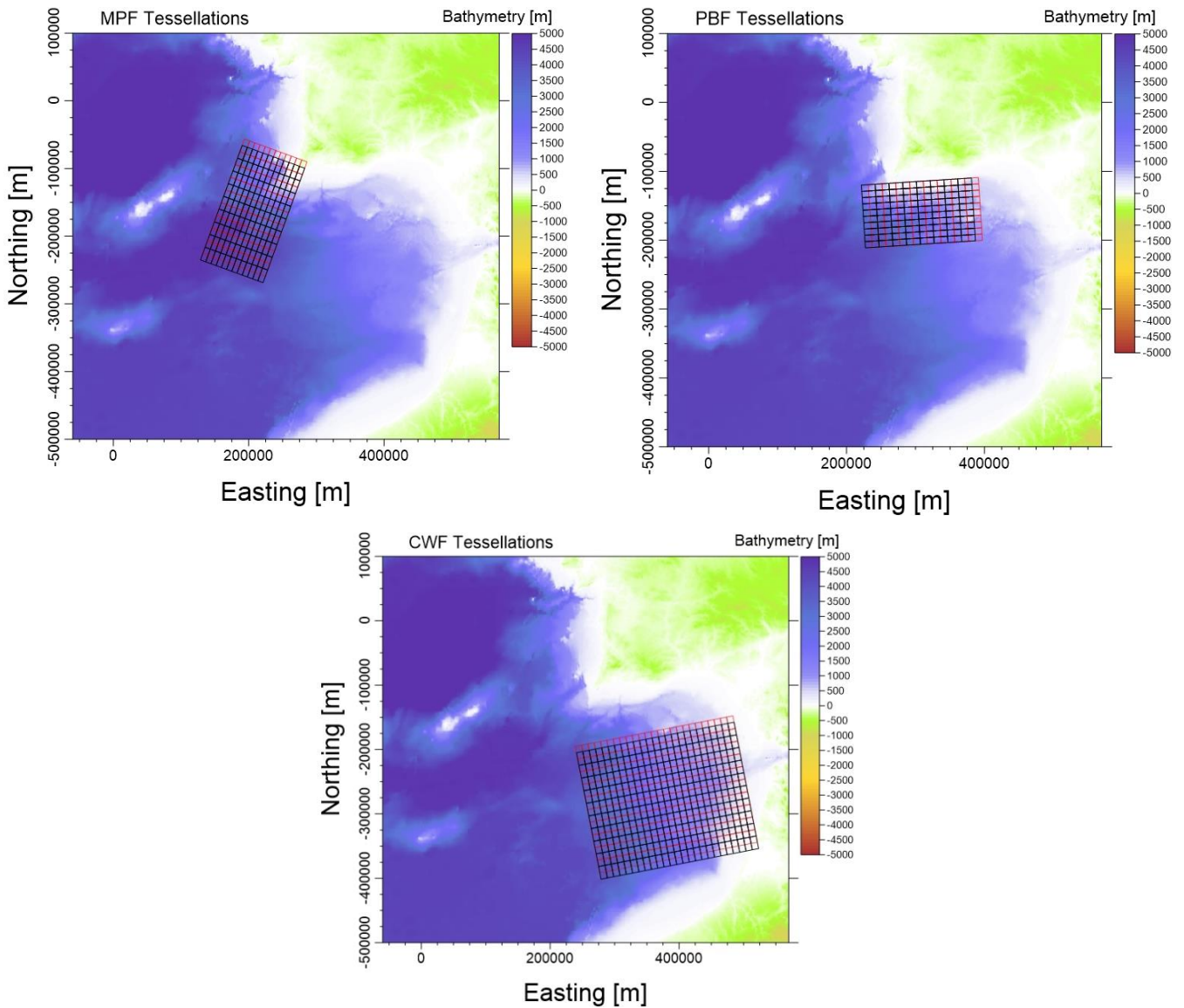
Figure 2.3: MSDB tessellations are shown. For each designed fault, two tessellations have been defined, with one (red one) shifted by 10 km along the strike direction with respect to the other (black one).

2.5 MSDB storage format

To the interested reader, here it is presented how the MSDB content is stored in memory, following the format agreed within the TRIDEC project.

For every tessellation, a folder containing the results of every associated scenario is given. Then, for every single subfault, the results of the computation are stored as follows:

- **Water elevation fields**: We have 8 eight .tar archives containing the solutions computed over the 8 available nested grids. For each grid, the water

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elevation solution is given every 2 minutes, from the initial condition at time 0 to 240 minutes after the triggering seismic event. Hence we have the results of 4 hours of simulation (the files contain only one sorted column with the elevation values, without the grid coordinates to save storage space). Solutions have been normalised to a 5 m peak-to-peak amplitude to improve the signals to noise ratio.

- **Virtual tide gauge records:** The virtual tide gauge records, at each available station (total number of defined stations is 1760), are given in terms of water elevation values and horizontal velocity components. Here the solutions are given every 15s. Hence, a post-processing interpolation has been performed over the original waveform signal solutions, which are given every 2 minutes.

2.6 Focus on the Gorringe Bank area

Despite the large number of studies and of specifically-devised scientific surveys focussing on the SW Iberian margin, the detailed tectonics of the area remains an open and largely debated problem (e.g. Terrinha et al., 2009; Zitellini et al., 2009; Grevemeyer et al., 2017). Similarly, a detailed and widely agreed-upon characterisation of active faults and of their earthquake and tsunamigenic potential is still lacking. The main driving mechanism for the regional tectonics of the area is the NW-SE convergence between the African and Eurasian plates. This convergence does not occur along a single, well-defined tectonic boundary/lineament; rather, the associated deformation appears to be accommodated in a diffuse way along a number of faults placed at different depths and with varying focal mechanism (e.g. Terrinha et al., 2009). On the contrary, seismicity seems to indicate that earthquake occurrence is clustered around a few structures (see Figure 2.4), especially the Gorringe Bank, the Horseshoe Abyssal Plain and the Sao Vicente Canyon (e.g. Custodio et al., 2015; Gravemeyer et al., 2017). Among these, the Gorringe Bank is the most prominent morphotectonic feature observed in the bathymetric maps of the SW Iberian margin. It is an approximately 200-km long, 80-km wide and 5-km high ridge separating the Tagus Abyssal Plain to the NW and the Horseshoe Abyssal Plain to the SE. It strikes approximately normal to the direction of convergence between the African and Eurasian plates.

The Gorringe Bank was taken into account by several authors among the possible structures responsible for the 1755 earthquakes. Some studies, like the one by Grandin et al. (2007) based on the modelling of the distribution of macroseismic intensities reported in SW Iberia, are in favour of the Gorringe Bank as the responsible for the 1755 event, others are instead skeptical on the basis, for instance, of the analysis of tsunami data (e.g. Baptista et al., 2003).

The choice of a fault placed in correspondence with the Gorringe Bank in the present thesis is justified by several reasons. The first is that it is a seismically active structure, as described in Grevemeyer et al. (2017). Secondly, being the most prominent structure in the area, the Gorringe Bank, together with other structures offshore SW Iberia, is being taken into serious account by researchers for both

seismic and tsunami hazard assessment for the southern coasts of Portugal, of the Gulf of Cadiz and of Morocco (e.g. Omira et al., 2009; Matias et al., 2013). In particular, Grevemeyer et al. (2017) argue that a fault with approximately the length of the Gorringe Bank has the potential to cause a Mw = 8.7 earthquake, i.e. a 1755 Lisbon-type earthquake and tsunami. Finally, some recent studies (Lo Iacono et al., 2012) mapped and characterised the tsunamigenic potential of a huge mass failure (80 km^3 and 35 km of runout), known as the North Gorringe Avalanche (NGA), along the northern flank of the Gorringe Bank. It is thus evident that the tsunami hazard for the coasts facing the SW Iberian basin is significantly increased in relation of possible large-volume landslides set in motion by moderate-to-large magnitude earthquakes occurring in the Gorringe Bank area (see also Tinti et al., 2012c).
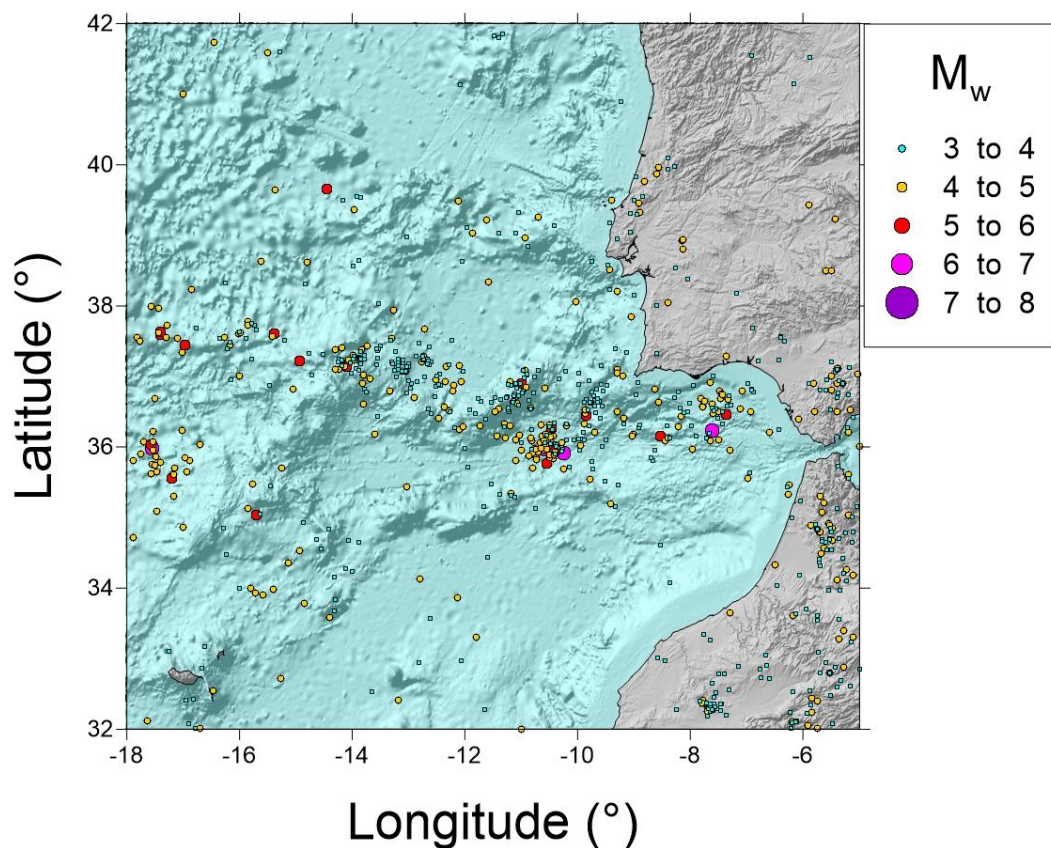
Figure 2.4: Seismicity map for the SW Iberia [ISC bulletin].

3 Analysis of Database

Throughout this chapter, a detailed analysis of the database content properties is presented, focusing on the Gorringe Bank tessellation. The main objective is to study how the waveform signals recorded at stations and the initial water level conditions may vary, by moving the elementary seismic sources over the fault plane.

Each of the initial elevation fields has been subjected to a 2-D Fast Fourier Transform (FFT), while the waveform signals have been compared to each other by means of cross-correlation and relative differences.

The analysis performed has two main purposes:

- On one side, we seek for an evaluation of the frequency content of each initial water elevation field. The initial sea level elevation, associated with each tsunami scenario of the database, is determined by the co-seismic seafloor vertical displacement. Comparing the Fourier transforms of different water elevation fields could highlight a dependency of the frequency content on the seismic source parameters, i.e. on the position of the unitary source over the space-oriented fault plane;

- On the other side, analysing the waveform signals can let us understand how both the physical propagation process and the position of the seismic source over the fault plane can affect the virtual tide gauge record.

For both aspects, the analysis procedure will be explained and the results relevant to our scope will be highlighted.

3.1 Analysis of frequency content

A representative group of three subfaults have been selected, to discuss the results of this preliminary analysis. The subfaults are located over the fault plane at different rows, hence at different depths. The subfaults selected are shown in Figure 3.1.

The depth of the subfaults increases moving down the column, as shown in Table 3.1.

The purpose of this preliminary analysis, is to highlight meaningful differences in the initial sea level conditions, associated with each of the subfaults. It is straightforward that subfaults, located at different depths, induce a different co-seismic vertical displacement of the seafloor. Consequently, we expect that differences in the co-seismic vertical displacement fields, hence in the water elevation fields, can affect the waveforms generated at the various stations.
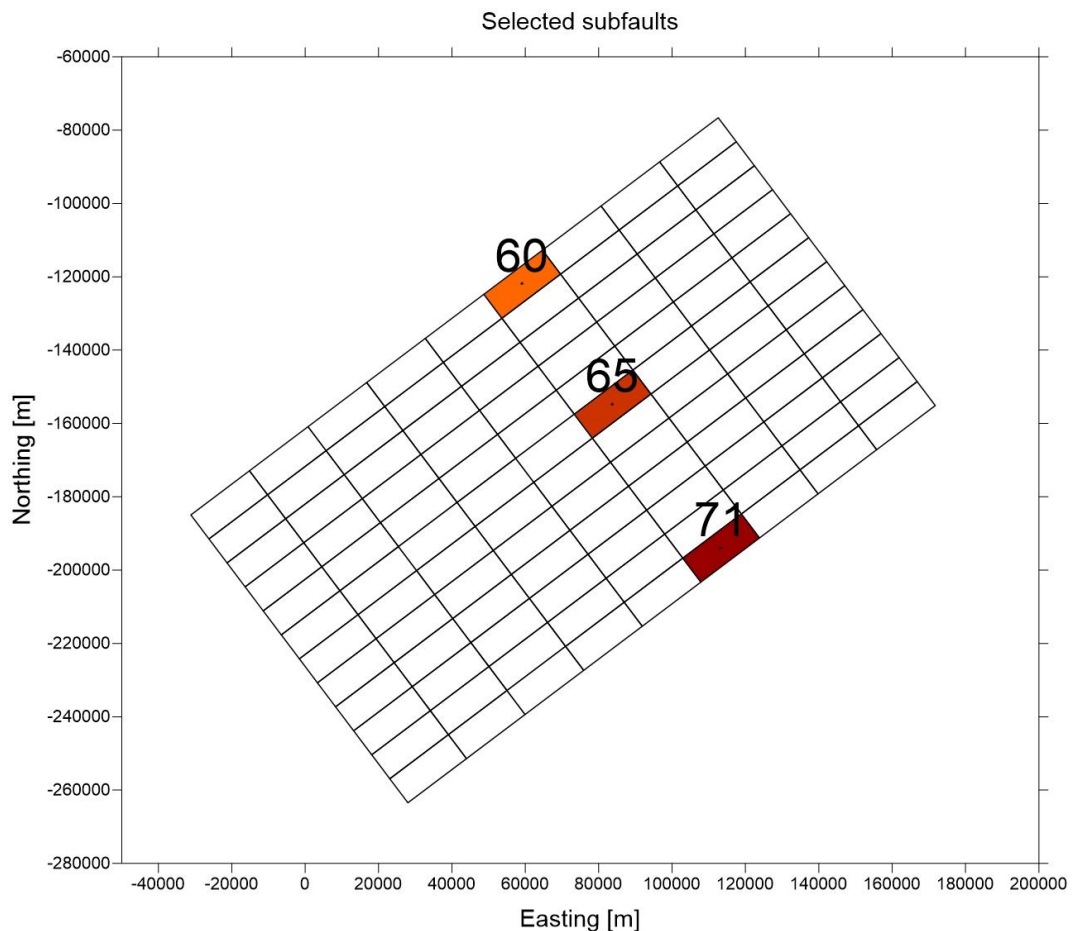
Figure 3.1: Location of the selected subfaults of the tessellation named GBF1 for this analysis, together with the indexes used to label the subfaults.

Subfaults	Central Point Depth (m)
60	7868
65	36547
71	70961

Table 3.1: The table presents the depth of the selected subfaults. At the same row, they share the same depth, which increases going down the column.

As expected, initial sea level conditions, shown in Figure 3.2, present remarkable differences in spatial shape and extension. The subfault located in the first row, which is the most superficial one, induce a sea level initial elevation field with smaller spatial extension than the others. The more we move down in the column, and hence the more the seismic source is located at depth, the wider becomes the initial *bump* at the water surface.
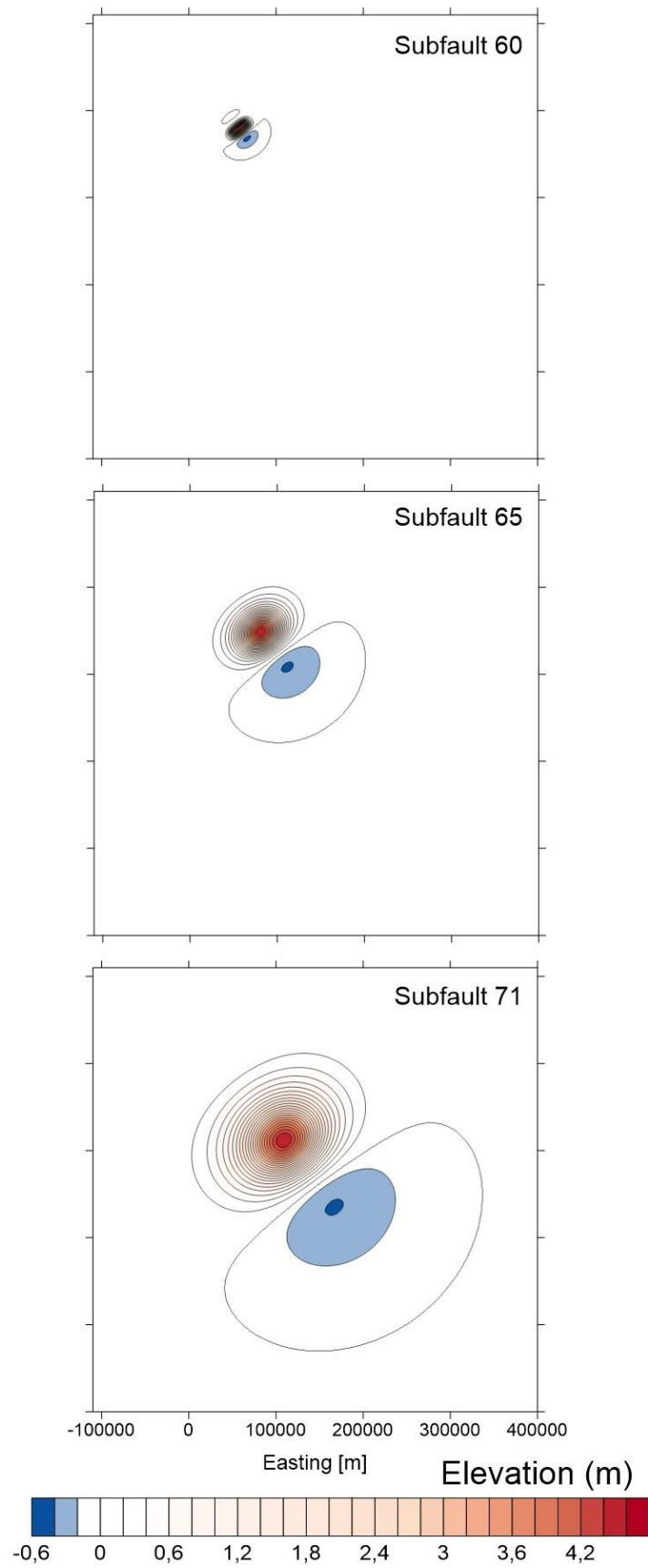
Figure 3.2: Initial water elevation fields associated with each of the elementary sources considered. The subfigures present the same spatial arrangement of the subfaults on the fault plane, as shown in Figure 3.1.

Each of these initial fields has been subjected to a post-processing procedure to perform a 2-D Fast Fourier Transform (FFT), using the open source python package Numpy for scientific data analysis (see www.numpy.org).

Before computing the FFT, the current fields have been rotated to align their symmetry axis with Easting and Northing directions. Then, a taper has been applied to smoothly bring the elevation field to zero, for elevation values smaller than 1 cm (notice that all the fields from the database present a normalised peak-to-peak amplitude of 5 m).

The 2-D frequency spectrum of each elevation field has been computed and it is shown for each of subfaults considered from Figure 3.3 to Figure 3.5.

By qualitatively analysing the results some remarkable feature can be outlined. As for the elevation fields in Figure 3.2, the frequency spectrum changes with the location of subfaults.

The most remarkable feature is that the frequency spectrum shows a tendency to sharpen and to get close to the origin of the frequency domain, when considering deeper and deeper subfaults (i.e. moving down the column).

The sharpening of the frequency spectrum, around the origin of the frequency domain, means that smaller frequencies, hence longer wavelengths, become increasingly dominant within the frequency content of the initial water elevation field.

This graphical evaluation suggests that the depth of the seismic sources could affect the results of the wave propagation process, in terms of waveform signals recorded at the various stations. In fact, deeper sources produce water elevation fields with higher content of longer wavelengths. Hence, we could expect smaller variations in waveform signals, by moving sources located at larger depth.

This evaluation is meaningful to the purpose of this thesis as, at this step, we shall expect that also the optimal resolution, in terms of fault tessellation, could depend on the location over the fault.
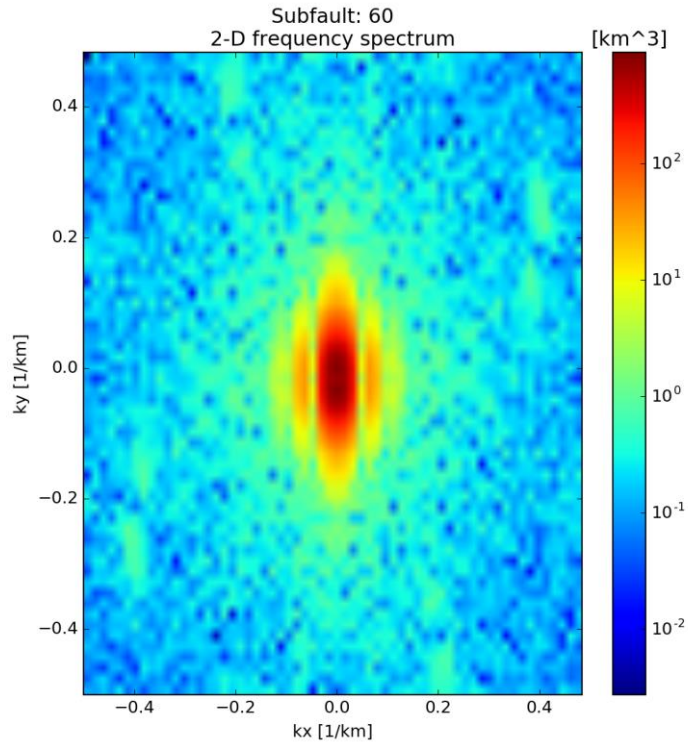
Figure 3.3: Frequency spectrum for Subfault 60. Scale is logarithmic to enhance differences. Kx and Ky represent the wavenumber along Easting and Northing direction respectively. This subfault is located at <u>smaller depth</u> with respect to the others.
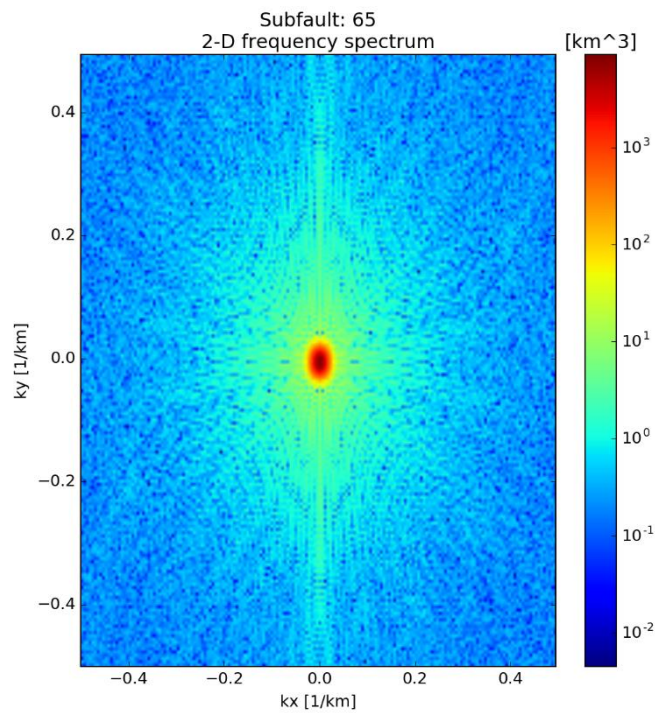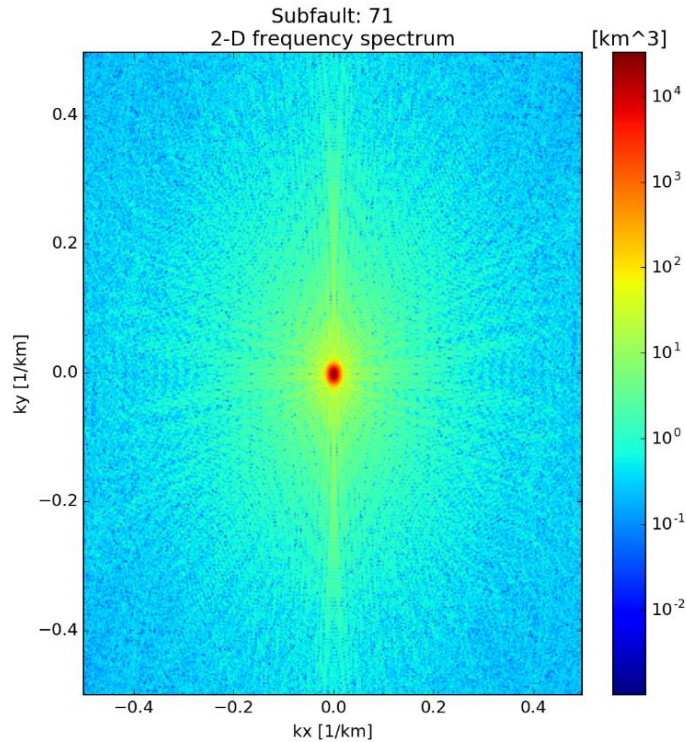

Figure 3.4: Frequency spectrum for Subfault 65. Scale is logarithmic to enhance differences. Kx and Ky represent the wavenumber along Easting and Northing direction respectively. This subfault is located at <u>medium depth</u> with respect to the fault plane.

Figure 3.5: Frequency spectrum for Subfault 71. Scale is logarithmic to enhance differences. Kx and Ky represent the wavenumber along Easting and Northing direction respectively. This subfault is located at the maximum depth availableover the fault plane.

3.2   Analysis of the waveform signals

In this paragraph, the results of the quantitative analyses performed over the waveform signals available are presented. The analyses conducted aim at quantifying the degree of similarity and continuity between signals recorded at the same station, but coming from different seismic sources.

This is rather important to the purpose of this work. In fact, highlighting possible seismic areas over the fault plane, within which the produced waveform signals vary slowly, would help understand how to realise an optimal tessellation of the fault plane.

For the sake of clarity, the analysis procedure will be firstly developed over two signals produced at a single station (with index 912), by two different subfaults (with index 29 and 65 respectively).

The two subfaults and the station selected, are shown in Figure 3.6.
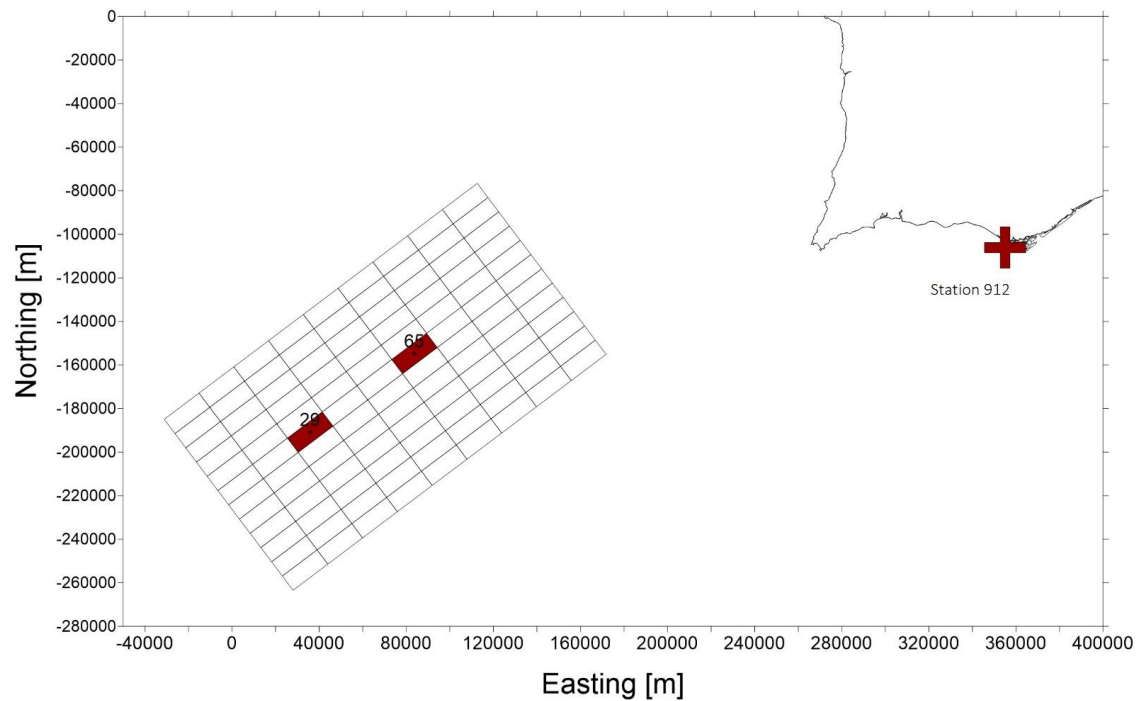
Figure 3.6: Location of the two subfaults and of the station chosen to illustrate the analysis procedure.

The complete waveform signals produced at the station 912, by the subfaults 29 and 65, as they are stored in the database, are shown in Figure 3.7. The recorded signals range in length from 0 to 961 time steps, each time step having the duration of 15s. Hence, we have four hours of recorded signal.

Before quantitatively comparing the signals to each other, a series of processing operations is required.
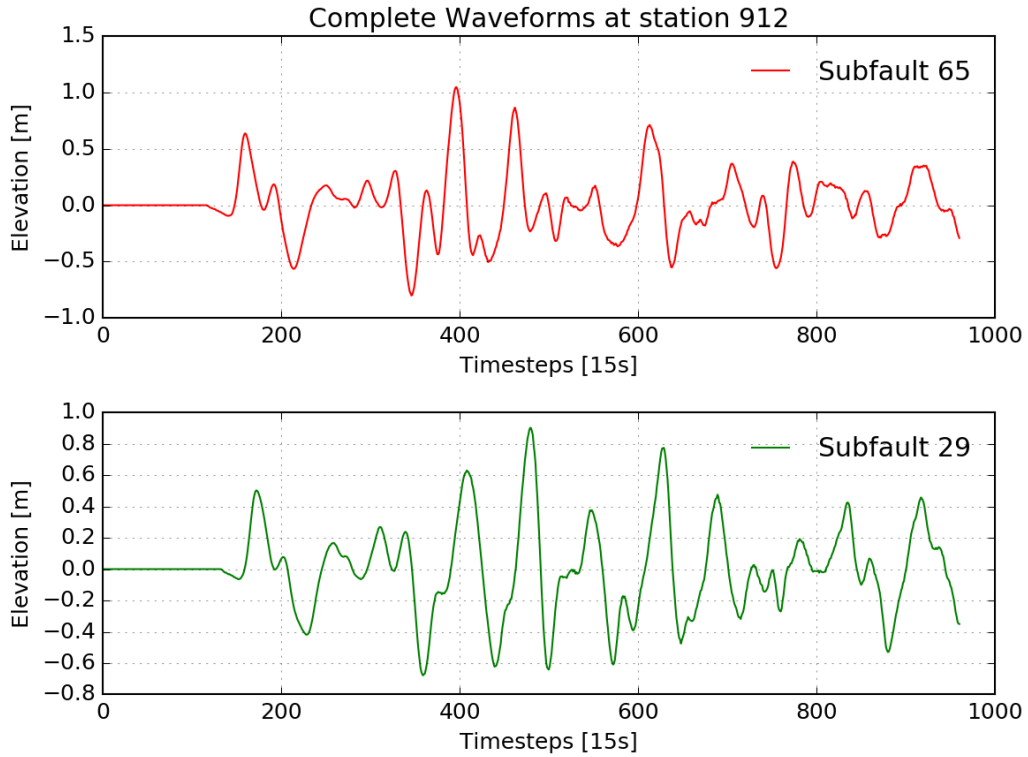
Figure 3.7: Complete waveform signals produced at the station 912 by the two subfaults considered (29 and 65), for a total duration of 961 time steps (4 hours).

3.2.1 Removing the zeros

A first fundamental operation to perform, is removing the zero-part of the signals, which is present at the beginning of the recording and whose extension depends on the distance of each station from the seismic source associated with the considered scenario.

Concerning the aim of this analysis, we do not want initial zeros to enter the computations over the amplitude of the signals, as we want to perform a meaningful comparison between the oscillations, produced at a single station by different subfaults.

Therefore, each signal is cut until a non-zero amplitude is reached.
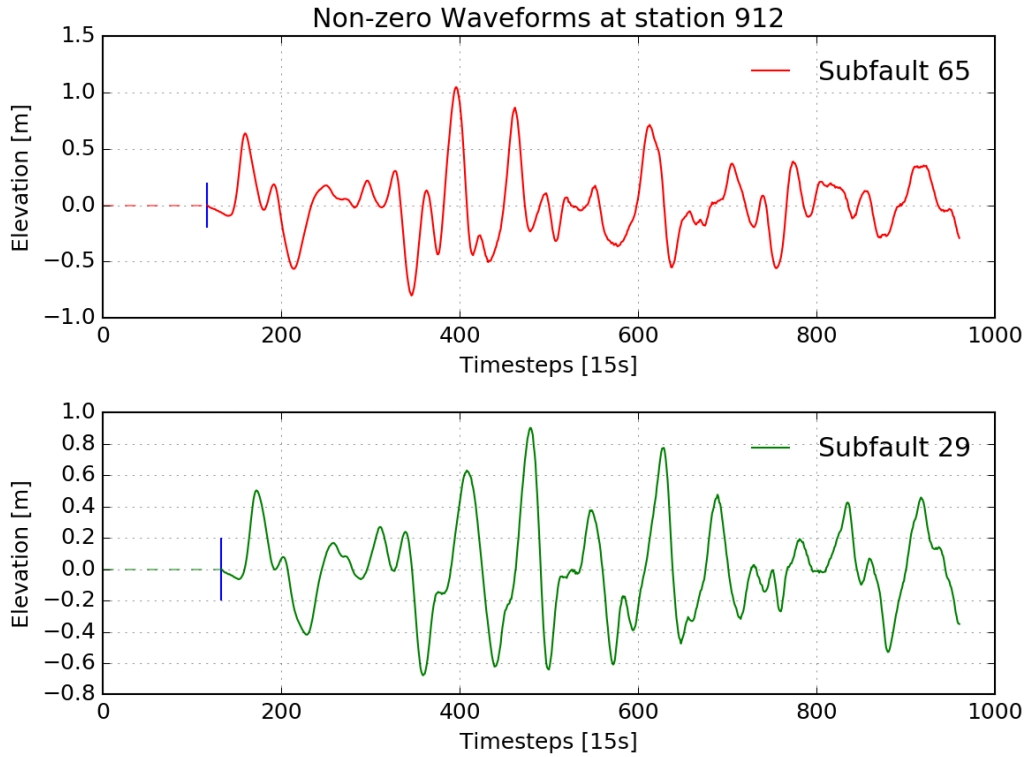
Figure 3.8. Complete signals with highlighted initial part constituted by zeros. The blue bar marks the boundary between the oscillations and the part of the signal which has seen no waves yet and hence is cut.

Figure 3.8 shows the zero-part of the signals and the part containing the oscillations, separated by a blue marker. Because of the different location of each subfaults with respect to the same station, the extension of the initial zeros varies from subfault to subfault.

We could refer to the time step, at which the first non-zero signal is detected as the *reference* time step, which represents a first rough approximation of the tsunami wave arrival time. A precise estimation of the true arrival time would have required a tough frequency analysis, which has not been performed in this work.

Nevertheless, we shall now see the procedure adopted to account for the potential inaccuracy of the reference time step estimation and how to deal with it.

3.2.2   Shifting procedure

At the present status, the two signals have been corrected for their initial zeros but they are not yet ready for a meaningful comparison. A further processing is required to account for inaccuracies coming from the cut of the signals at the reference time.

At this part of the analysis, the two signals look like in Figure 3.9 (a).
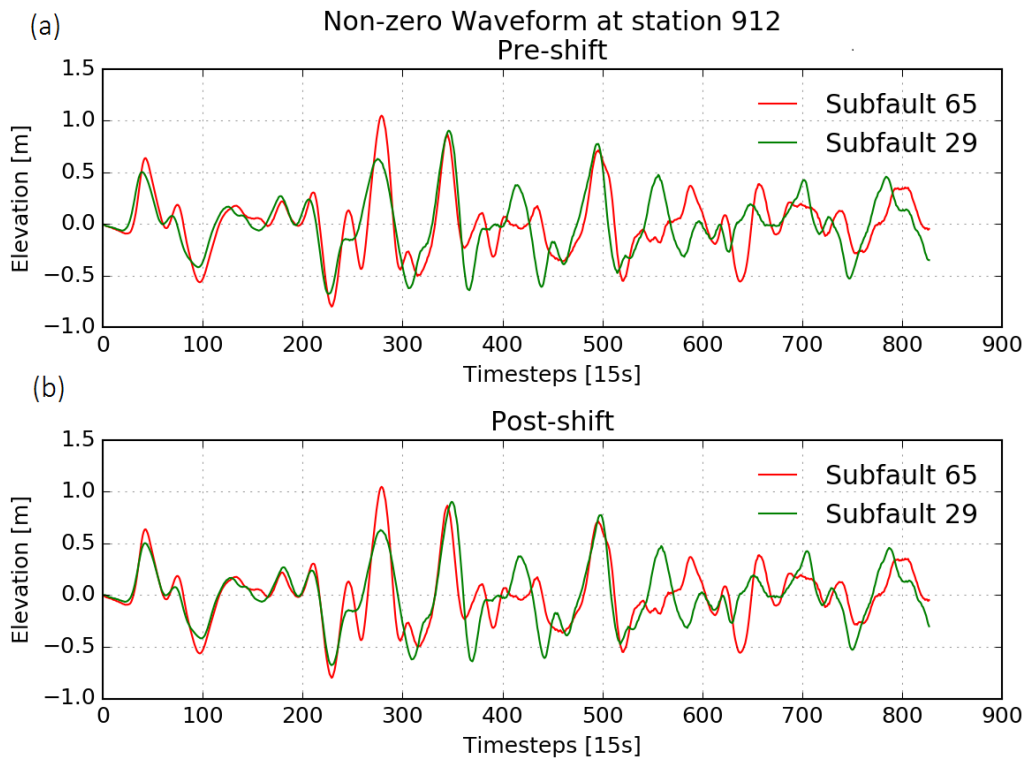
Figure 3.9: The figure shows: (a) a comparison between the signals that have been corrected only for their initial zeros and (b) a comparison of the two signals after a further processing operation, i.e. a shift to maximise their cross-correlation over the first oscillations.

When comparing two waveform signals recorded at a station, the most meaningful time window is the one containing the first oscillations. This time window, for the considered scenarios within this database, usually extends by no more than one or two hundred time steps from the reference time.

If we look again at Figure 3.9 (a), we can see that the two signals are quite like each other, within the first three or four hundred time steps. Then, the difference starts increasing.

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In this part of the processing, we should account for the time shift between the two signals, which is clearly visible by looking at the first oscillations in Figure 3.9 (a). Hence, we proceed as follows.

Firstly, we compute the cross-correlation function of the two zero-cleaned signals. Then, we evaluate the necessary shift to align at best the first oscillations of the two signals.

The cross-correlation operation computes an integral, i.e. a summation, over the two signals as a function of their relative shift. For discrete functions f and g, the cross-correlation is defined as follows:

$$(f \bullet g)[n] = \sum_m f^*[m]g[m+n]$$

where f* is the complex conjugate of f, m is the discrete index that ranges through the signals and n the discrete shift between the two signals.

The cross-correlation curve for the two signals previously considered is shown in Figure 3.10. For this computation, the open source python package Scipy for signal analysis has been used (see www.scipy.org/).

In this case, cross-correlation is computed only over the first hundred time steps of the zero-cleaned signals, to enhance the weight of the first oscillations.

Once the curve is available as a function of the shift, as shown in Figure 3.10, we seek for the maximum within a suitable window of few steps around the zero shift. The window is used to search for a value of the shift that gives a local maximum, without moving too far from the zero-shift condition.

In fact, our prior-knowledge is that the signals are almost aligned and the correction needed to account for the inaccuracy in reference time step estimation, is likely to be small. Once that we have picked up a suitable maximum, we add in front of one of the signals, depending on the sign of the shift, a *shift* number of zeros, i.e. we re-define the reference time step.
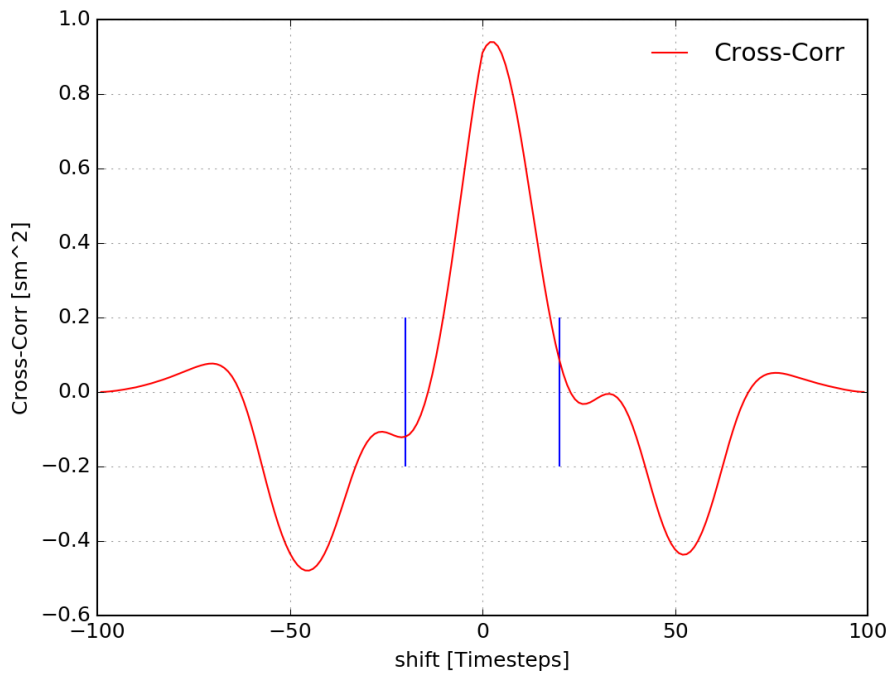
Figure 3.10: Cross-correlation curve for the signal produced at the station 912 by subfault 29 and 65. The curve is computed only over the first hundred time steps of the two signals, to enhance the importance of the fist oscillations recorded. The blue bars represent the window within which we seek for the maximum of the cross-correlation.

Once the cross-correlation over the first hundred time steps of the signal has been maximised through shifting, the two signals look like in Figure 3.9(b).

At this point, they are <u>ready to be compared</u> by means of two indicators:

- <u>Relative difference</u>: given the two processed signals f and g, we define the relative difference of g with respect to f as:

$$\Delta_{f,g} = \frac{\sqrt{\sum_{i=0}^{N-1}(g_i - f_i)^2}}{\sqrt{\sum_{i=0}^{N-1} f_i^2}}$$

- <u>Cross-correlation value:</u> it is the cross-correlation computed over the two processed signals with no shift, i.e. we calculate the cross-correlation function over the whole duration of the final processed signals (shown in Figure 3.9(b)) and we take the zero-shift value of the cross-correlation. This is useful to quantify the degree of similarity of the oscillations produced at a single station by two different sources;

For the processed signals at the station 912, produced by subfaults 29 and 65, we have the value of relative difference and cross-correlation:

$$\Delta_{29,65} = 0.71 \qquad\qquad xCorr = 0.75$$

3.2.3   Cross-correlation curves

In this paragraph, the xCorr, as previously defined, has been computed over the fault plane.

This time, several couples of subfaults have been strategically selected and the cross-correlation have been computed for each of them.

In this case, all the stations available have been used. Hence, given a single couple of seismic sources, a cross-correlation curve has been generated, showing how the waveform signals produced by the two sources cross-correlate at the various stations.

To show the main results of this analysis, two different subfaults, located at different depth, have been selected as reference subfaults. Their location over the fault plane is shown in Figure 3.11.
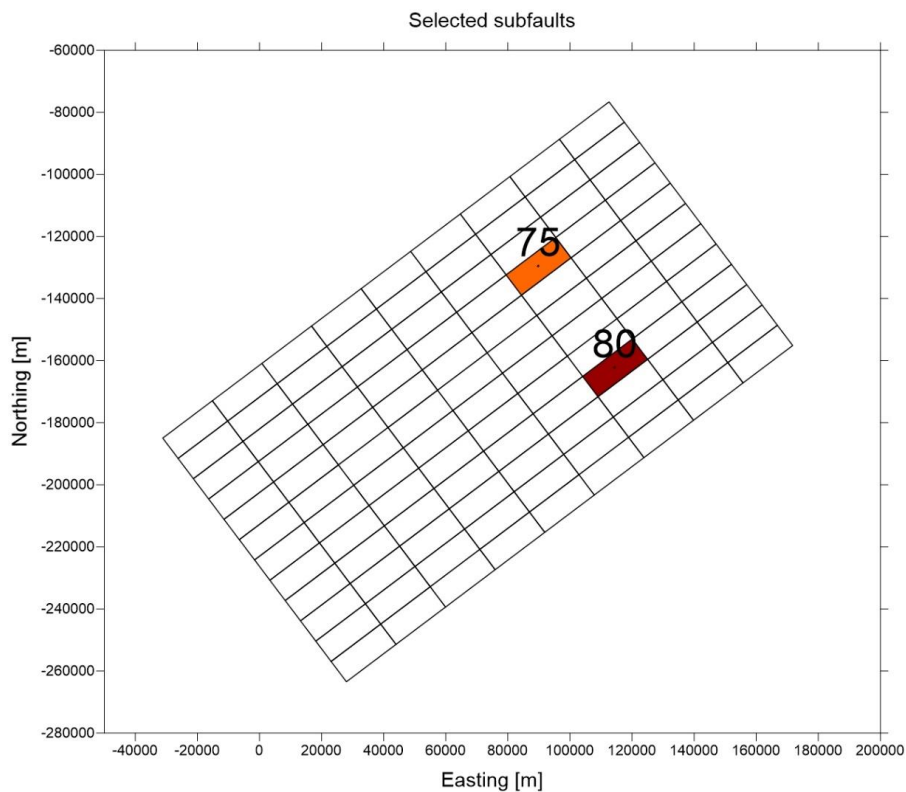
Figure 3.11: Location of the subfaults chosen as references for the correlation curves.

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Once that a reference source has been fixed, we are interested in quantifying how the cross-correlation changes, by computing it with subfaults at increasing distance with respect to the reference.

To this aim, three different configurations have been designed for a single reference subfaults as shown in Figure 3.12.
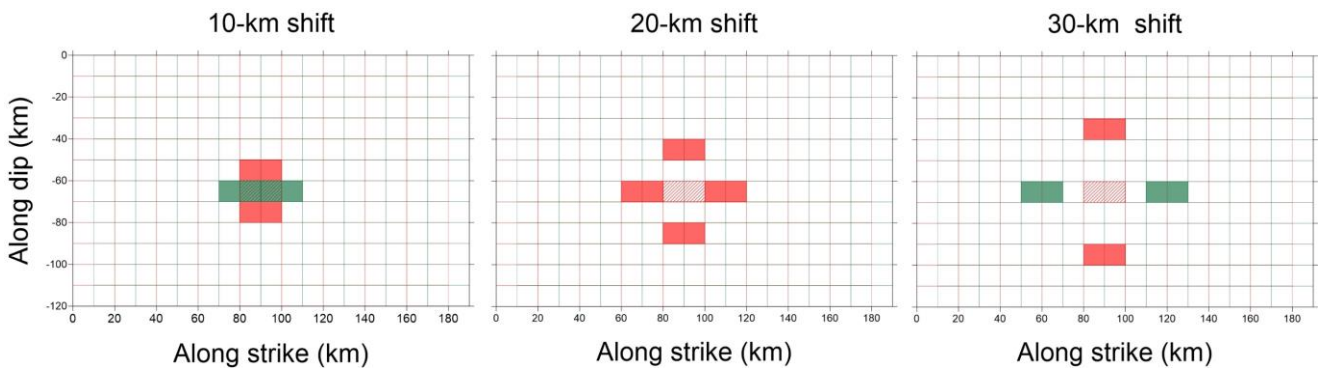
Figure 3.12: The figure shows the three configurations adopted for calculating the cross-correlation curves. The central shaded subfault is the reference one. As can be seen, by using GBF1 (red shaded grid and red subfaults) and GBF2 (green shaded grid and green subfaults) tessellations, we have a 10 km per 10 km grid. The subfaults to be cross-correlated with the reference are chosen at increasing distances every 10 km, as can be seen from left side to right side of the figure.

In these cases, we managed to use both tessellation GBF1 and GBF2, which are shifted by 10 km with respect to each other, providing us with a 10 km per 10 km regular grid, over which every point represents the epicentre of an elementary seismic source.

For each configuration, four subfaults are chosen equidistant from the reference, with the distance being 10 km, 20 km and 30 km for each configuration.

The results are shown for the considered reference subfaults, 75 and 80, as their behaviour well represents the behaviour seen along their rows during this work.

By looking at the subfault 75, we see that values of the cross-correlation curves are close to one within the first configuration (Figure 3.13), i.e. when the neighbour subfaults are at 10 km distance. Values become lower when the distance of subfaults increases to 20 km and 30 km (Figure 3.14 and Figure 3.15). The waveforms concerned with the Madeira archipelago (from 1400 on in the previous figures), show a tendency of decreasing faster in terms of cross-correlation. A

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common feature throughout the three configurations, is that cross-correlation computed with subfaults located higher (i.e. at smaller depth) than the reference cell, shows the lowest values. While cross-correlation computed with faults located on the left and on the right, i.e. at the same depths the reference subfault, presents the highest value of cross-correlations throughout the three configurations.

The features can be seen also by looking at three figures concerning the reference subfault number 80, which is located deeper in the fault plane than subfault 75.

A remarkable feature is that, given a fixed configuration and a given choice of the subfault to correlate with the reference, the subfault 80 shows cross-correlation values systematically higher than the ones shown by subfault 75.

This demonstrates that at major depths, the closer the subfaults are, the more similar are the signal they produce, hence revealing that the tessellation of the deeper area of the fault could be subject to an optimization process.
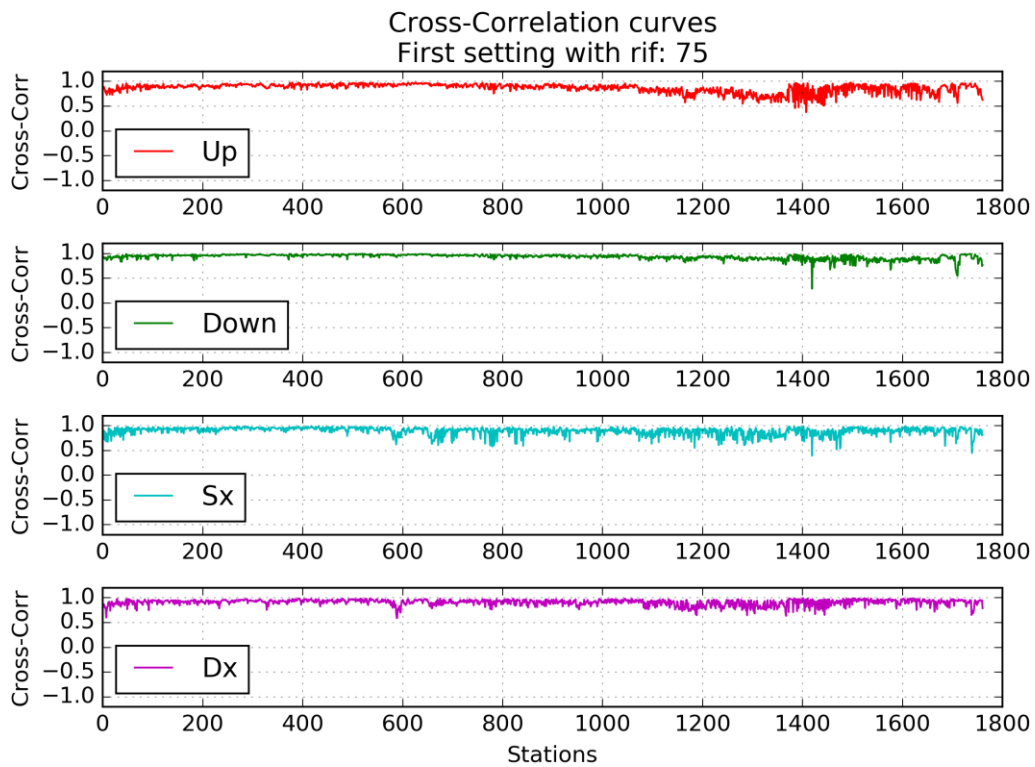
Figure 3.13: Cross- correlation curves for reference subfault number 75, obtained in the first configuration (10 km separation). The legend tells which subfault has been cross-correlated with the reference.
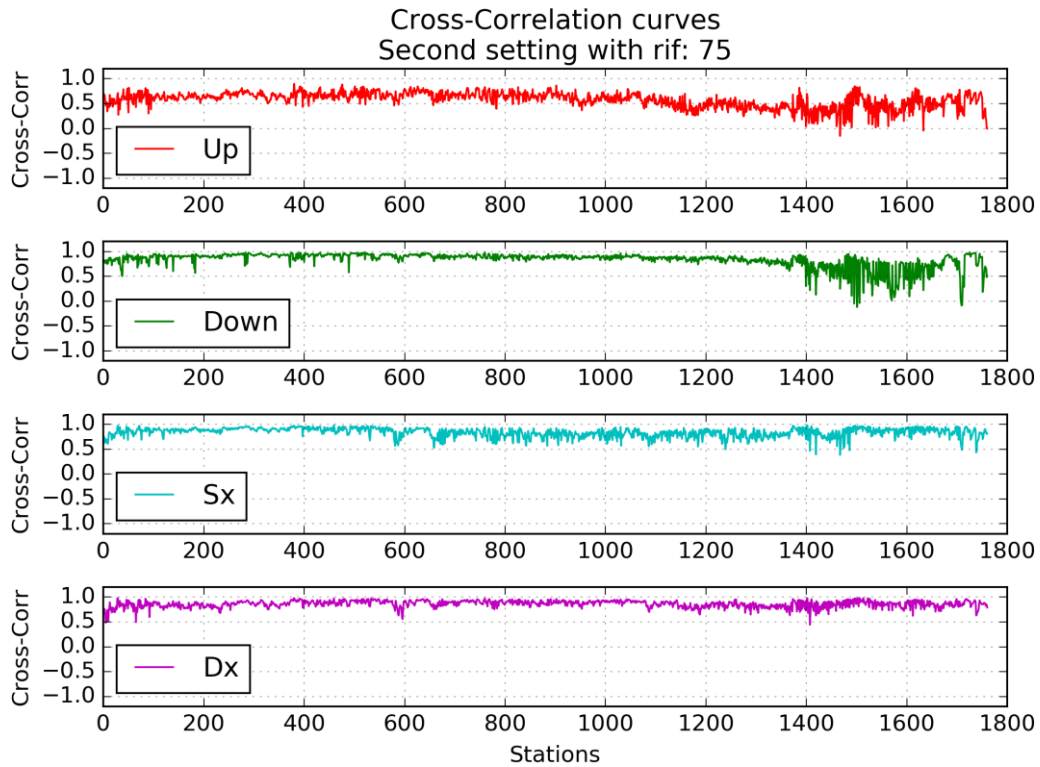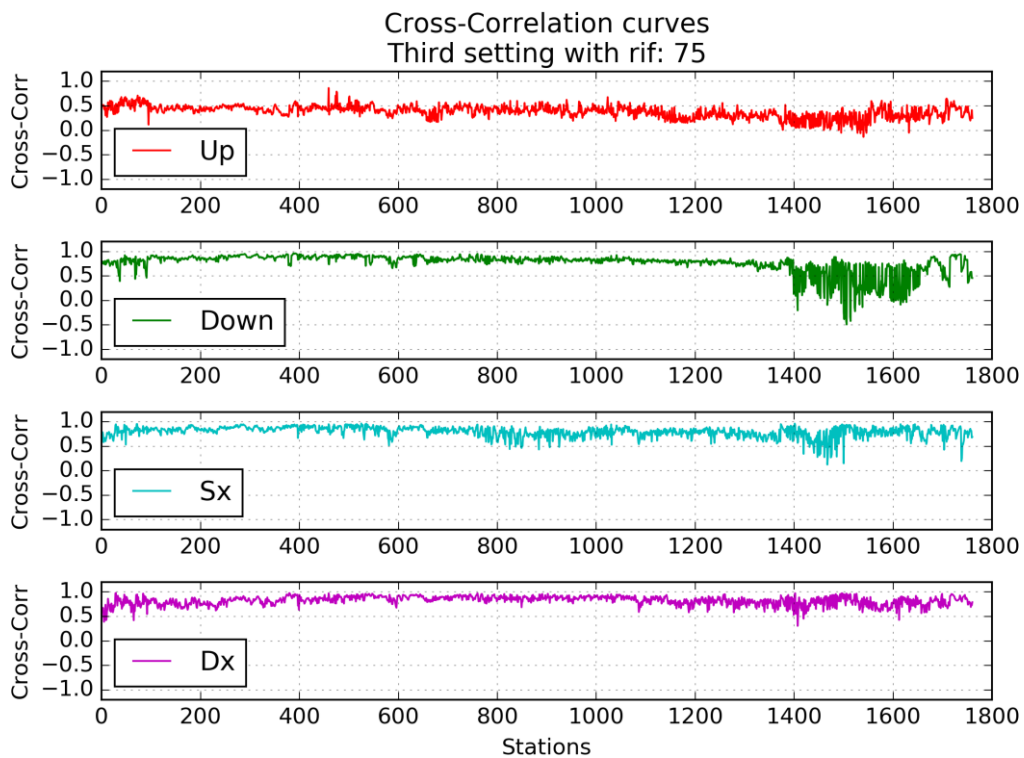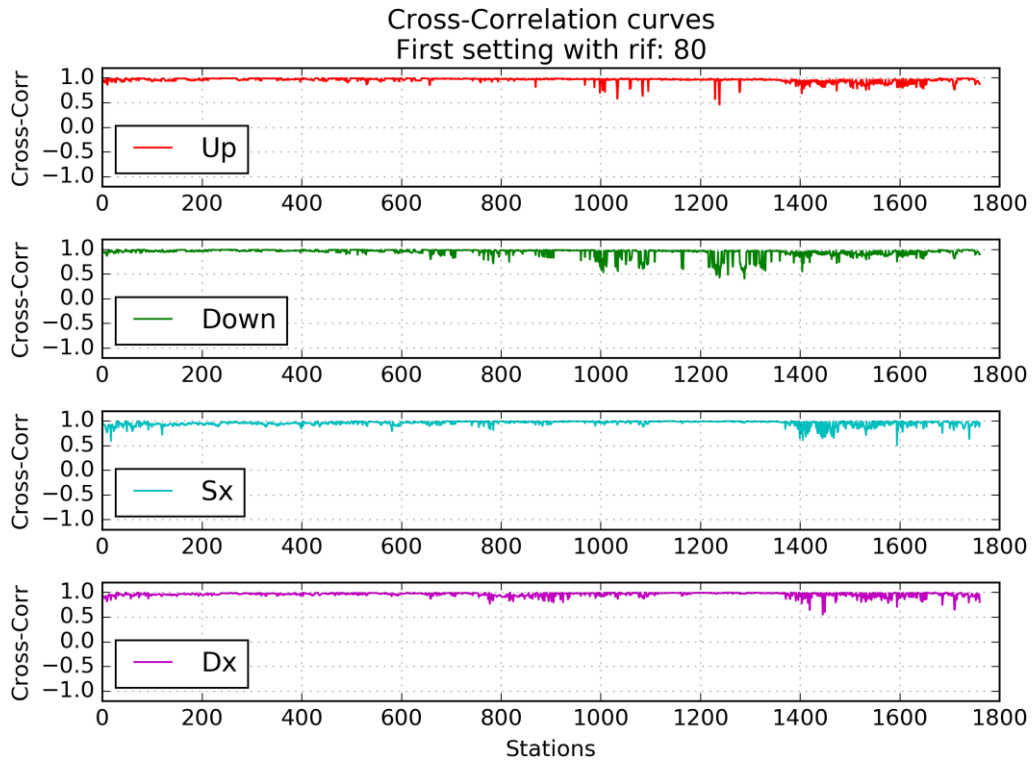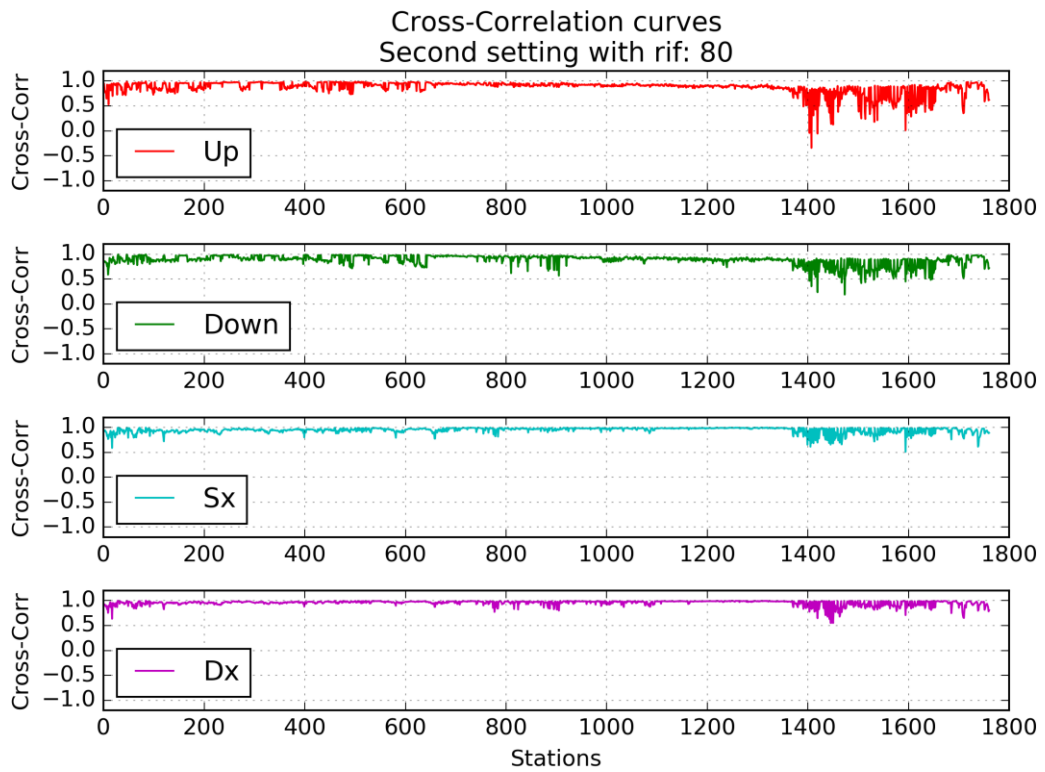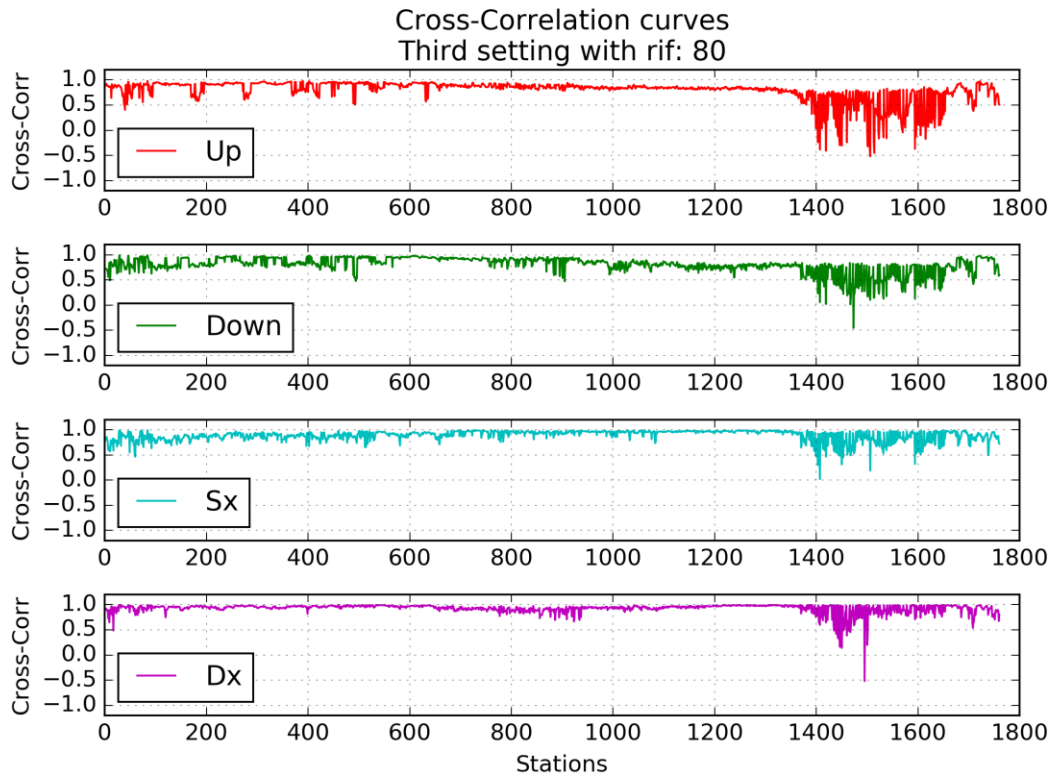
Figure 3.14: Cross- correlation curves for reference subfault number 75, obtained in the second configuration (20 km separation). The legend tells which subfault has been cross-correlated with the reference.

Figure 3.15: Cross- correlation curves for reference subfault number 75, obtained in the third configuration (30 km separation). The legend tells which subfault has been cross-correlated with the reference.

Figure 3.16: Cross- correlation curves for reference subfault number 80, obtained in the first configuration (10 km separation). The legend tells which subfault has been cross-correlated with the reference.

Figure 3.17: Cross- correlation curves for reference subfault number 80, obtained in the second configuration (20 km separation). The legend tells which subfault has been cross-correlated with the reference.

Figure 3.18: Cross- correlation curves for reference subfault number 80, obtained in the third configuration (30 km separation). The legend tells which subfault has been cross-correlated with the reference.

3.2.4 Quantifying the relative difference over the fault plane

Similarly to the previous sections, relative differences in waveform signals, produced by different seismic sources over the fault, have been computed.

To this aim, a reference row and a reference column over the fault have been chosen as shown in Figure 3.19.
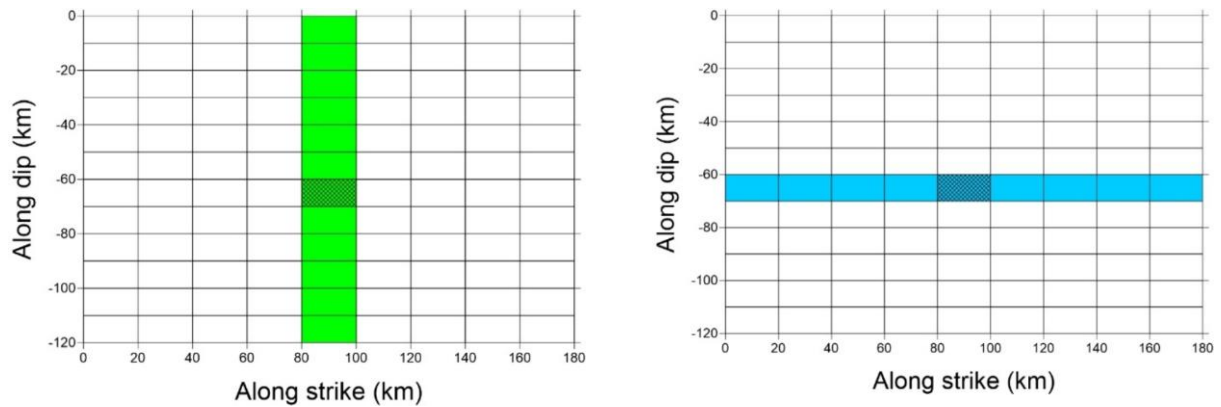
Figure 3.19: The figure shows the reference column (green column on the left) and the reference row (blue row on the right), chosen as references in computing relative differences between subfaults. Once a row has been chosen, we calculate differences between the green reference of subfaults for that row, at increasing distances. Similarly, once that a column has been chosen, we calculate differences selecting subfaults at increasing distances from the blue reference for that column.

Then, we proceed as follows in selecting the subfaults to be compared:

In this case, we proceed by taking a single row at a time and, successively, a single column at a time.

For every fixed row, we have a reference subfault, i.e. the central one, and we start computing relative differences in waveform signals, by considering subfaults of increasing distance from the reference.

By using both tessellation GBF1 and GBF2, we manage to achieve 8 different selections of subfaults at gradually increasing distance from the reference.

The relative errors along a fixed column are computed selecting subfaults in a similar manner, by increasing the distance from the central row of reference.

The results are shown from Figure 3.20 to Figure 3.25. They are given as scatter plots representing the relative difference between a subfault, at a given distance with respect to the reference, for every single station available.

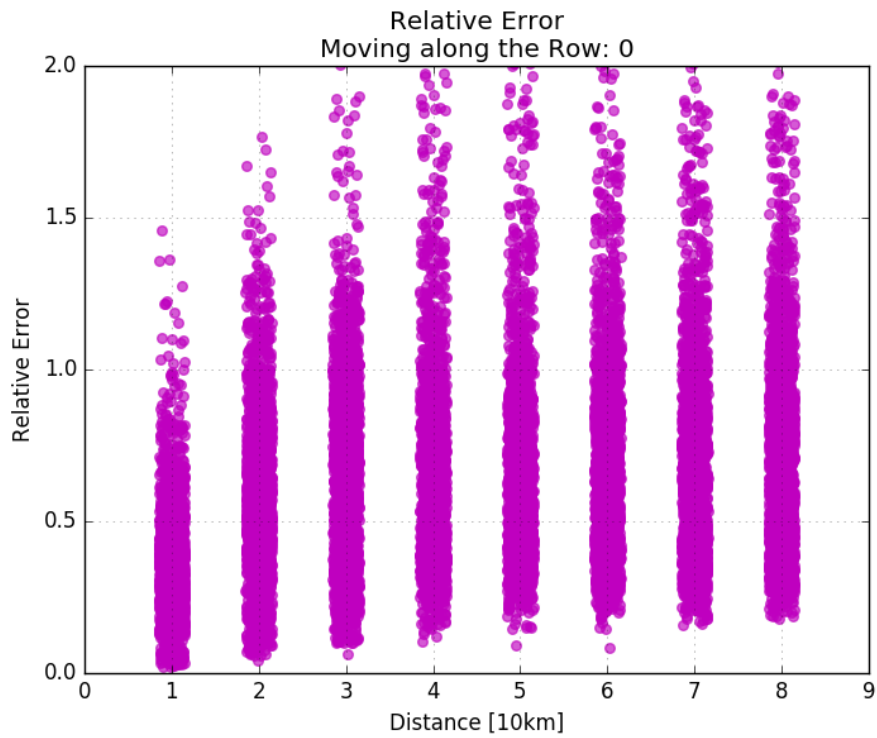Hence, each dot of the scatter plot represents a station.

Figure 3.20 Relative difference at various distances from the central element of the first row, moving along the same row. Each dot represents the relative difference associated with a single station.
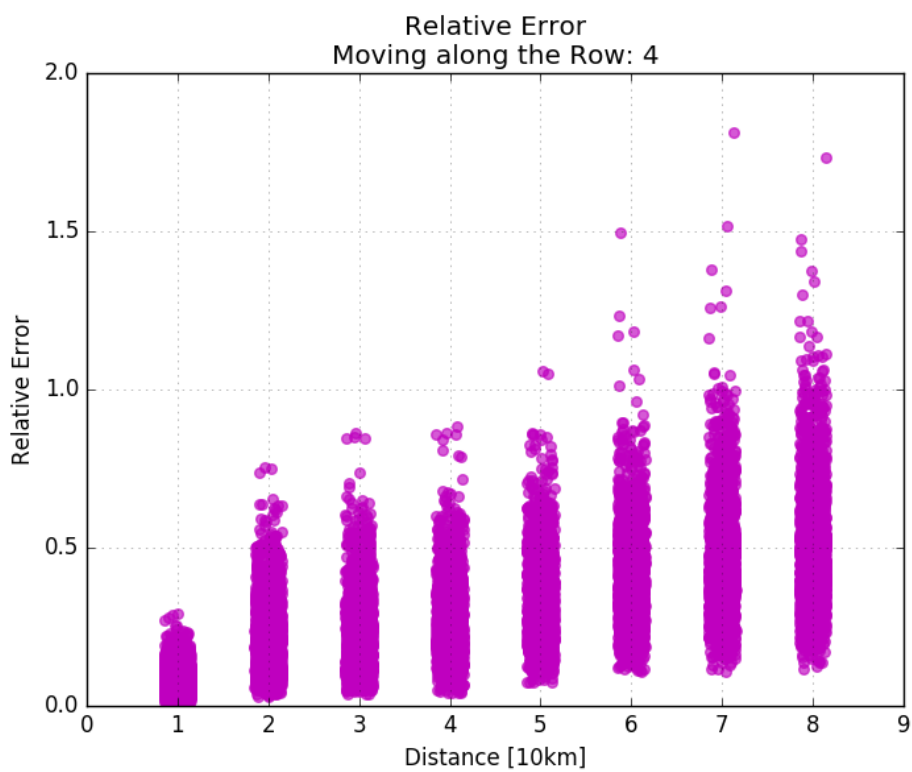

Figure 3.21: Relative difference at various distances from the central cell of the fifth row, moving along the same row. Each dot represents the relative difference of a single station.
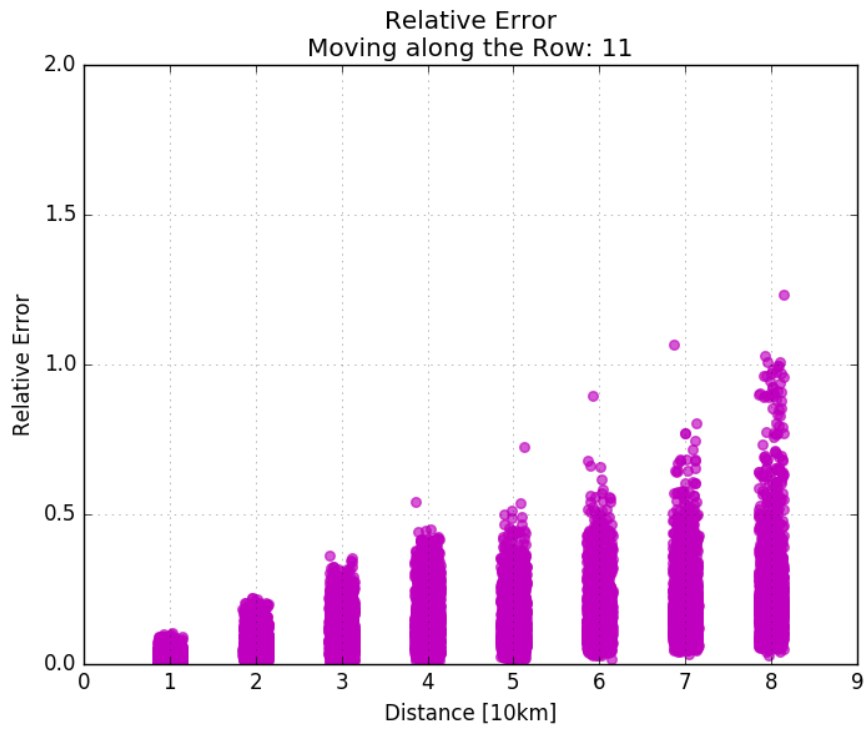
Figure 3.22: Relative difference at various distances with respect to the central element of the last row.
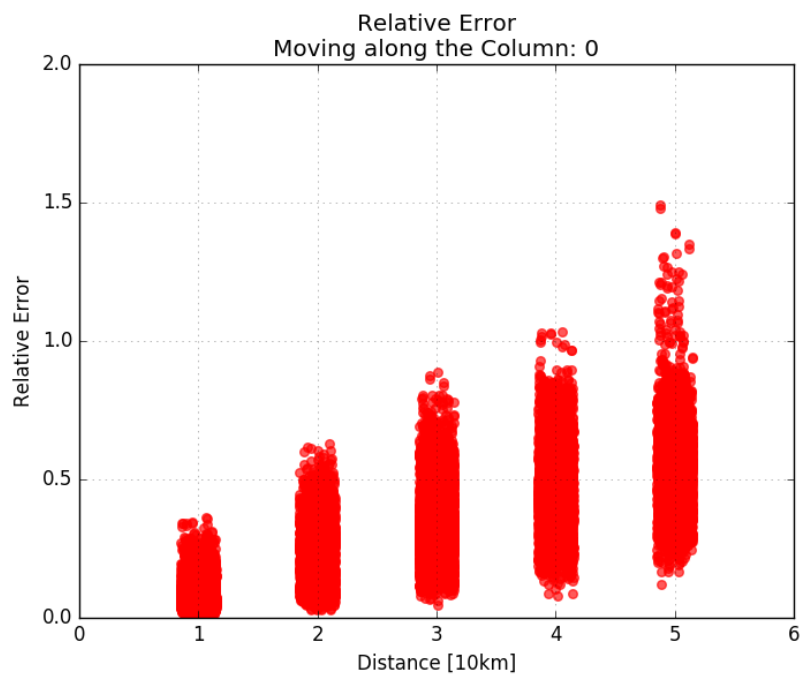
Figure 3.23: Relative difference with respect to central element of the first column at various distances, moving along the column. Each orange dot represents a single station.
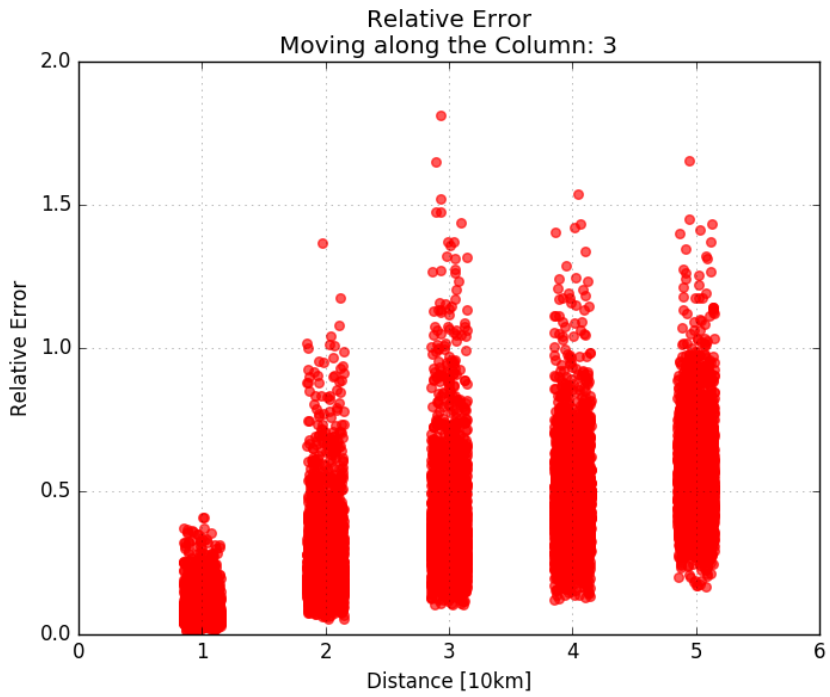
Figure 3.24: Relative difference with respect to central element of the fourth column at various distances, moving along the column. Each orange dot represents a single station
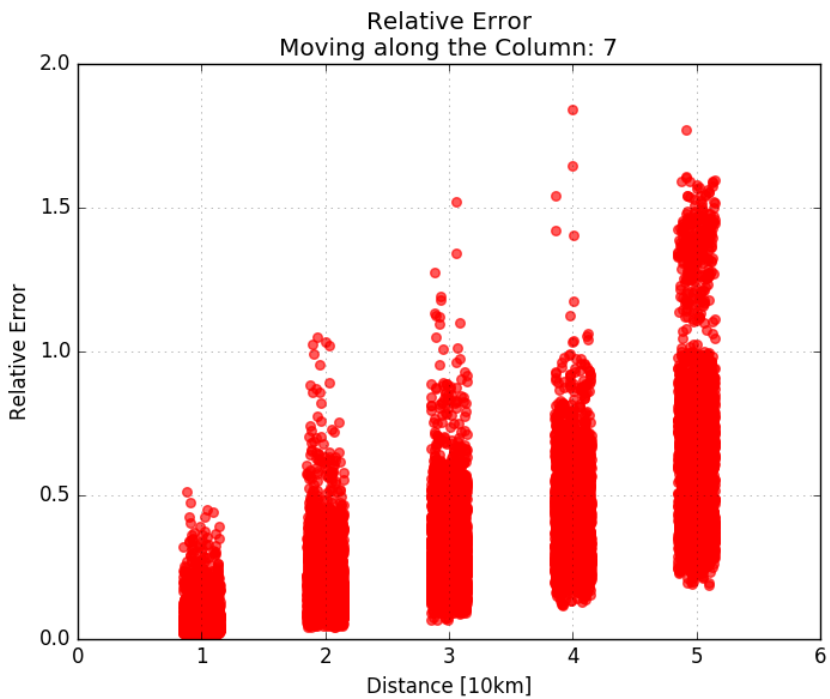

Figure 3.25: Relative difference with respect to central element of the eighth column at various distances, moving along the column. Each orange dot represents a single station.

Some remarkable results can be highlighted by looking at the relative differences computed both along the columns and the rows:

As expected, the relative difference in produced signals, with respect to central reference, increases at increasing distances, both along the columns and the rows. In fact, at a certain distance, the relative difference reaches high values around 1 or more than 1, as can be seen by inspecting graphs from Figure 3.20 to Figure 3.25.

Even if all configurations, both along columns and along rows, present increasing relative differences at increasing distances, the rate at which the difference increases may change, depending on the configuration considered. In fact:

- Moving along different columns does not provide any remarkable difference in the difference growth, as can be seen in Figure 3.23, Figure 3.24 and Figure 3.25.
- Moving along different rows provides very different growing trends for the relative differences. In the most superficial row, the average difference is very high, and some stations present differences over 1 also at a 10 km distance, as can be seen in Figure 3.20.

  By considering a deeper row, shown in Figure 3.21, we can see that the growth of difference in waveform signals, obtained while moving along the row itself, is a minor growth and differences are generally lower than the ones obtained at the first superficial row.

  By considering the deepest row available, shown in Figure 3.22, we can see that relative differences have sharply decreased with respect to the previous cases and their growth is smaller when moving along the same row.

The results of these analyses, conducted both over the water elevation fields and over the waveform signals generated by the elementary sources, suggest that an optimization of the unitary sources' arrangement can be achieved, especially working along the rows.

In fact, subfaults along the same rows share remarkable properties. On one side, along the same row we have the same average frequency content and we have seen that, moving along a single fixed row, cross-correlation values are higher and differences are smaller.

Moreover, these analyses show that the signals produced by deeper rows present larger values of cross-correlation and lower differences, even with respect to the rows located at smaller depths.

These evident features have directly affected and driven the development of our optimization strategy as we have chosen to work mainly along the rows to search for suitable optimizations.

Given these preliminary results, in the following chapters our work and its main results are presented.

4   The Building algorithm

Producing a forecast in terms of waveform signals at sensible locations, e.g. along the coast, is a novel approach with respect to the routinely adopted Decision Matrix.

In the first part of this chapter, a reference tsunamigenic event is proposed and its expected waveform signals are produced, by matching the event with the elementary seismic sources of the MSDB database.

Based on the results of the previous analyses, a *"Building"* algorithm is designed and suggested to optimise the forecast production.

The main objective is to approximate at best the reference forecast, by using a smaller number of subfaults upon a strategic processing.

The goal of the Building process is to search for a better exploitation of the information, obtainable from a smaller number of elementary sources. Different configurations of subfaults will be considered to eventually define a strategy towards the optimization of the forecasting procedure.

The first paragraph of the chapter is devoted to the description of the reference event and the associated reference forecast.

In the second the strategy of the building process is explained by means of a simple case with two subfaults and a single station.

In the third paragraph the strategy is applied and generalized all over the surface of interest and the results are discussed.

4.1   The reference event

The reference event is a Mw 8.1 earthquake located over the GBF plane. It is modelled as a homogeneous slip distribution over a rectangular area. The source parameters are given by Hanks and Kanamori (1979) and shown in Table 4.1, together with easting and northing coordinates.

	Reference Event
Mw	8.1
Slip (m)	5.4
Length (m)	189670.6
Width (m)	51404.4
Easting (m)	72755.16
Northing (m)	-173304.1
Depth (m)	42282.5

Table 4.1 Source parameters of the reference seismic event

The considered event is consistent with the tsunamigenic potential of the area and its historical events (Johnston, 1996). The horizontal proje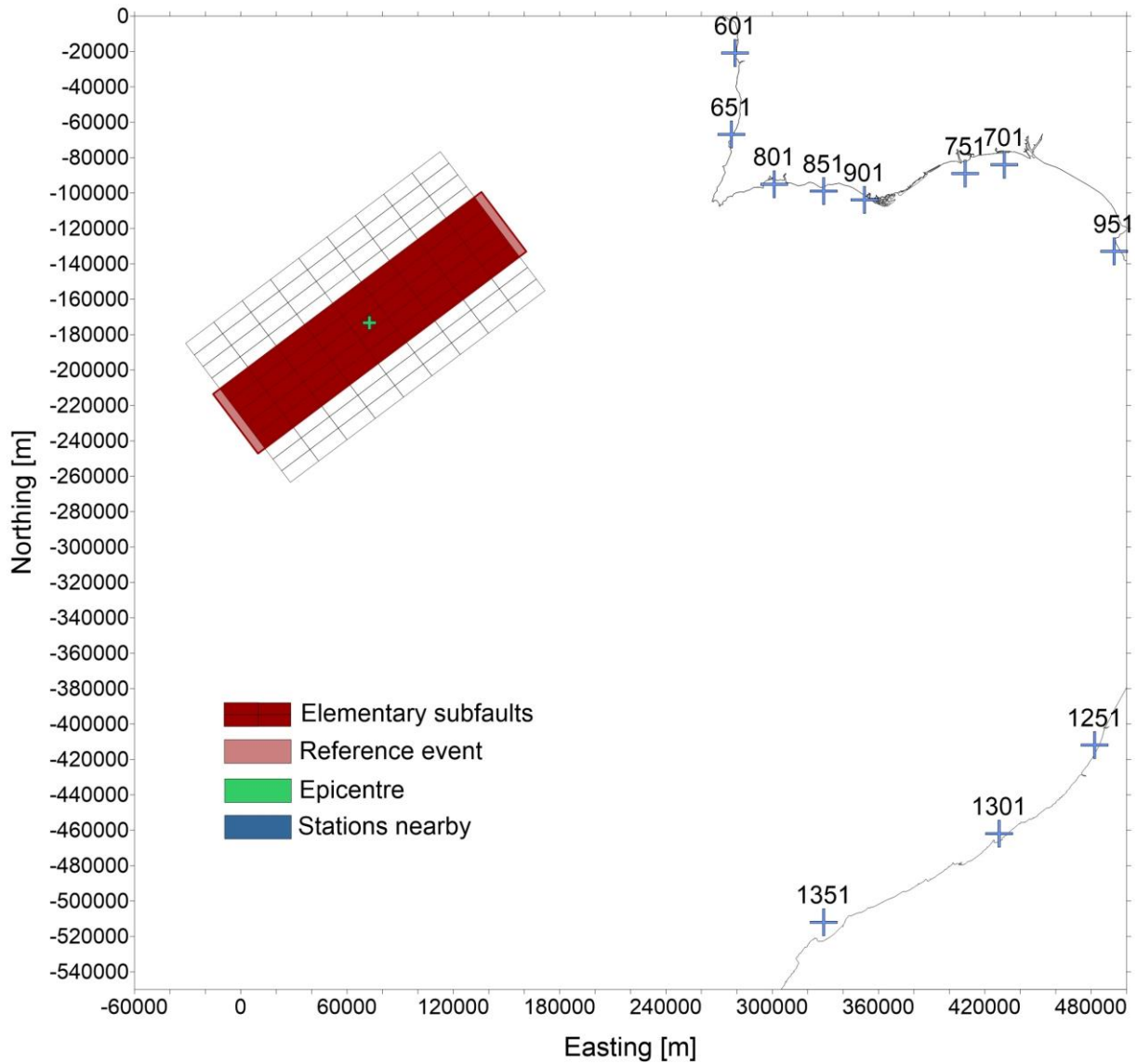ction of the seismic source is shown in Figure 4.1 The figure shows the reference event located over the GBF plane, matching the underlying unitary sources. In this figure, the projection at the horizontal surface is shown both for the considered seismic event and the GBF tessellation. The epicentre location is shown, together with some sample stations along the coastal line. together with some sample stations located along the coast.

Figure 4.1 The figure shows the reference event located over the GBF plane, matching the underlying unitary sources. In this figure, the projection at the horizontal surface is shown both for the considered seismic event and the GBF tessellation. The epicentre location is shown, together with some sample stations along the coastal line. The epicentre is far no more than few hundred kilometres from the Portuguese coast and the North-western Morocco coast. The subfault in red have been selected to produce the reference forecast.

The reference event is matched with the underlying 45 regularly-spaced subfaults, that have been highlighted in red in Figure 4.1.

Being the tsunami equations linear, the expected signals induced by the waves propagation are obtained by summing over the matched unitary sources' signals, whose amplitude has been corrected to guarantee the conservation of seismic moment (before correction, the elementary signals are associated with 1 m slip over the elementary sources).

In this way, a _reference forecast_ is produced by summing over the elementary sources involved in the event.

An example of forecasted waveform signals at four stations is shown in Figure 4.2
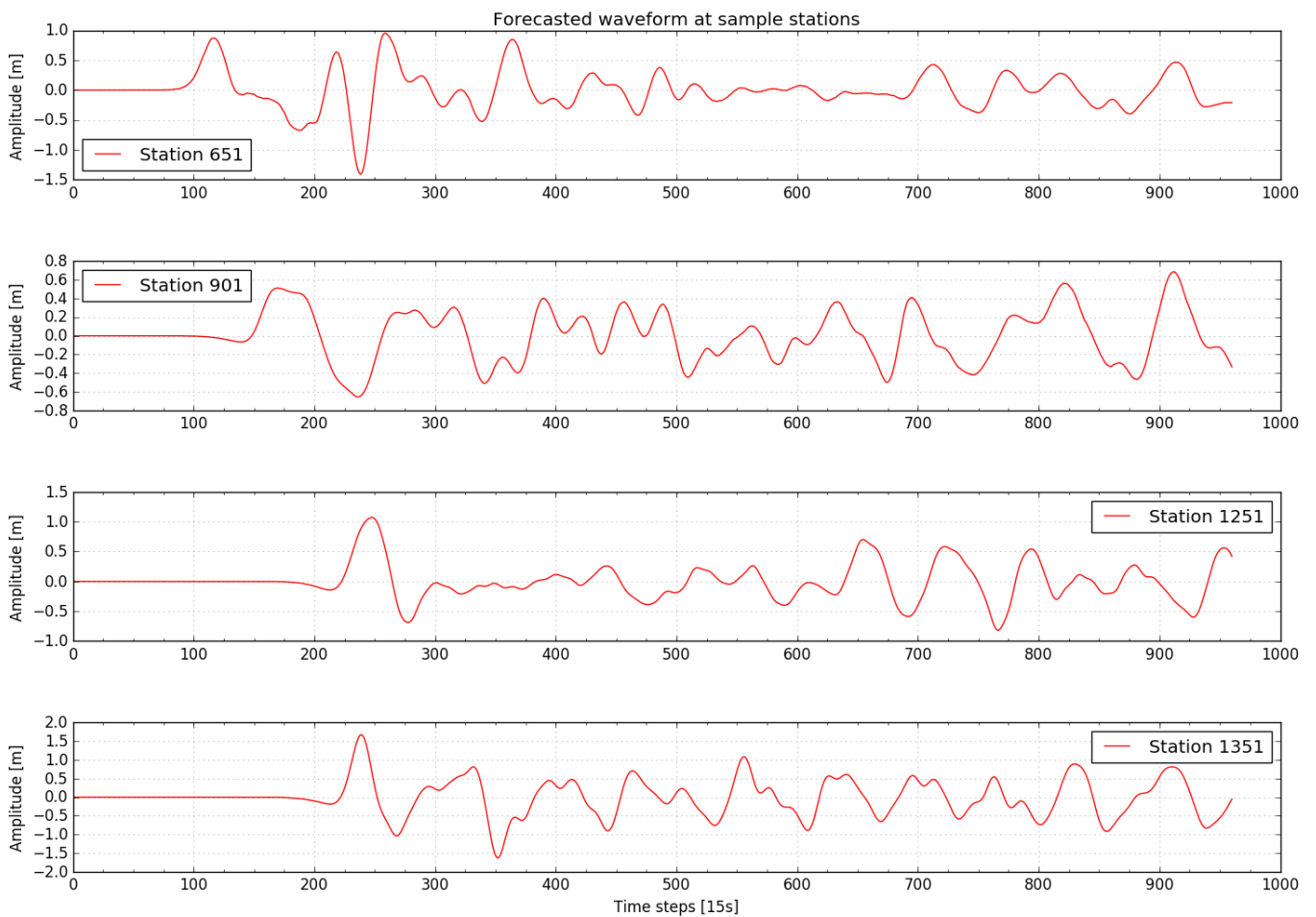
Figure 4.2 Example of waveform signals forecasted for the new event using all the 45 subfaults available, at four different stations.

Example of waveform signals forecasted for the new event using all the 45 subfaults available, at four different stations.

Figure 4.2 Example of waveform signals forecasted for the new event using all the 45 subfaults available, at four different stations. shows the forecasted signals concerning four sample stations, two of which, the 651 and 901, are located at the Portuguese coast, while the other two, the 1251 and the 1351, are located at the Morocco coast.

By looking at these reference forecasts, tsunami waves are expected to impact Portuguese coasts within 20-minute time and Morocco coasts within 50-minute time.

Producing these forecasts has a time cost. Accessing the database for the 45 matched elementary sources and reading the associated 1760 signals (one for each station available), has required 62.17 seconds, hence little more than a minute. The specification of the used CPU is:

Intel ®Core™i7-4790 CPU @ 3.60GHz

The order of the minute becomes relevant when compared to an expected impact within 20 minutes.

This thesis work suggests that this time cost can be reduced, by paying an affordable price in terms of accuracy with respect to the reference forecast. To explore this possibility, a building algorithm is presented in the next paragraphs.

The purpose of the algorithm is to use a smaller number of subfaults (less than 45) to approximate the refence forecast. Different configurations of subfaults are tested and the performance of the building process evaluated.

4.2   The Building strategy

We refer to a *building process* when, given an unknown subfault, we try to reconstruct the signal it produces at a certain station, using the signals produced by neighbour subfaults.

We start considering a simple case with two known subfaults, i.e. 28 and 52, and a single station, 901. They are shown in Figure 4.3.
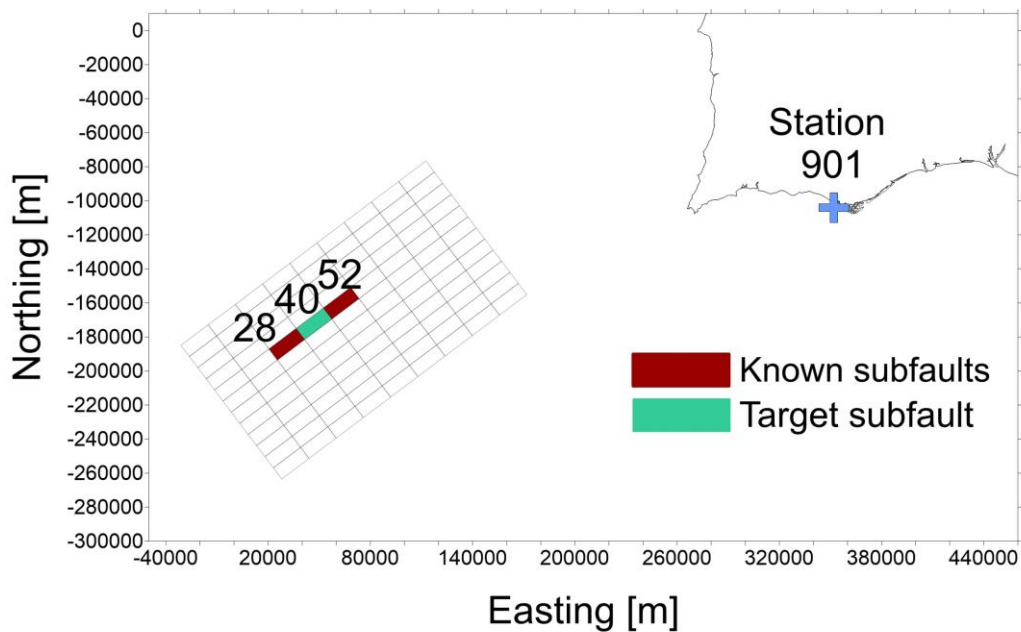

Figure 4.3 Simple configuration to explain the Building strategy. We consider a single station (901) and two known subfaults (ruby red ones), which we want to use to build the waveform signal associated with the unknown target subfault 40 (sea green).

By using the signals produced by subfaults 28 and 52 at the given station, we want to build an approximation of the signal, that would have been produced by the unknown subfault 40.

The known signals produced by 28 and 52 are shown in Figure 4.4, where the blue bar represents the *reference time step* as defined in paragraph 3.2.2. In this case, we have:

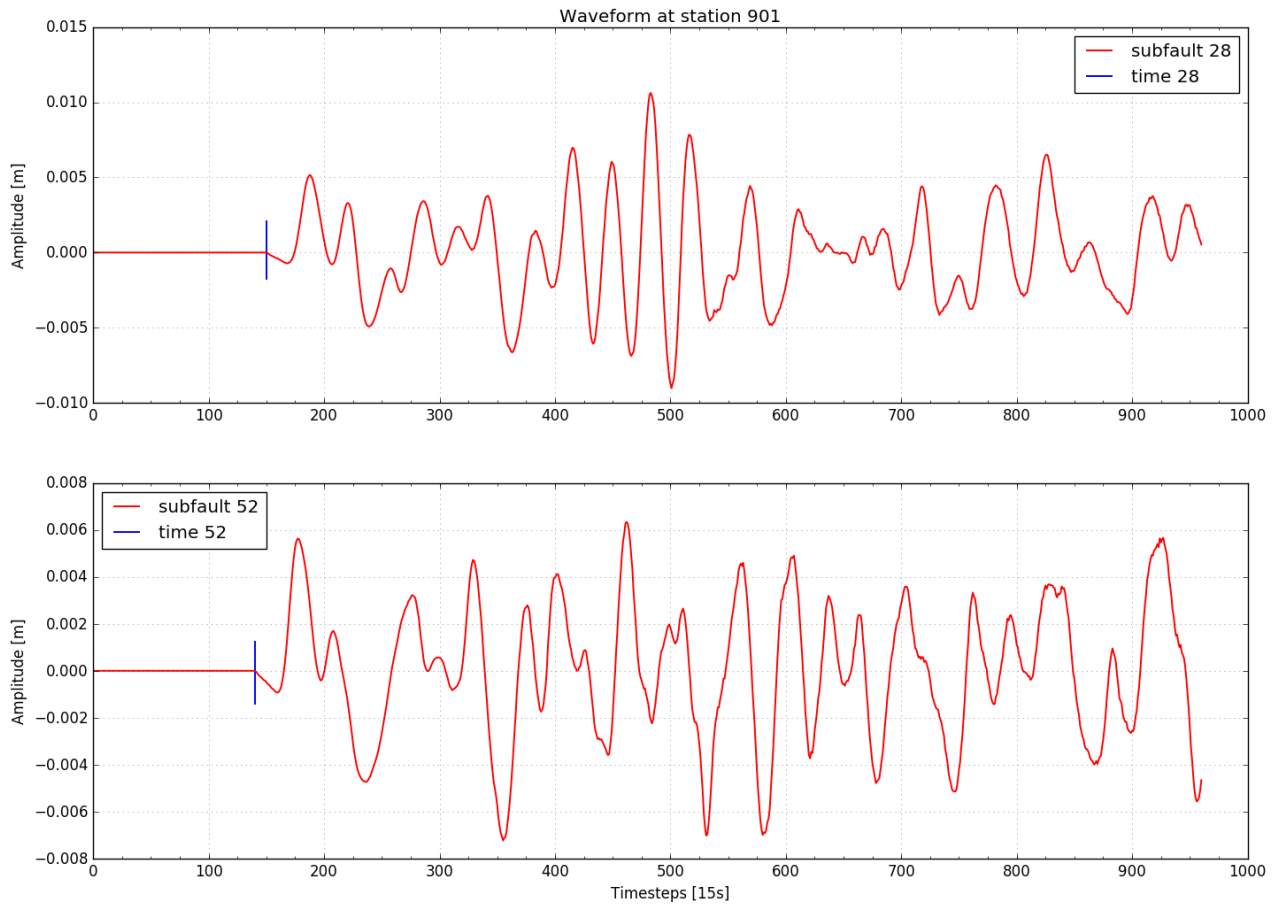- $t_{28} = 150$ time steps
- $t_{52} = 140$ time steps

Figure 4.4: The figure shows the known waveform signals of subfaults 28 and 52, together with the blue bar that marks the first non-zero value of the signal.

To build the signal of the subfault 40, we must account for two fundamental aspects:

- The reference time: The oscillations produced at the given station, by the three different subfaults, begin after a suitable amount of time, necessary for the tsunami wave to travel from the source to the considered station. Hence, we must define a proper reference time for the unknown subfault when building its signal;

- The oscillations: The oscillations produced at the given station vary with a certain continuity throughout the elementary sources (as analysed in chapter 3) and we have to define a proper interpolation/extrapolation operation to build the oscillations of the unknown subfault;

We take care of these two aspects in a separate way by defining two gradients and the target signal is built by merging the results of two linear expansions.

4.2.1 Time gradient

Given two known subfaults, the 28 and the 52 in this case, we define time gradient as the difference of reference time steps over the distance of the two subfaults:

$$gradt = \frac{t_{52} - t_{28}}{x_{52} - x_{28}}$$

Where x_{52}, x_{28} represents the position of the subfaults along the row.

The gradient is defined with an orientation as we take the first subfault along the row and we subtract it to the second.

In this way, we can compute the approximate time reference by means of a linear expansion starting from the first subfault:

$$t_{40} = t_{28} + gradt * (x_{40} - x_{28}) = 145 \; time \; steps$$

where x_{40} is the position of the target subfault along the row. We obtained a first estimate for t_{40}, which may need a little further correction, depending on the shift between the oscillations of signals 28 and 52.

4.2.2 Amplitude gradient

We then define a second gradient in terms of the amplitude of the oscillations. To this purpose, we consider only the oscillatory part of the signals, delimited by the blue bar in Figure 4.4.

Let f_{52} and f_{28} be the non-zero signals associated with subfaults 52 and 28 respectively. We then define the amplitude gradient as:

$$gradf = \frac{f_{52} - f_{28}}{x_{52} - x_{28}}$$

This is a point-to-point difference and, before computing it, the two signals are normalised in length and subjected to the same shifting procedure described in paragraph 3.2.2, to account for possible shifts between first oscillations. If a shift is required, hence a time reference of the two signals is re-defined, and t_{40} is properly corrected.

Therefore, we can write:

$$f_{40} = f_{28} + gradf * (x_{40} - x_{28})$$

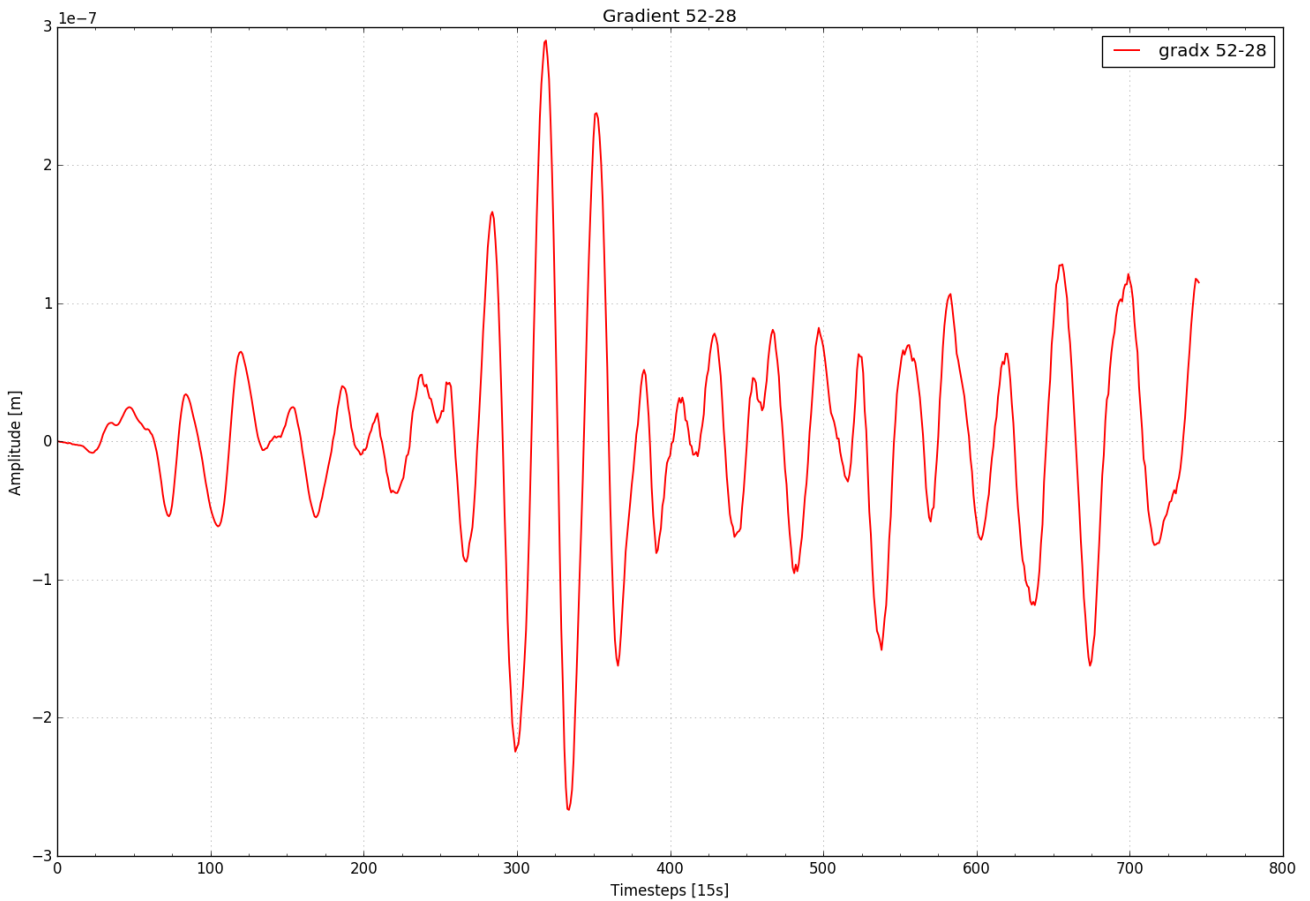An example of gradf for this sample case is given in Figure 4.5. Point-to-point

Figure 4.5. Point-to-point difference between the non-zero signals produced by subfaults 28 and 52.

difference between the non-zero signals produced by subfaults 28 and 52. As it can be noticed, the gradient is small within the few first hundred time steps, then it reaches instability as the signals become different.

At this point the target signal for subfault 40 is obtained by merging the oscillatory part f_{40}, with a suitable number of zeros given by t_{40}.
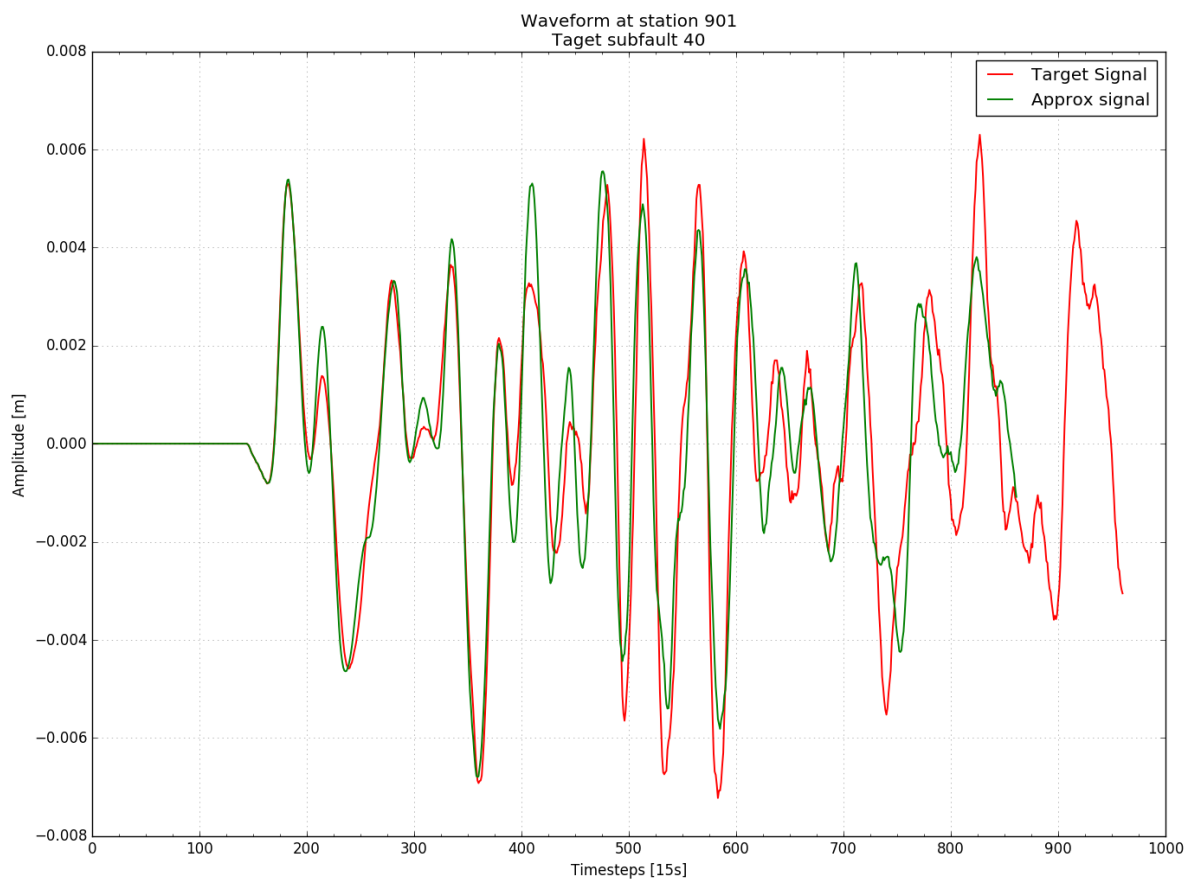
Figure 4.6 Comparison between the true signal produced by the subfault 40 at the station 901, with its approximation.

Figure 4.6 Comparison between the true signal produced by the subfault 40 at the station 901, with its approximation shows the comparison between the true forecasted signal for subfault 40 at station 901 and its approximation, built by using the known neighbour subfaults.

The approximate signal shows some inaccuracies, but it performs well in recovering the true reference time step, the frequency and the amplitude of the oscillations within the first few hundreds time steps.

This is a remarkable result in terms of optimization of the forecasting procedure as we managed to obtain three useful signals by accessing the database only twice, for subfault 28 and 52.

In the next paragraphs, we will generalise this approach over the 45 matched subfaults, used to produce the reference forecast, and we will try to approximate it by using a smaller number of subfaults from the database.

4.2.3 Exceptions in the building process

Every time an amplitude gradient is computed between two known subfaults, the cross-correlation is computed over the first oscillations to account for a potential shift, for every station available.

If the normalised cross-correlation maximum is below the threshold value of 0.5, neither amplitude or time gradients are defined between the two subfaults for the considered station. In this case, the target signal is estimated as the simple mean of the two known signals.

Adopting a simple mean in building an unknown signal coincides with performing no building at all and just increasing the amplitude of the known signals. When building a forecast, this means only accounting for the conservation of the seismic moment without any further operation.

4.3   The Heart of the work: building the forecast

In this chapter the generalization of the building process over the fault plane is presented.

To understand the functioning of the algorithm, let us suppose we have a certain amount of missing subfaults, underlying a tsunamigenic event as shown in Figure 4.7: The reference seismic event is shown over the tessellation. Some subfaults, underlying the seismic event area, are supposed to be missing for this example. The building process is applied over the fault area to fill the relevant vacancies:
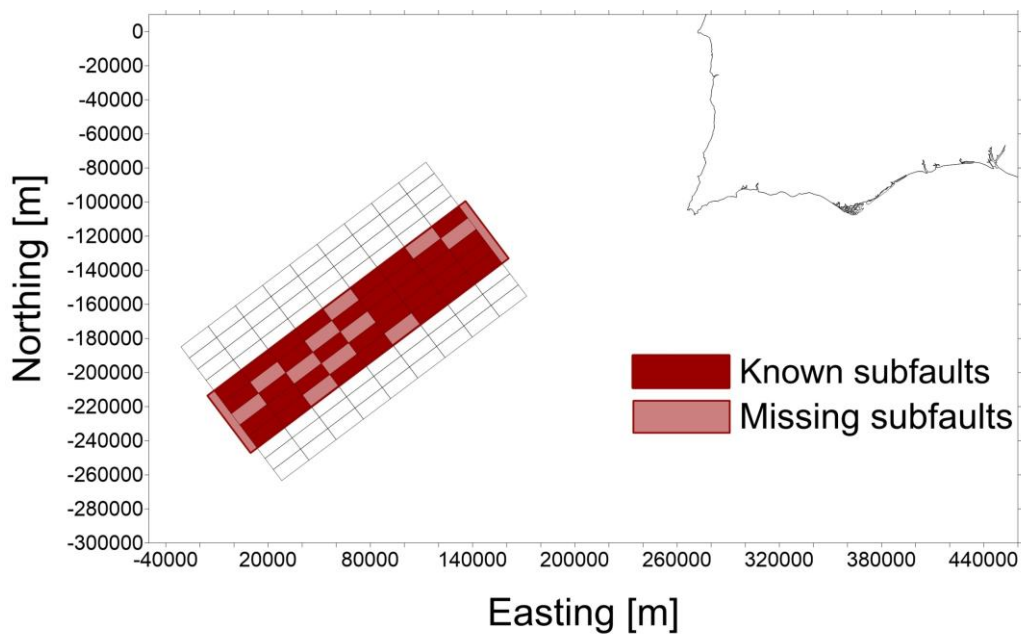
Figure 4.7: The reference seismic event is shown over the tessellation. Some subfaults, underlying the seismic event area, are supposed to be missing for this example. The building process is applied over the fault area to fill the relevant vacancies.

The reference forecast is produced by summing over all the complete set of 45 subfaults from the database. Our objective is then to estimate the waveform signals, associated with the missing subfaults, and to produce an approximate version of the original forecast.

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Hence, given the initial subfault selection, the building algorithm works as follows:

- <u>Computes the gradients</u>: every single row is scanned to build time and amplitude gradients with the available subfaults. In this case, we make use of the known subfaults to define the differences along the rows.
- <u>Fills the vacancies</u>: every vacant subfault is filled by linear interpolation or extrapolation, depending on which is the nearest subfault over which a gradient has been defined;
- <u>Synthesises the waveforms</u>: once that all vacancies have been filled, the approximate forecast is produced by summing over all contributions, both the ones from the database and the new ones;

Concerning the results of this procedure, two questions arise:

- Do we receive real benefit from replacing the vacancies with approximate signals?
- How many subfaults do we need to find a compromise between accuracy and time needed to access the database?

To answer these questions a series of training tests have been designed as follows:

being N_{max} the maximum number of subfaults, necessary to cover the area of interest, with N_{max} = 45 for the reference event, we select increasing numbers of subfaults, starting from $N_{min} = 10$.

For fixed N, we then select different arrangements of the same amount of known subfaults over the fault plane. Once a configuration has been fixed, we evaluate the performance of the building algorithm as follows:

- On one side, we use the N selected subfaults without any further processing. The amplitude of their signals is augmented to guarantee the conservation of seismic moment and the approximate forecast is produced simply by summing over the available signals;

- On the other side, we apply the building algorithm using the N subfaults available from the given configuration. Hence, starting from N, we get to N_{max} by performing interpolation and extrapolation to fill all the vacancies throughout the interested part of the fault. Once that computation has been carried on, the approximate forecast is obtained by summing over the known subfaults and the approximated ones where needed;

The performance of the algorithm is then evaluated by means of the <u>relative error</u> with respect to the reference forecast. We shall see that the error computed with the building process is smaller than the error computed without building process.

For fixed N, three kinds of configurations have been designed.

4.3.1   RANDOM1 mode: A completely random selection

The first designed configuration is driven by casualty. Once we have fixed the number of subfaults N, they are picked up randomly over the fault plane underlying the target event. The only constraint is that at least two subfaults must be selected from each row, to let the gradients be computed. Example of this configuration are shown in Figure 4.8:
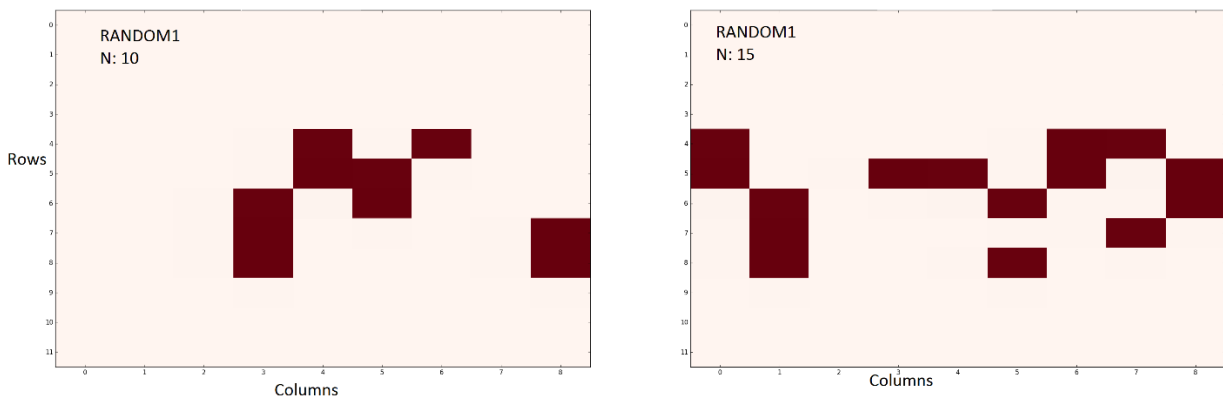
Figure 4.8: This figure represents an example of a group of subfaults (the red ones), selected following the RANDOM1 criterion. Subfaults are selected randomly with the only constraint to be at least two for each row underlying the seismic fault considered.

4.3.2   RANDOM2 mode: A driven selection with some casualties

The second designed selection still presents some randomness. The subfaults are selected randomly within a single row per time. Once satisfied the constraint of having at least two known subfaults in each row, the selection is focused on the

most superficial rows. Hence, the highest number of subfaults, is randomly gathered in the higher part of the considered fault. Examples at increasing N are shown in Figure 4.9:
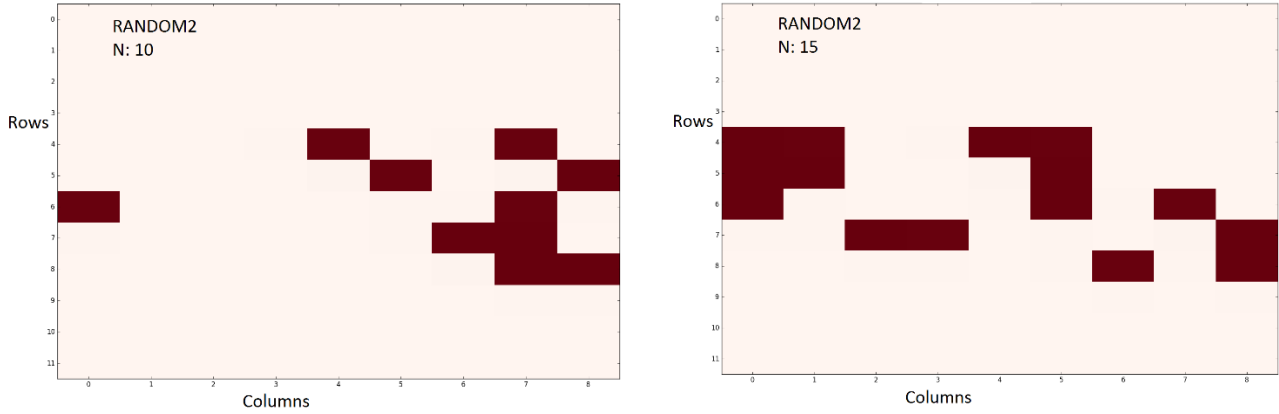

Figure 4.9: This group of subfaults is selected following the RANDOM2 criterion. On the left the minimum number of subfaults, i.e. 10, is selected, guaranteeing two subfaults for each row considered. On the right, 15 subfaults are selected by privileging the most superficial rows available.

4.3.3   ACCURATE SELECTION mode: an ad-hoc built selection

In this case, an accurate selection has been designed. The minimum number of subfaults is used to guarantee at least two subfaults in each row and contemporarily to fill the most lateral columns of the reference area. By doing this, we try to minimize extrapolation in favour of interpolation, which is safer in terms of accuracy, as the gradient is modulated by distances smaller than the distance between the subfaults used to build it.

When N is bigger than N_{min}, we start populating the most superficial rows and then we gradually reach the lowest rows, as shown in Figure 4.10. This selection is tested only with the building process active.
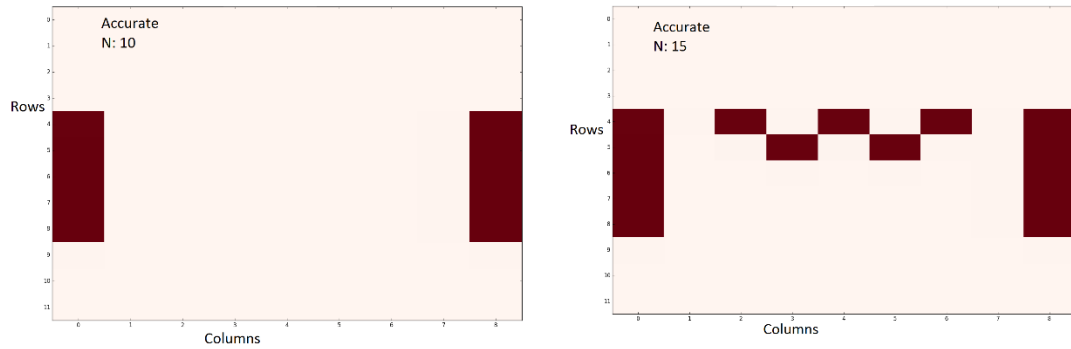
Figure 4.10: On the left the arrangement of 10 subfaults in the ACCURATE mode is shown. The subfaults are placed at the external columns to minimise extrapolations in favour of interpolations. When more than 10 subfaults are given, as shown on the right, the subfaults are placed in the middle of the area to minimise distances between known subfaults at each row, starting from the higher ones.

N.B. If the configuration is RANDOM1 or RANDOM2, the whole process of comparison between approximated forecasts, either with building or without building, is repeated 10 times at fixed N. This is done to have a better understanding of the performance of the algorithm upon a random selection of the subfaults.

In the next paragraph, general results are presented.

4.4 General results for the reference event

In these computations, all the available stations have been considered. The general results are given in form of scatter plots for each of the three configurations considered (i.e. RANDOM 1, RANDOM2 and ACCURATE selection modes).

Within a single scatter plot, each dot represents the average relative error committed at given N with respect to the reference forecast. Each average relative error value has been obtained upon averaging over the errors committed for every single station available, at given N.

Hence a single dot represents the mean behaviour of an approximate forecast with respect to the reference one.

For both RANDOM1 and RANDOM2 configurations, the results obtained with the ACCURATE selection mode are shown as a comparison.

The results are shown from Figure 4.11 to Figure 4.14.
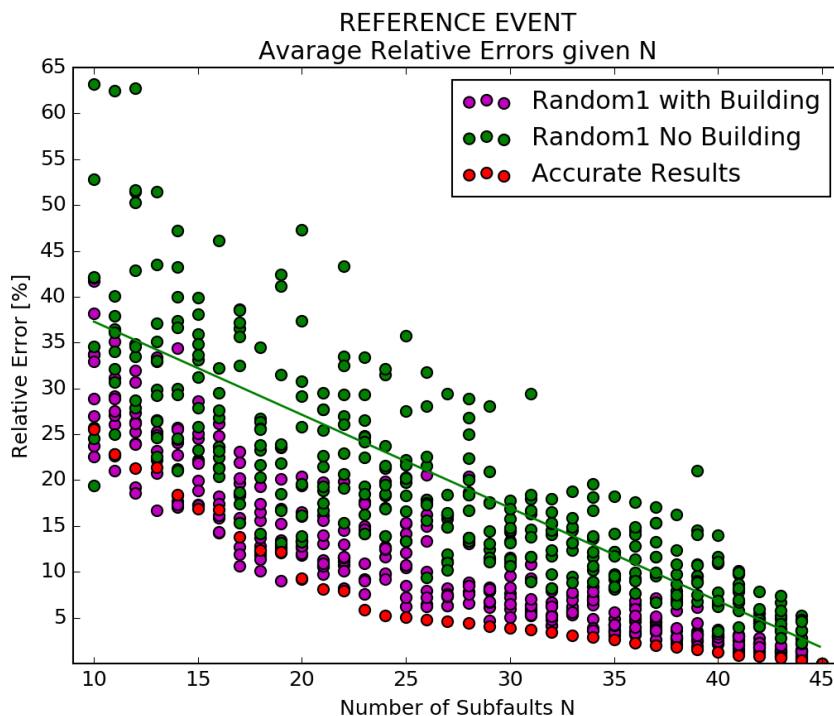
Figure 4.11: Results concerning the RANDOM1 configuration, varying the number of subfaults available from 10 to 45. Each dot represents the average error in a single iteration of the RANDOM1 configuration and associated N. Green dots represent the errors associated with the RANDOM1 selection mode without using the building algorithm. Purple dots represent the error obtained using the same selection mode with the building algorithm implemented. The ACCURATE mode results (red dots) are shown for comparison.
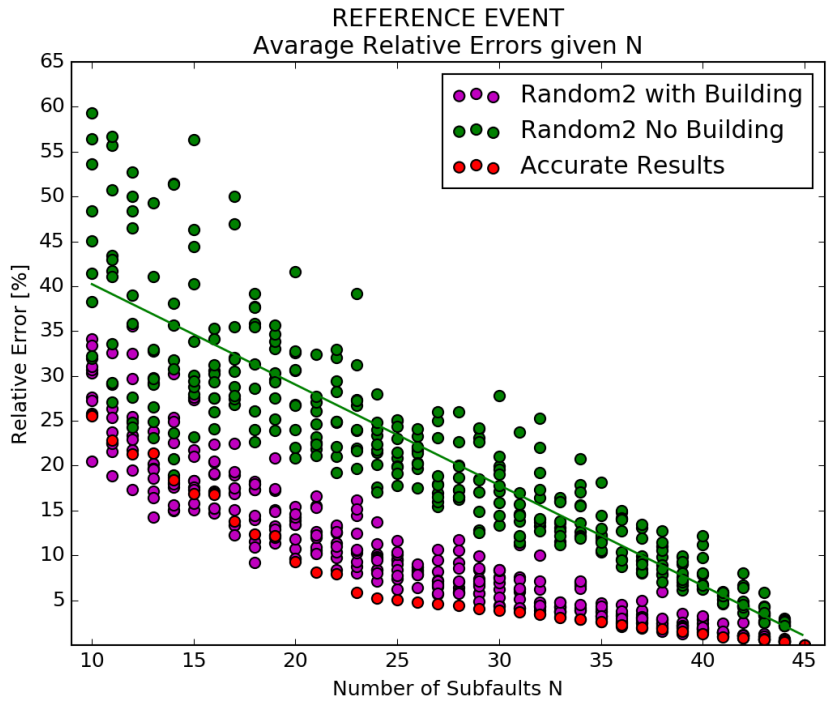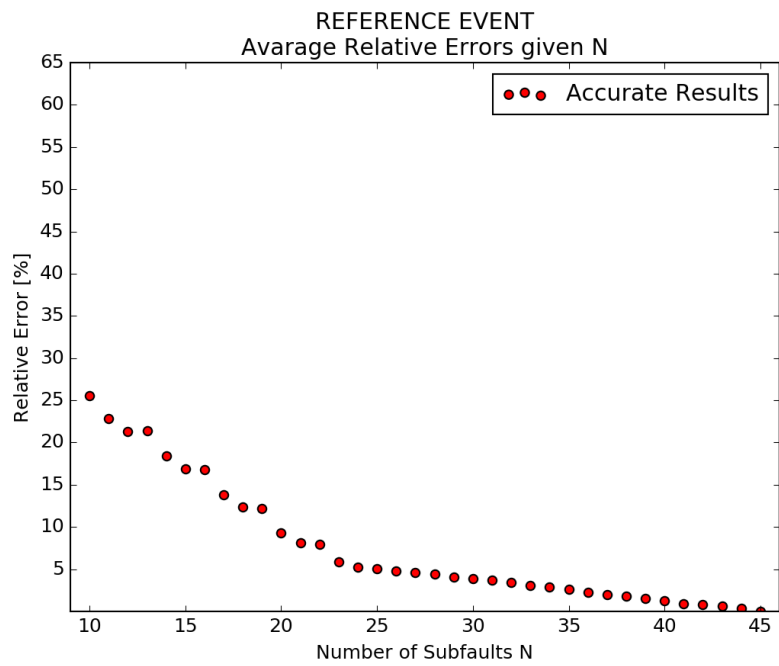
Figure 4.12: Results concerning the RANDOM2 configuration, varying the number of subfaults available from 10 to 45. Each dot represents the average error in a single iteration of the RANDOM2 configuration and associated N. Green dots represent the errors associated with the RANDOM2 selection mode without using the building algorithm. Purple dots represent the error obtained using the same selection mode with the building algorithm implemented. The ACCURATE mode results (red dots) are shown for comparison.

Figure 4.13: Results concerning the ACCURATE selection mode, varying the number of subfaults available from 10 to 45. Each dot represents the average error over the whole signals, committed at given N.
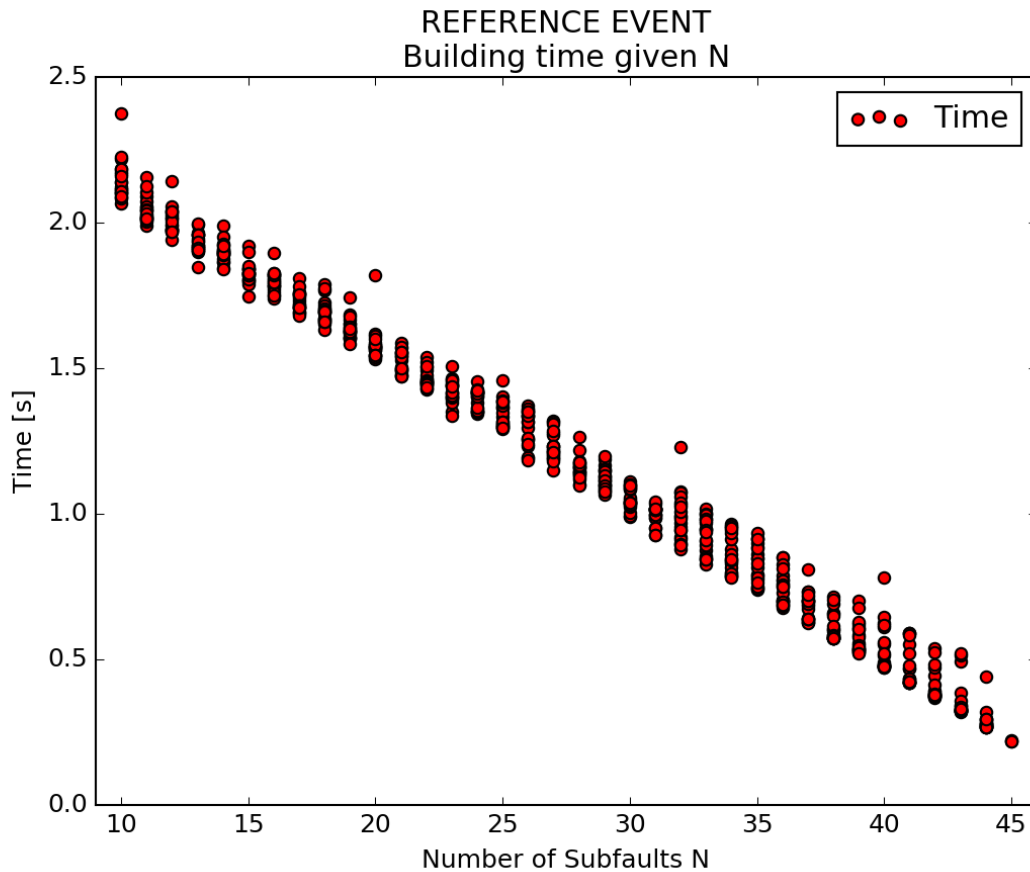
Figure 4.14: Scatter plot representing the time needed to perform a complete run of the building algorithm for a given N.

We shall highlight some remarkable features within these general results.

By looking at Figure 4.12 and Figure 4.11, we can see that extracting random subfaults and creating a forecast without applying the building forecast, leads to the worst results in terms of average relative error.

In the same figures 4.11 and 4.12, we can see that the application of the building procedure for the randomly selected subfaults induces a remarkable improvement in terms of relative error.

We can see that the results obtained with the ACCURATE selection mode, shown in Figure 4.13, are the best ones compared to the results obtained with the other selection modes, either with or without the building procedure. In fact, for N around 25, which is almost half of the subfaults available, the average relative error flattens around 5%.

Figure 4.14 shows the computational time required to perform the building procedures at given N. By comparing it with the results obtained within the ACCURATE selection mode, we can achieve a remarkable conclusion.

The time required to rebuild all the vacant subfaults starting from N = 20, is in the order of seconds and, with the same number of subfaults, the error committed in approximating the reference forecast is around 5%, on using half of the subfaults available.

Hence, by paying an inaccuracy of 5% in the final forecast, we can produce forecasted waveform signals by accessing the database half of the times, around 20, with respect to the number of accesses needed to produce the reference forecast. Therefore, accepting a small inaccuracy of 5% over the whole forecasted signal, we can halve the time required to produce the expect waveform signals.

4.5   Two additional case studies

Analogous results with some peculiar features have been obtained by shifting the reference event upward and downward the fault plane, as shown in Figure 4.15.
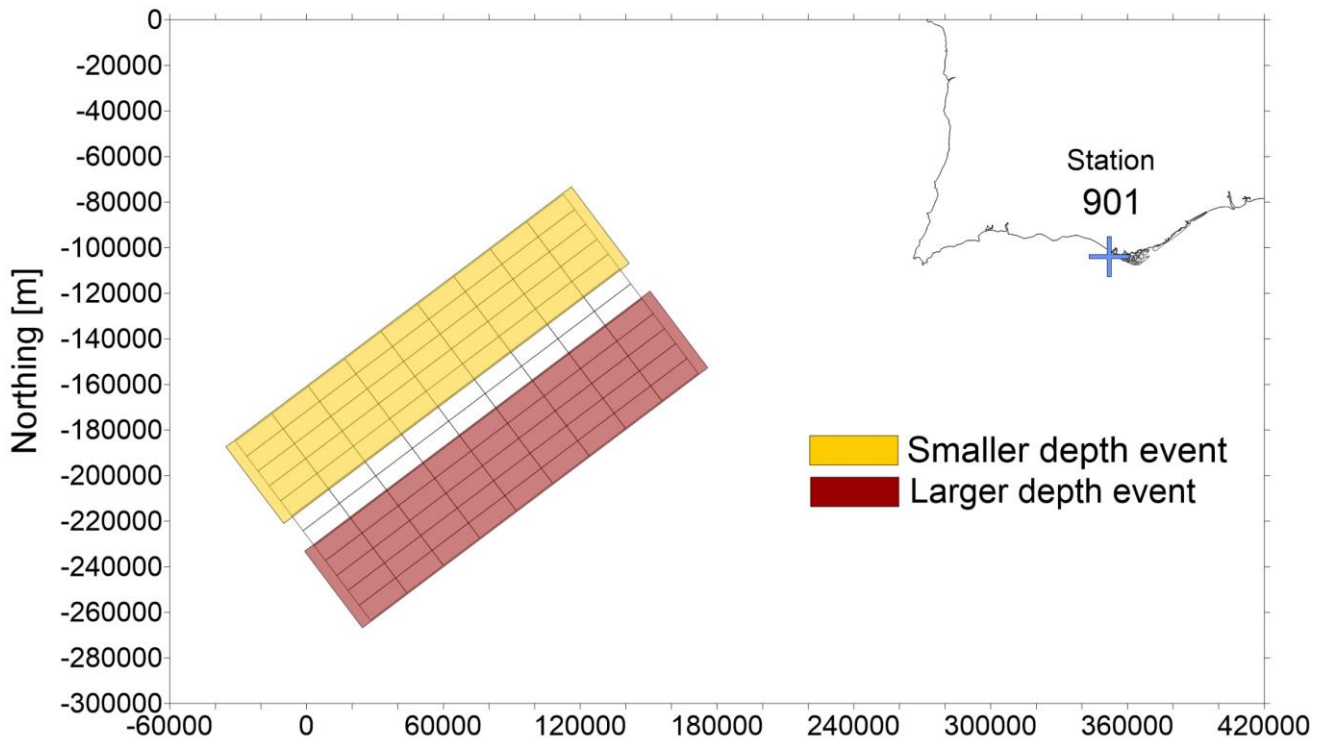
Figure 4.15: Two more reference events have been considered, by shifting the previous event upward and downward the fault plane.

In these two additional cases the same seismic parameters of the reference event have been considered, hence the same Mw as well as length and width of the fault as shown in Table 4.1.

4.5.1 Event located at smaller depth

In this case the reference fault has been shifted upwards with respect to the reference one. Hence, we are considering the most superficial unitary sources available from the database, as shown in Figure 4.15. As previously presented, the results are given in terms of average relative errors with respect to the reference forecast from Figure 4.16 to Figure 4.19.
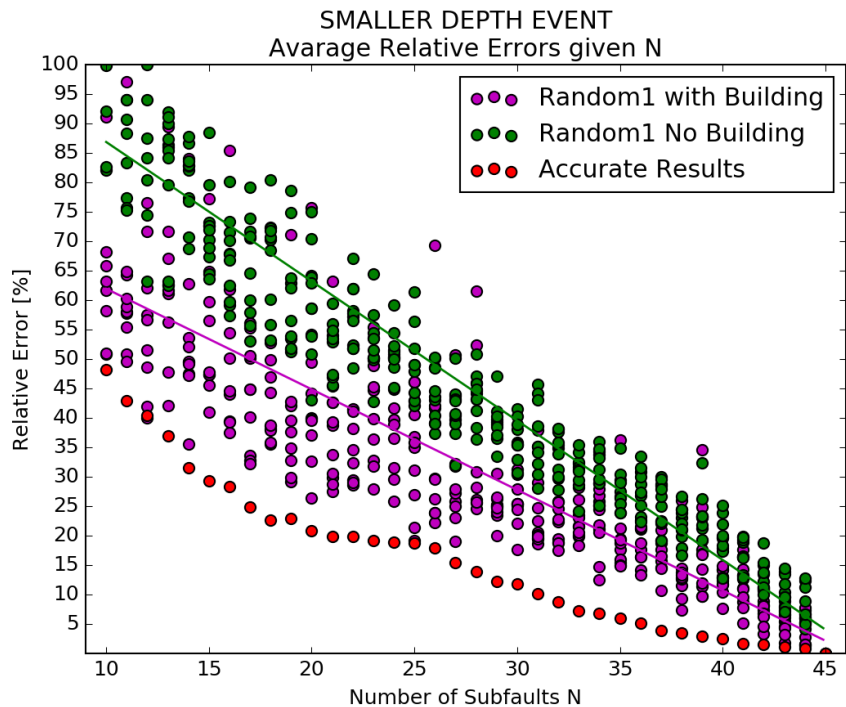
Figure 4.16: The figure represents the relative errors committed in the approximate forecast using the RANDOM1 selection mode for the smaller depth event. Green dots represent the average relative errors committed without using the building procedure, but only accounting for the conservation of seismic moment. Purple dots represent the error committed with the building procedure. Green and purple straight lines interpolate the green and purple dot points, to underline the improvement obtained on using the building procedure. The red dots represent the results obtained with the ACCURATE selection mode.
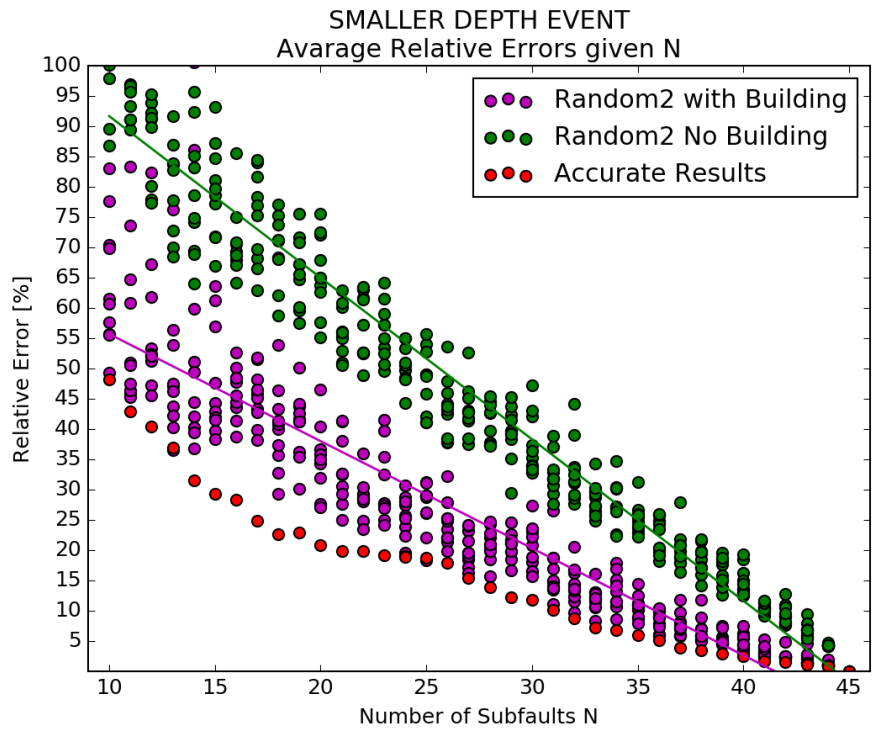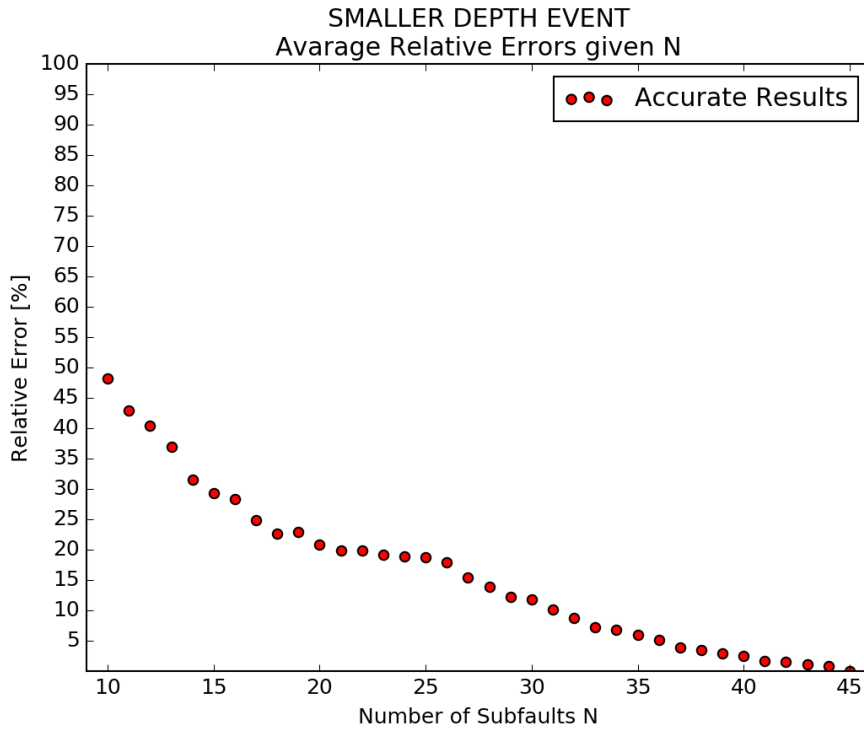
*Figure 4.17: The figure represents the relative errors committed in the approximate forecast using the RANDOM2 selection mode for the smaller depth event. Green dots represent the average relative errors committed without using the building procedure, but only accounting for the conservation of seismic moment. Purple dots represent the error committed with the building procedure. Green and purple straight lines interpolate the points, to underline the improvement obtained on using the building procedure. The red dots represent the results obtained with the ACCURATE selection mode.*

Figure 4.18: The figure represents the relative errors committed in the approximate forecast by using the ACCURATE selection mode over the uppermost event.
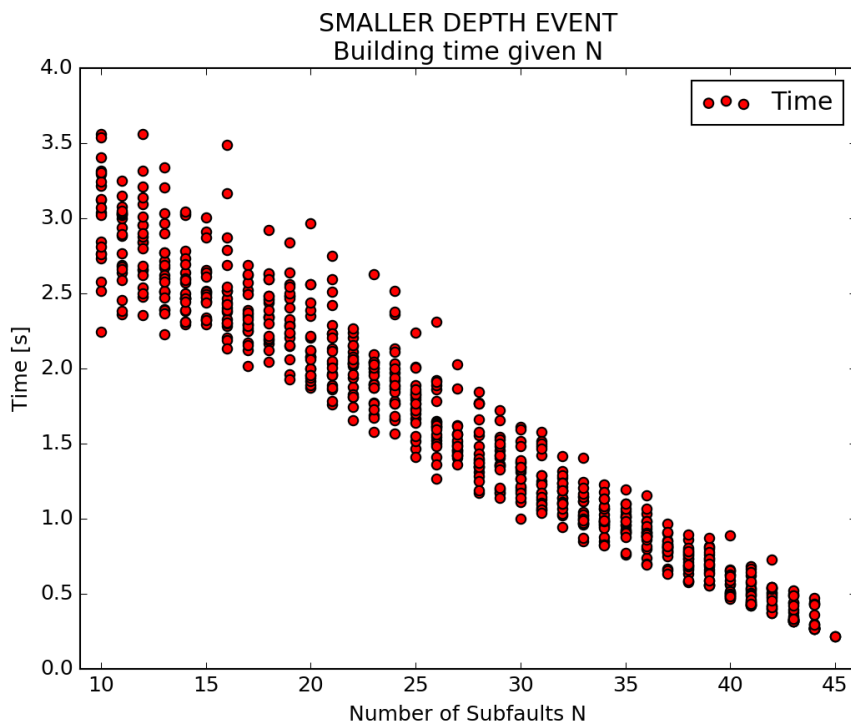
Figure 4.19: This figure represents all the computational times required to perform a single run of the building algorithm for a given N. We can see that using only half of the 45 subfaults available, the time required to produce an approximate forecast is around a few seconds.

We can outline some remarkable features present in these general results, concerning the uppermost event. The same trend seen in the reference case is obtained. By looking at Figure 4.16 and Figure 4.17, we can see that the adoption of the building algorithm induces remarkable improvements in the average relative errors.

Results obtained using the ACCURATE selection mode, together with the building algorithm, as shown in Figure 4.18, still are best ones compared to the others.

Even though the building procedure determines an overall improvement of the results, with the ACCURATE mode being the best performing case, we can see that errors for this uppermost case, are remarkably higher than errors obtained for the reference middle depth case, shown in Figure 4.11, Figure 4.12 and Figure 4.13.

4.5.2   Event located at larger depth

In this case, the reference event has been shifted downwards with respect to the reference case, hence we are working with the deepest sources available within the database, as shown in Figure 4.15. The results in term of average relative errors are given from Figure 4.20 to Figure 4.23.
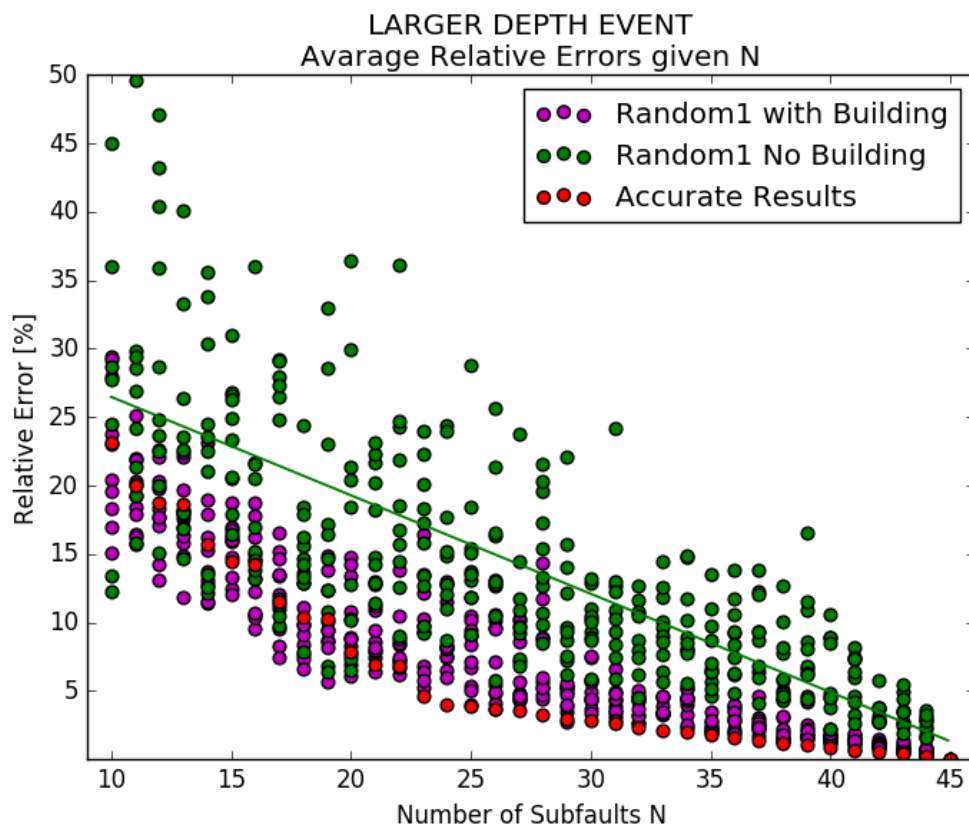

Figure 4.20: The figure represents the relative errors committed in the approximate forecast using the RANDOM1 selection mode over the larger depth event. Green dots represent the average relative errors committed without using the building procedure, but only accounting for the conservation of seismic moment. Purple dots represent the error committed with the building procedure. Green straight line interpolates the green dot points, to underline the improvement obtained on using the building procedure. The red dots represent the results obtained with the ACCURATE selection mode.
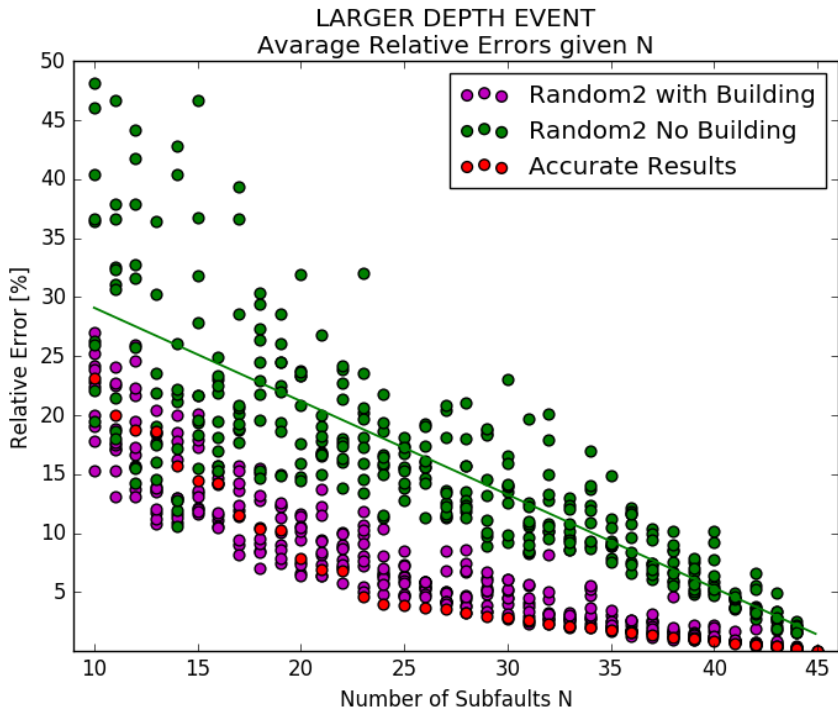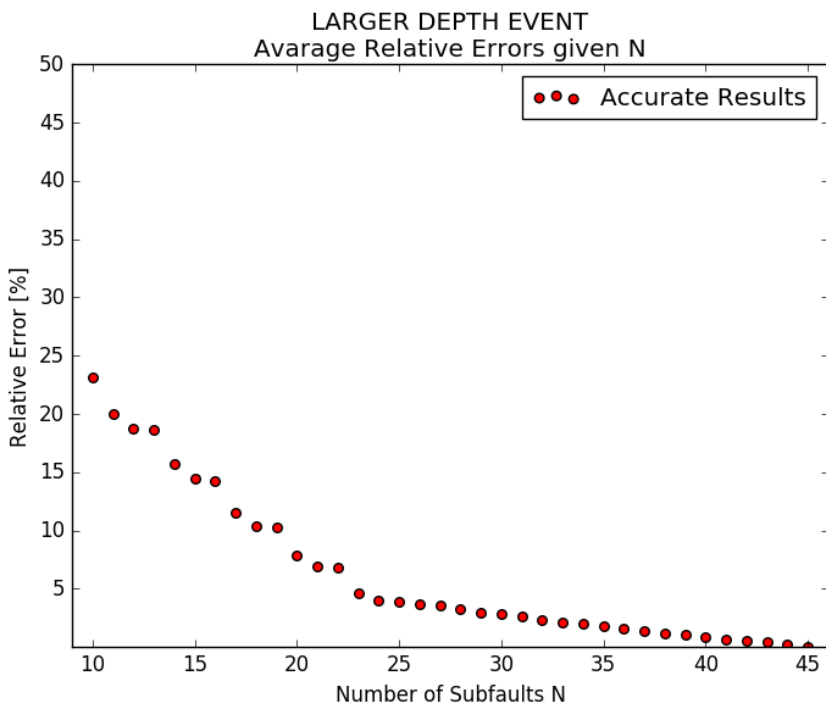
Figure 4.21: The figure represents the relative errors committed in the approximate forecast using the RANDOM2 selection mode over the larger depth event. Green dots represent the average relative errors committed without using the building procedure, but only accounting for the conservation of seismic moment. Purple dots represent the error committed with the building procedure. Green straight line interpolates the green dot points, to underline the improvement obtained on using the building procedure. The red dots represent the results obtained with the ACCURATE selection mode.

Figure 4.22: The figure represents the relative errors committed in the approximate forecast using the ACCURATE selection mode over the larger depth event.
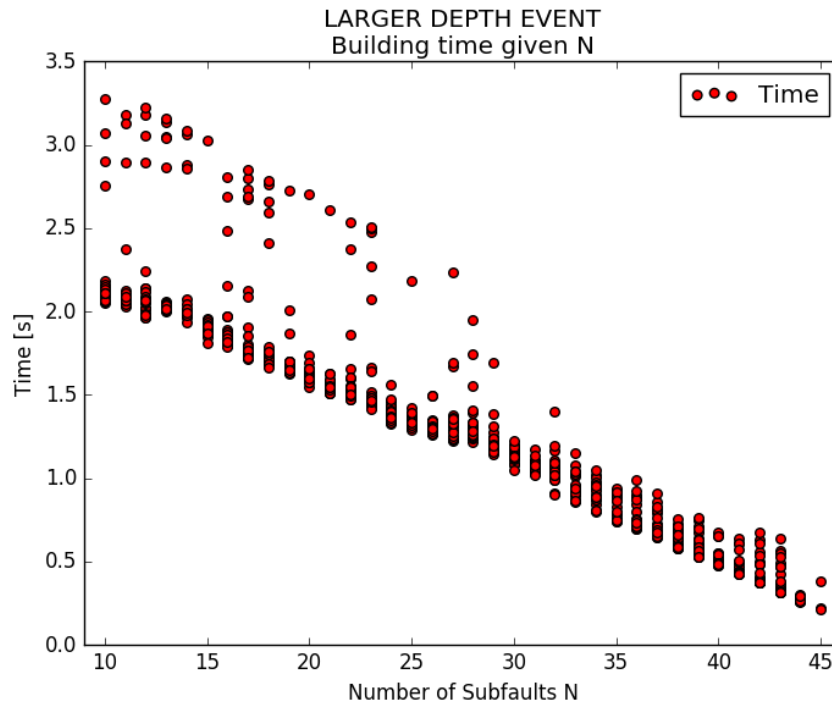
Figure 4.23: This figure represents all the computation times required to perform a single run of the building algorithm given N. We can see that using only half of the 45 subfaults available, the time required to produce an approximate forecast is around a few seconds.

The results obtained in this case present the general trend that has been seen in the previous two case studies. If we look at Figure 4.20 and Figure 4.21, we can see that the adoption of the building procedure determines strong improvements in terms of average relative errors.

The results obtained with the ACCURATE selection mode are the best ones, since the average relative error flattens under 5% when N approaches 20/25 available subfaults, as shown in Figure 4.22.

Compared to the other two case studies, this event located at depth shows the best results in terms of accuracy of the forecast, at given N. The uppermost event is the worst event in terms of accuracy of the approximated forecast, as it requires larger values of N to reach the same degree of accuracy, obtained for deeper events.

The comparison is straightforward by looking at Figure 4.13 (reference event), Figure 4.18 (uppermost event) and Figure 4.22 (event located at larger depth).

This results could suggest that the optimal resolution, required to optimize the accuracy of the forecast produced with a given number of subfaults, does not require the unitary sources to be evenly-spaced throughout the whole fault plane. In fact, we are seeing that, given a fixed number of available subfaults N, the accuracy of the associated approximate forecast, varies depending on the depth of the considered event.

This major interesting feature is better investigated in the next chapter.

5 Focus on the stations with extreme elevations

We shall now explore in more detail the general results presented in the previous chapters. The work in this thesis aims at optimising real-time forecasting procedures for tsunami early warning systems. To this regard, a satisfactory approximation of stations presenting extreme elevations is of crucial importance.

In the next sections, we will focus on a meaningful subgroup of stations selected from the available ones. In the first part of the chapter, results are presented in terms of average relative errors. Together with these results, plots focusing on the extreme elevations obtained at each station are provided.

In the second part of the chapter, two events are considered: the uppermost event and the one located at the largest depth. In this case, only one single station has been selected for each of these two events, i.e. the station with the highest elevation value given by the reference forecast. The degree of accuracy in producing the associated waveform signal and the extreme value is quantified.

5.1   Top 50 stations

In these analyses, the uppermost event, the initial reference event and the deepest event have been considered.

For each event, only the stations that provide the 50 highest and lowest amplitude values, according to the respective reference forecast, are taken into consideration. In this case, we want to check the accuracy achieved in approximating these extreme values.

5.1.1   Smaller depth event

Figure 5.1 shows the location of the stations that produced the 50 highest and lowest amplitudes for the uppermost event. As we can see, the selected stations are located both at the Portuguese coasts and at coastal areas of north-western Morocco.
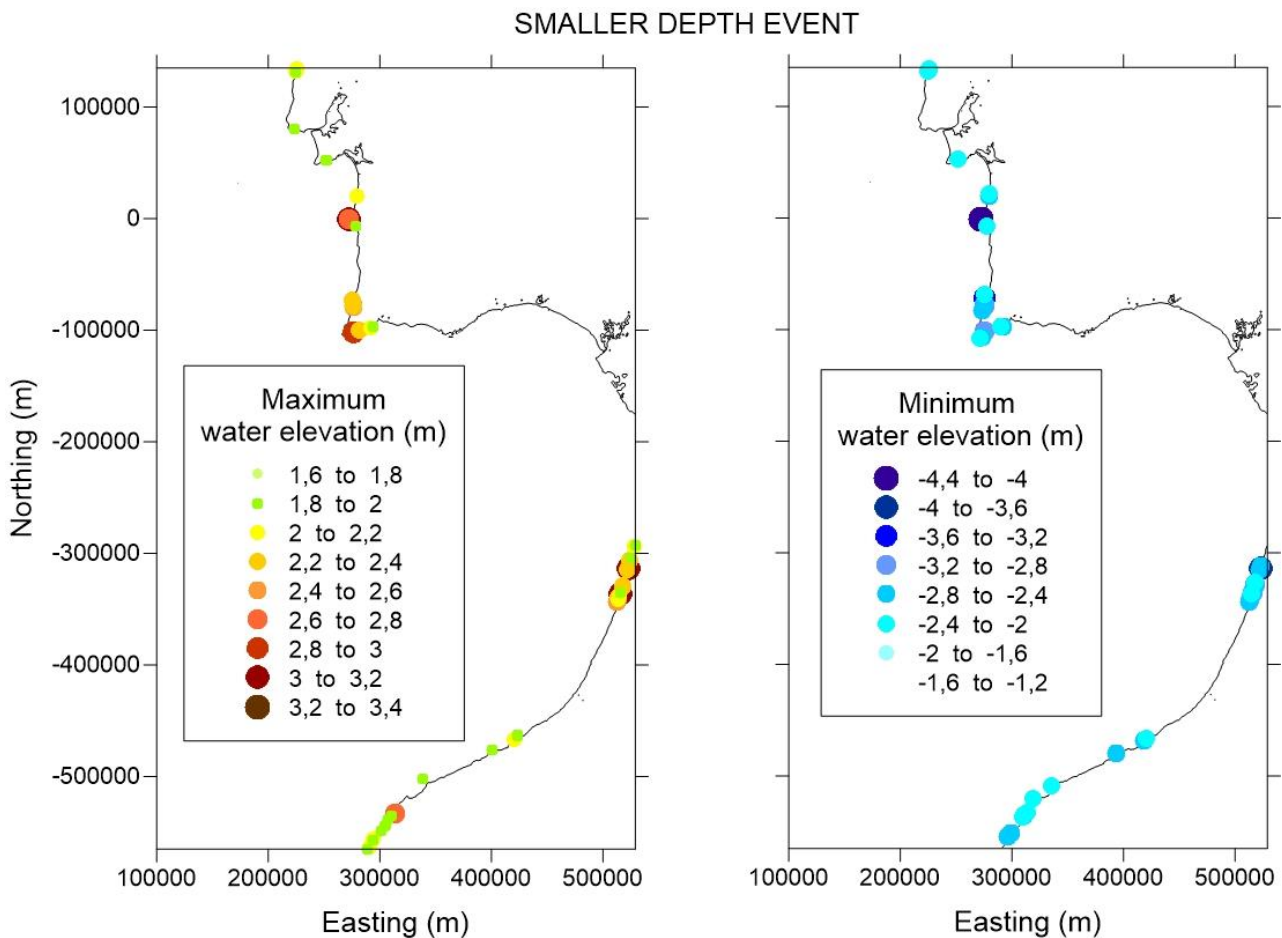
Figure 5.1: On the left, the 50 stations that produced the highest amplitude value in the reference forecast are shown. On the right, the ones that produced the lowest 50 elevation values.

As we have done in the previous chapter, the results in terms of average relative errors, for the stations considered, are shown from Figure 5.2 to Figure 5.4.
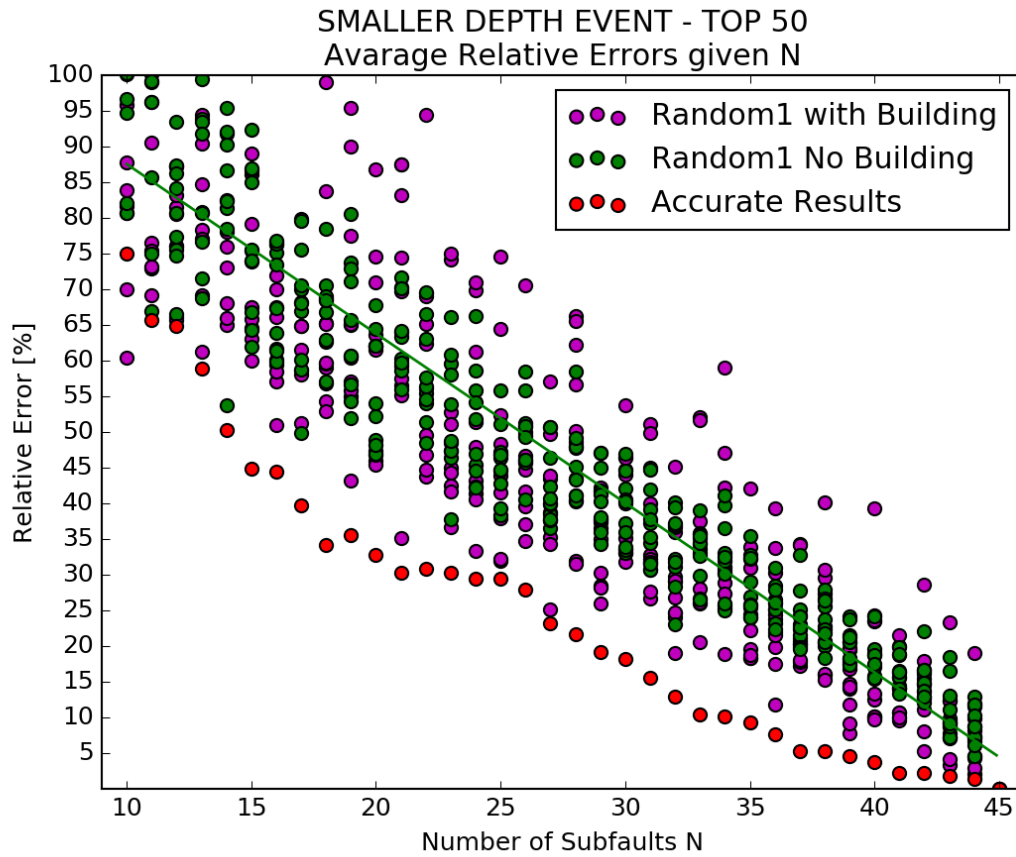

Figure 5.2: The scatter plot shows the relative error, averaged over the available stations, for a given number of subfaults N, adopting the RANDOM1 selection mode. The straight green line interpolates the relative errors associated with the approximation without building algorithm (green dots). As we can see, for this superficial event with RANDOM1 selection mode (purple dots), the building algorithm presents scattered performances with high errors and, only with increasing N, it starts performing better than the approximation obtained without building process. The results obtained with the ACCURATE selection mode are shown for comparison (red dots).
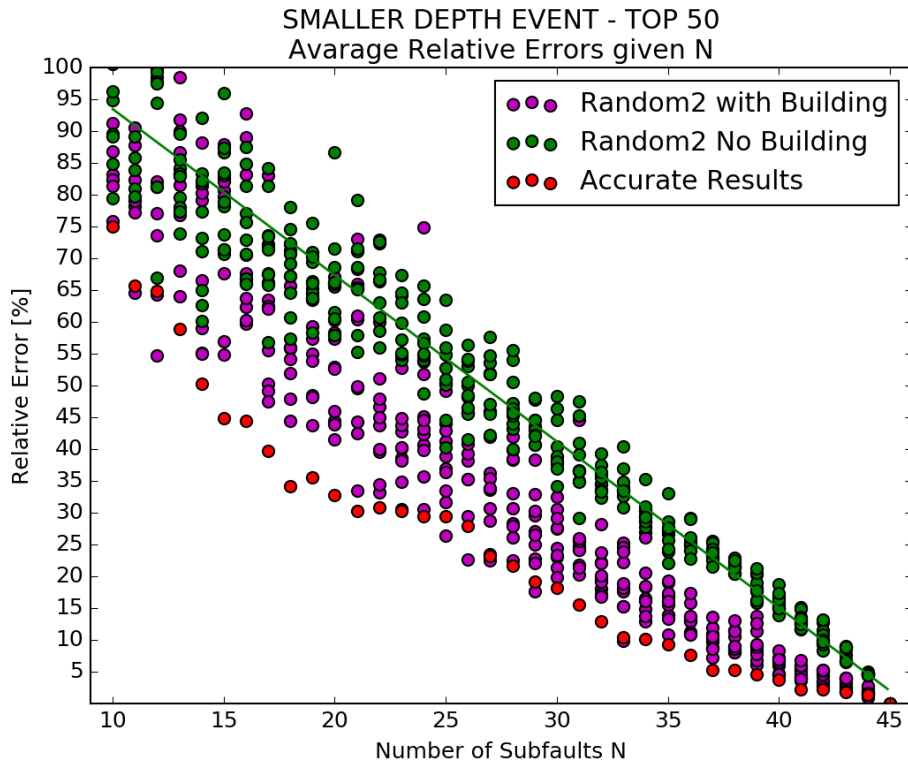
Figure 5.3: The graph shows the error committed with the RANDOM2 selection mode. The straight green line interpolates the errors associated with no building procedure (green dots). The building algorithm shows a remarkable improvement in approximating the reference signals (purple dots). The ACCURATE selection mode results (red dots) are shown for comparison.
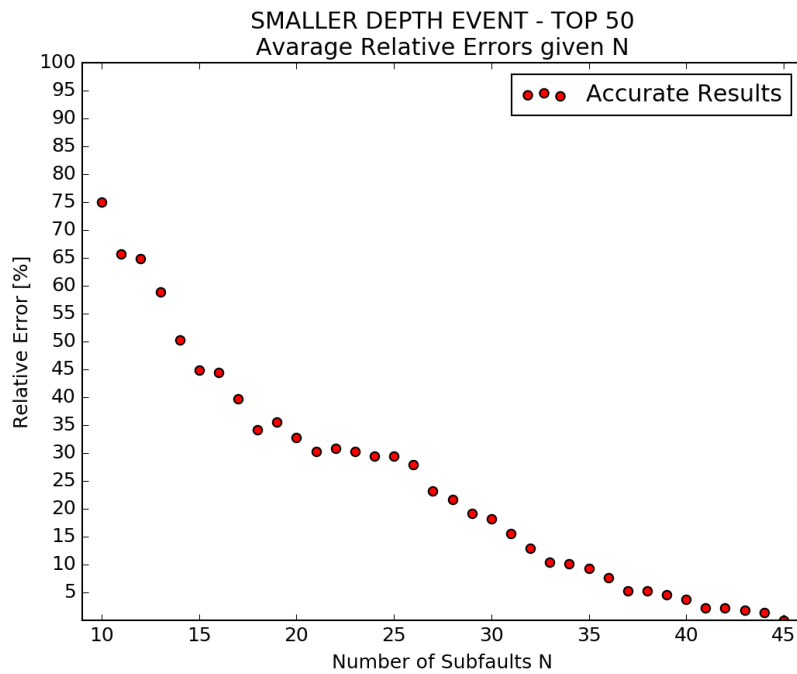

Figure 5.4: Errors associated with the ACCURATE mode at given N are shown. This mode gives the best results with respect to the RANDOM1 and RANDOM2 selection modes.

The results obtained in this case, follow the general trend highlighted in the previous chapter for the available stations. The building algorithm induces an improvement in the estimation of the target signals, with some difficulties within the RANDOM1 selection mode for this uppermost seismic event, as can be seen in Figure 5.2.

Within RANDOM2 selection mode, the results sharply improve if the building procedure is adopted (see Figure 5.3), but the ACCURATE mode constantly presents the lowest errors as shown in Figure 5.4.

Another series of scatter plots has been defined to better understand the quality of the approximation for these extreme selected stations.

From Figure 5.5 to Figure 5.8, the approximated maximum, obtained for each available station, is plotted against the reference maximum for the same station, at given N.

By looking at these graphs, the accuracy in the approximation of the maximum of a signal can be easily evaluated.

From Figure 5.9 to Figure 5.12, the same kind of scatter plot is furnished for the lowest values.

N.B.1 In these scatter plots, from Figure 5.5 to Figure 5.12, each circle represents a single station and its area represents the average error committed over the whole signal at that station. Hence, a single circle in the scatter plot contains multiple information:

- The <u>area</u> of the circle gives information about the accuracy of approximation of the whole signal;
- The <u>position</u> of the circle gives information about the accuracy of the approximation of the extreme value of the signal;

N.B.2 The results shown from Figure 5.5 to Figure 5.12, concern only the ACCURATE selection mode that is the best performing selection mode.
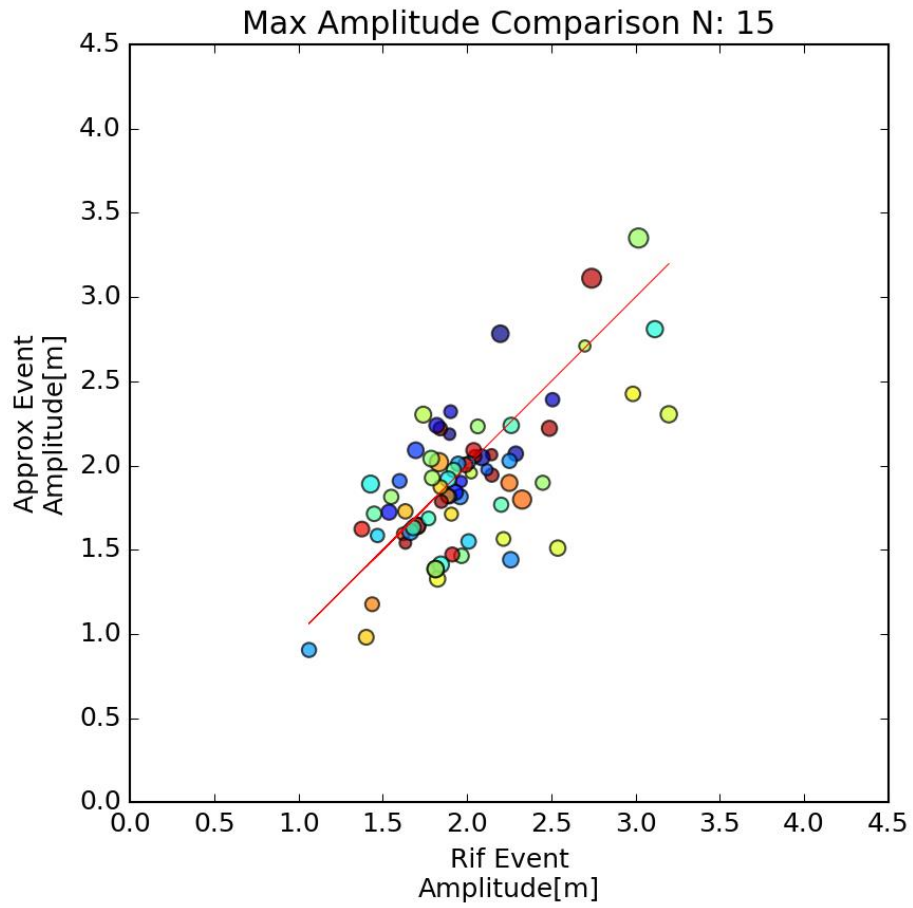
Figure 5.5: Scatter plot of the maximum approximated values against the maximum values given from the references. Each circle represents the maximum value estimated at a single station. The red straight line represents the perfect evaluation of the reference maximum. The area of the circle represents the relative error committed over the whole associated signal. In this case, with N = 15 for the uppermost event, values are still spread around the reference line.
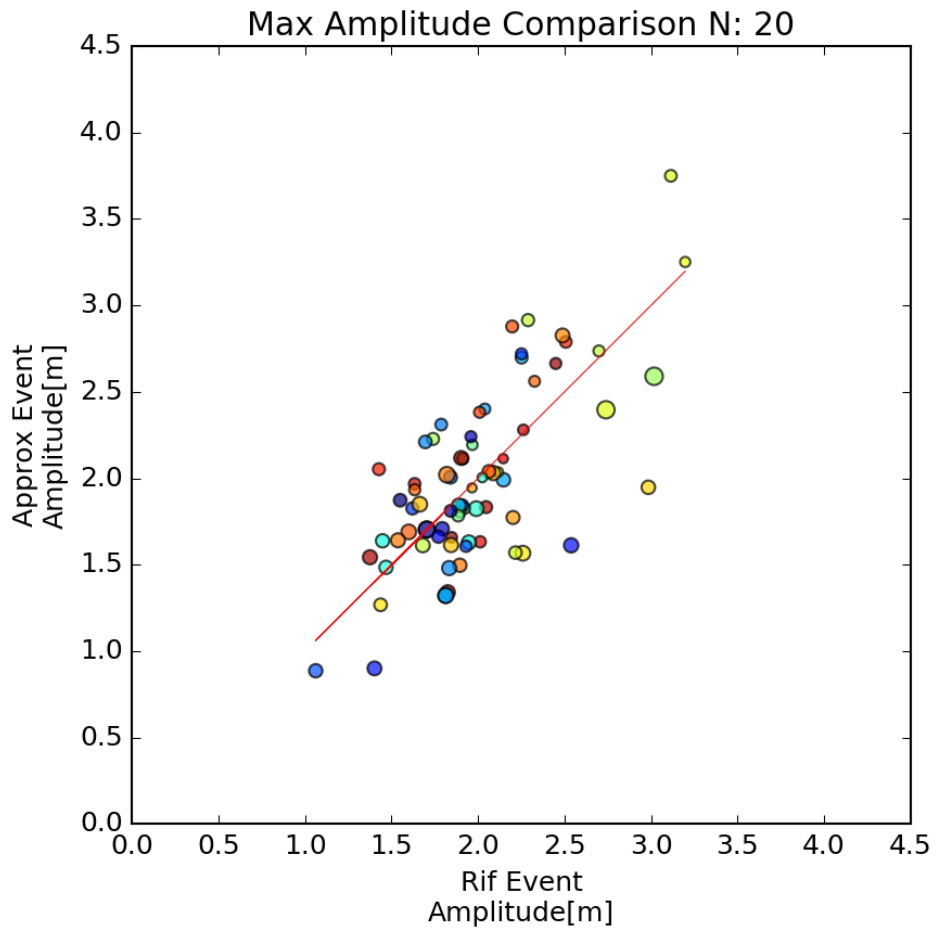
Figure 5.6: Scatter plot of the approximated maximum values against the reference maximum values. The straight red line represents the perfect accuracy. At increasing N, we can see a decrease in both the area of the circles and of their average distance from the perfect match line.
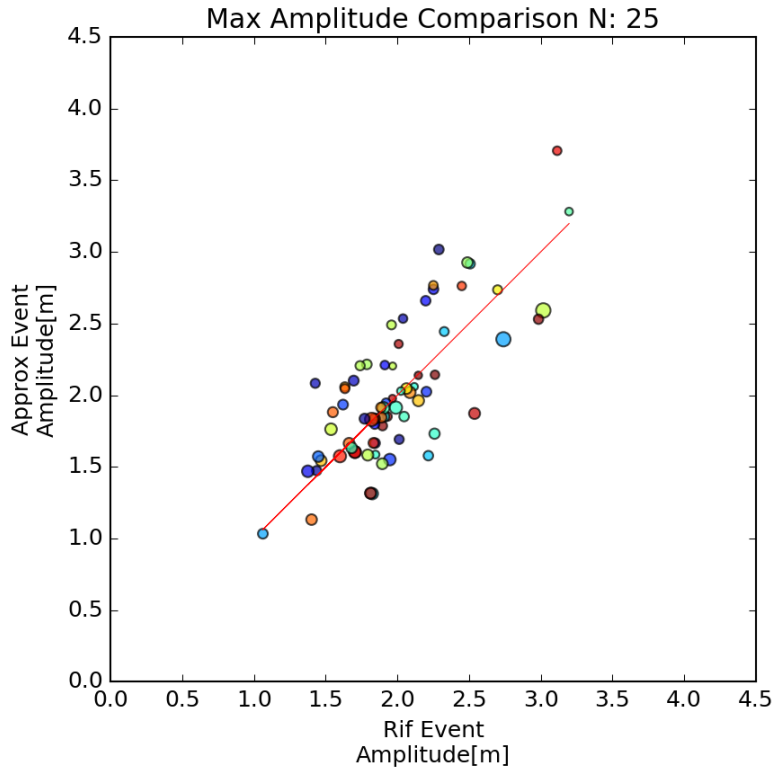
Figure 5.7: Scatter plot of the approximated maximum values against the reference maximum values. The straight red line represents the perfect accuracy.
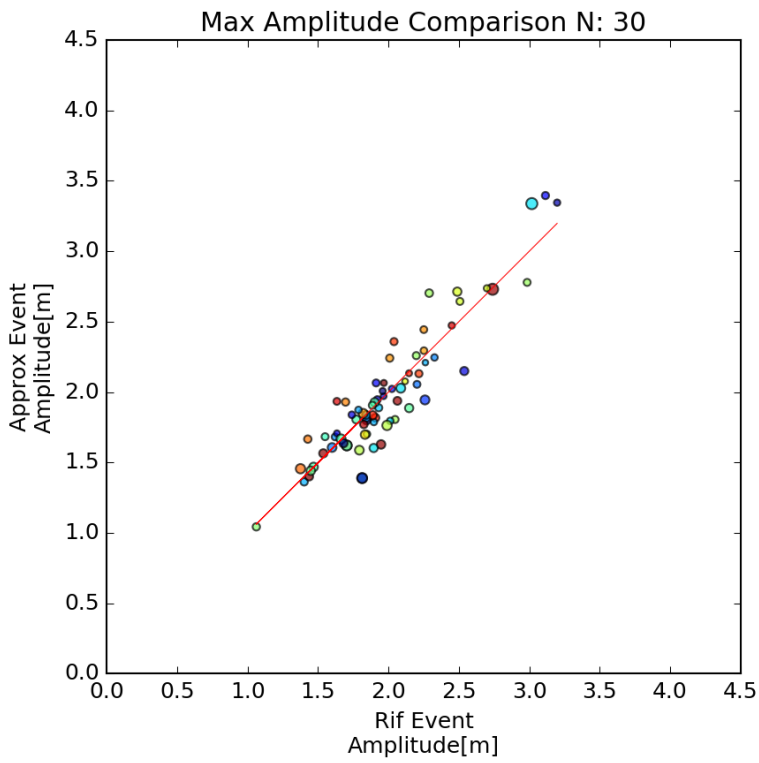

Figure 5.8: At N = 30, the areas have become small, demonstrating that the average approximation of the whole signal is good. Nevertheless, some approximated values are not perfectly estimated yet and they show a distance from the reference red line.
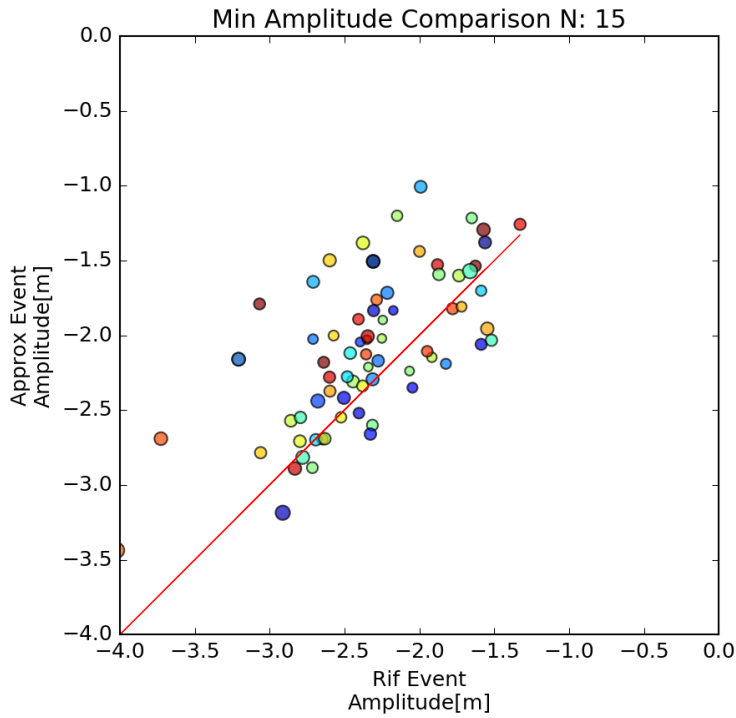
Figure 5.9: Scatter plots for the minimum values at each station. Positions of the circles represent the distance from the perfect accuracy in the minimum value estimation (red straight line) while the circle areas represent the relative error associated with the whole waveform at that point, i.e. at that station.
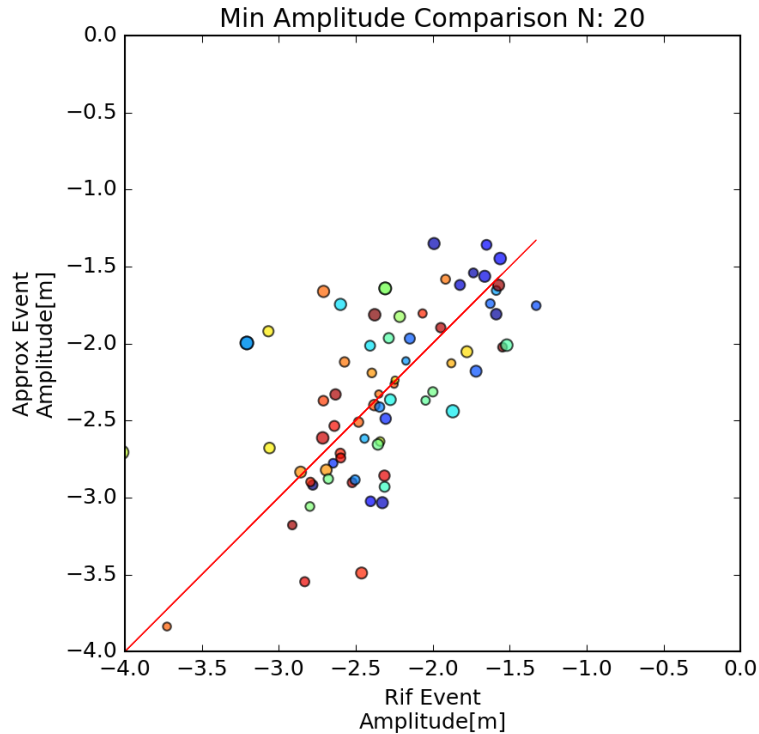

Figure 5.10: Scatter plot representing the approximation of the lowest elevation value for each station available. The single circle represents a single station. For this uppermost event, at N = 20, the circles still show a strong spreading over the plane.
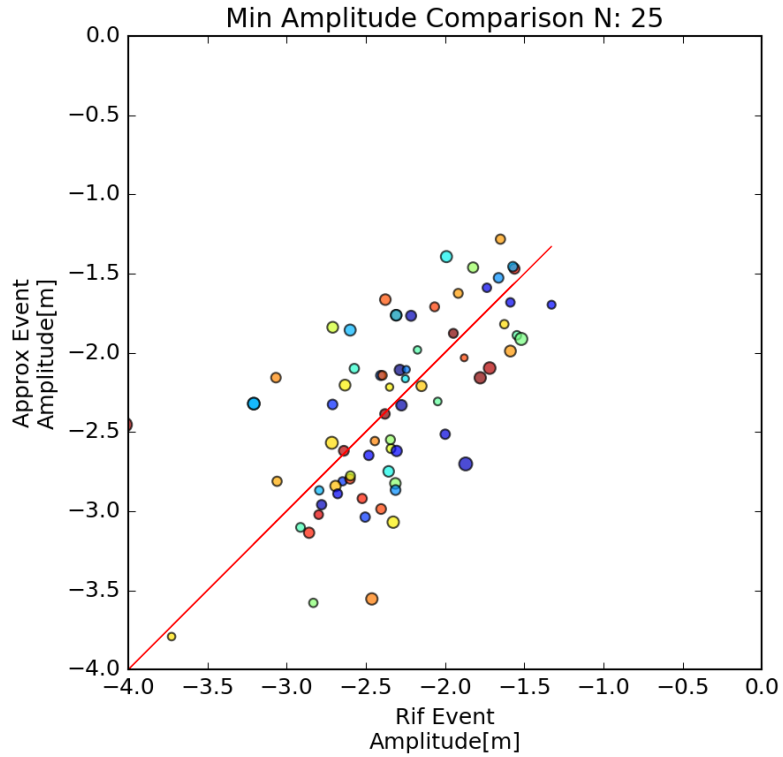
Figure 5.11: At N = 25 the area of the circle is getting smaller and smaller. It means that the average deviation of the whole signal from the reference is becoming small, but the maximum is not approximated with the highest possible accuracy.
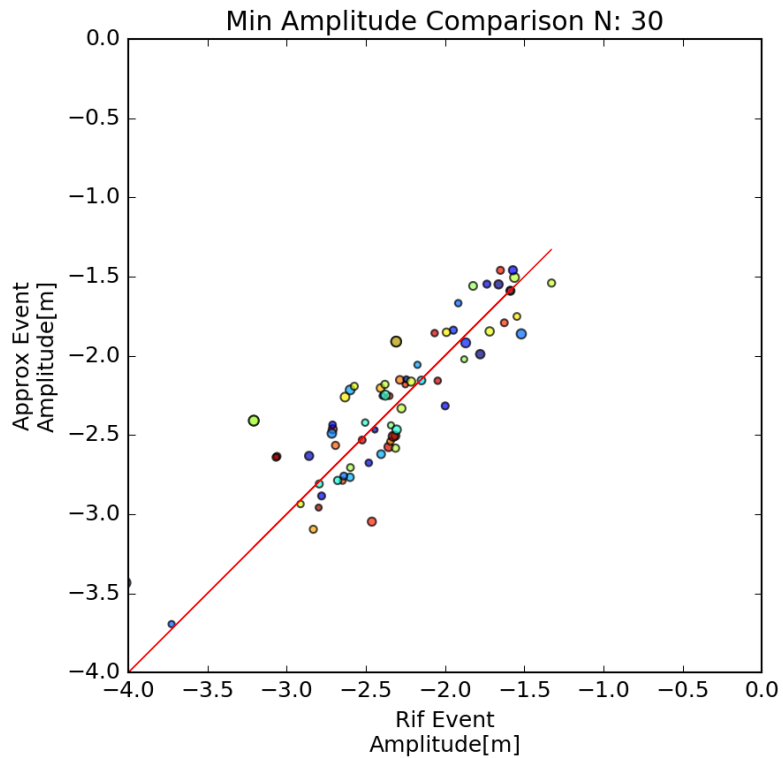

Figure 5.12: At N = 30, circles are getting closer to the reference value.

By looking at the scatter plots presented with default building procedure, the accuracy in estimating the extreme values of the given stations increases with increasing N, as the circles gradually get closer to the reference value. Also the accuracy in approximating the whole signals increases with N, as can be appreciated from the area of the circles in the scatter plot becoming smaller and smaller.

Nevertheless, at N = 30, still several circles are far from their reference value for this uppermost event, as can be seen in Figure 5.12 and Figure 5.8. Hence, we see that the building algorithm with the ACCURATE selection mode still has some difficulties in approximating the extreme values of the selected stations for this uppermost seismic event.

5.1.2   Reference event

Figure 5.13 shows the location of the stations that produced the 50 highest and lowest amplitudes for the reference event, located at middle depth over the fault plane, as shown in Figure 4.1 .
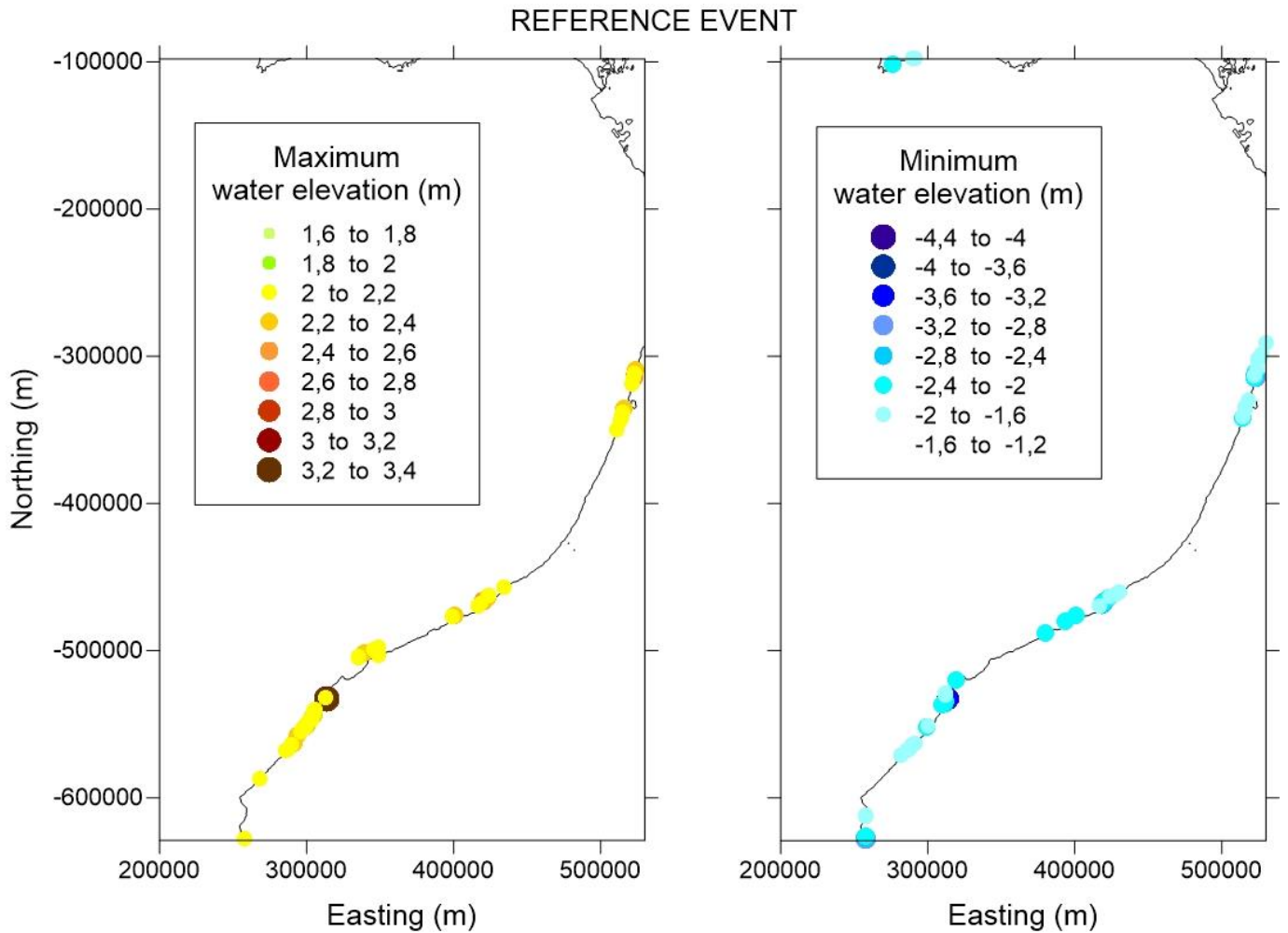

Figure 5.13: On the left, the 50 stations that produced the highest amplitude value in the reference forecast are shown. On the right, the ones that produced the lowest 50 elevation values.

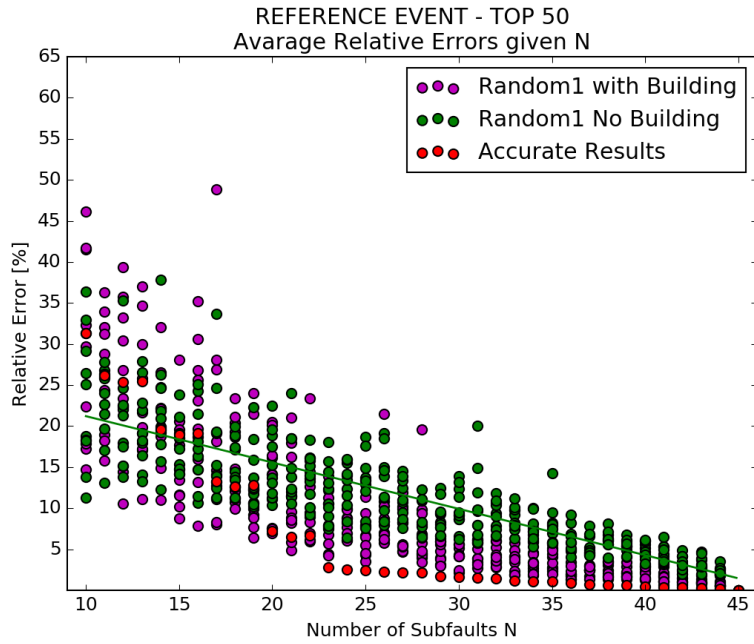The results in terms of average relative error are shown in Figure 5.14, Figure 5.15 and Figure 5.16.

Figure 5.14: The scatter plot shows the relative error, averaged over the available stations, committed at given N, adopting the RANDOM1 selection mode. The straight green line interpolates the relative errors associated with the approximation without building algorithm (green dots). As we can see, for this reference event with RANDOM1 selection mode, the building algorithm shows good performance with an overall reduction of the error (purples dots) Indeed almost all the purple dots are below the green line when N is around 20. ACCURATE selection mode results (red dots) are shown for comparison.
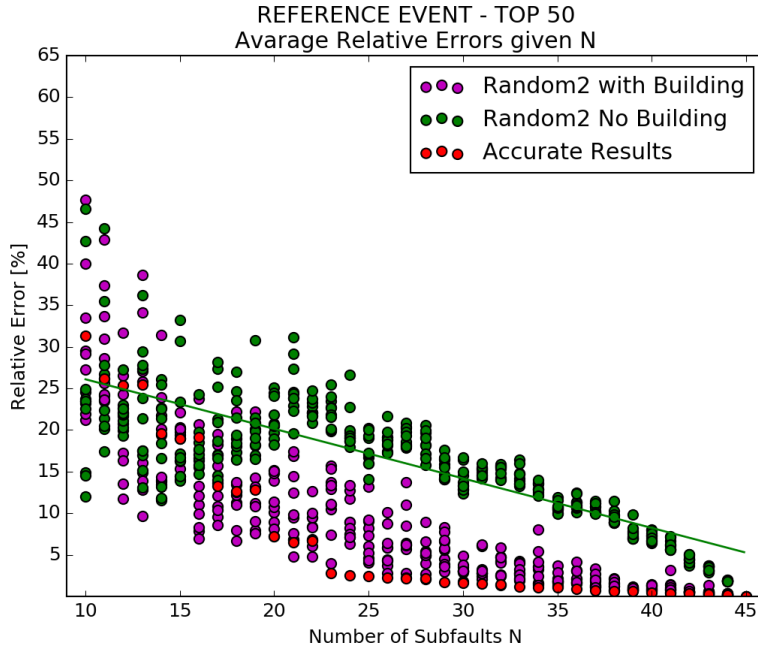

Figure 5.15: Adopting the building algorithm over the RANDOM2 selection (purple dots) mode shows a sharp improvement in the results. The green straight line represents the general trend in the results obtained without building process (green dots). At the beginning, with small N, the performances within RANDOM2 are quite similar either on using the building procedure or not. But with N > 15, the building algorithm shows remarkable improvements. ACCURATE selection mode results (red dots) are shown for comparison.

REFERENCE EVENT - TOP 50
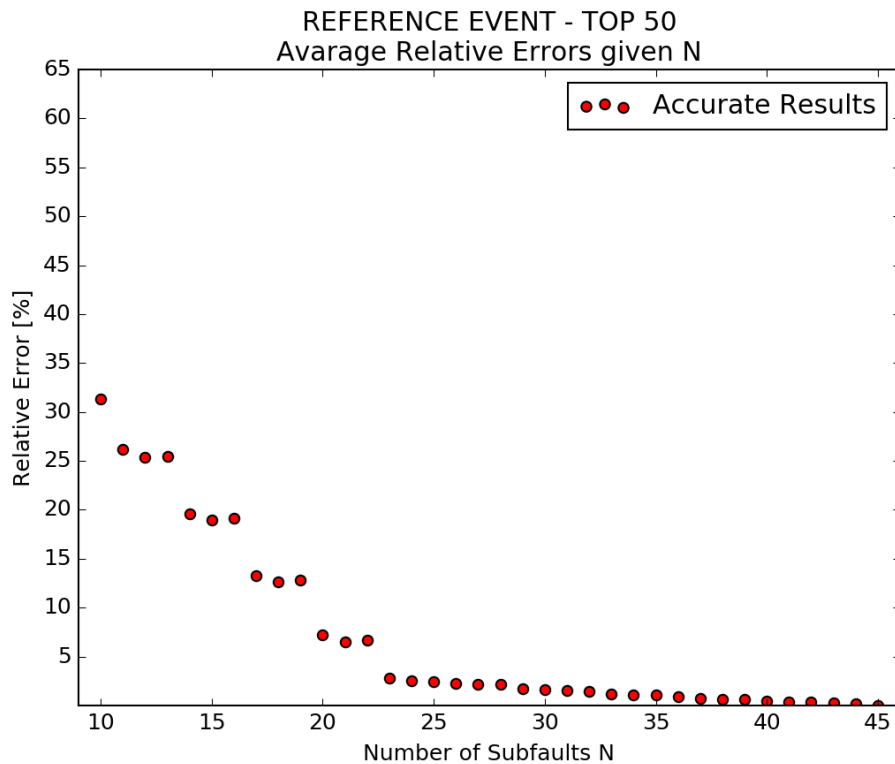Avarage Relative Errors given N

Figure 5.16: Results obtained adopting the ACCURATE selection mode and the building algorithm for the stations available in these analyses. When N gets around 25, the average relative error over the whole signal flattens under 5%.

By looking at plots from Figure 5.14 to Figure 5.16, we can see that the average relative errors committed in reproducing signals at given N, generally decrease when using the building algorithm for this middle depth event.

Both RANDOM1 and RANDOM2 selection modes present better errors when the building procedure is implemented.

Figure 5.16 shows some interesting features. In fact, in these results obtained with ACCURATE selection mode, we can see that committed errors, at given N, gather themselves into flattened groups (each of three elements) and the group shows a steady decrease at increasing N. This suggests that an even quicker decrease in relative errors is likely achievable by improving the way subfaults are selected in ACCURATE selection mode for this event. Nevertheless, the ACCURATE selection mode shows the best results.

By comparing the performances of the ACCURATE selection mode for the uppermost reference event and the reference event at middle depth, we can see

that the performance in terms of relative errors is sharply higher for the middle depth (compare Figure 5.16 and Figure 5.4).

The scatter plots showing the approximated extreme values against the reference ones are given from Figure 5.17 to Figure 5.22.

Figure 5.17: Scatter plot representing the approximated maximum values against the reference maximum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.

Figure 5.18: Scatter plot representing the approximated maximum values against the reference maximum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.
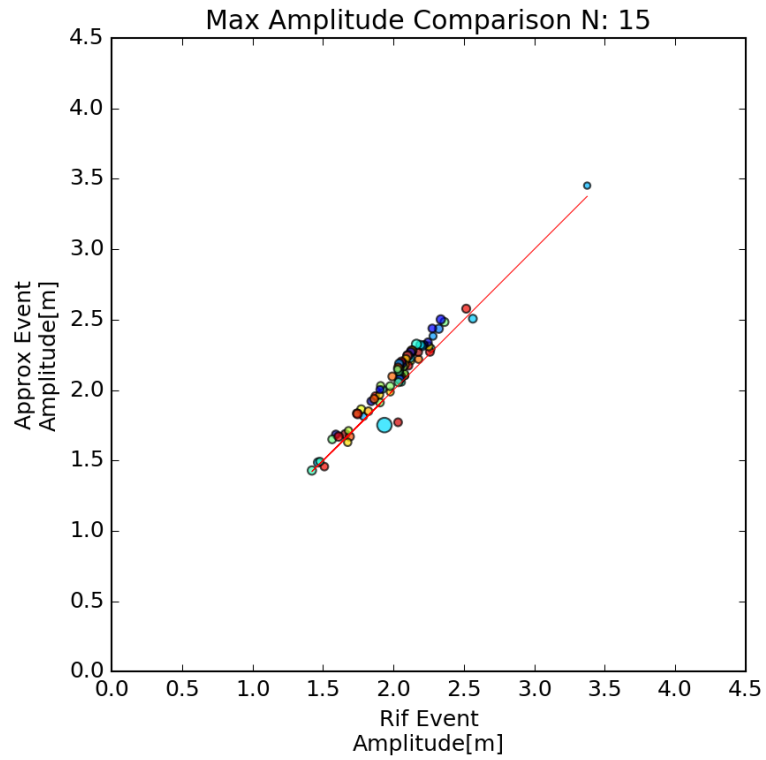

Figure 5.19: Scatter plot representing the approximated maximum values against the reference maximum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.

Figure 5.20: Scatter plot representing the approximated minimum values against the reference minimum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.
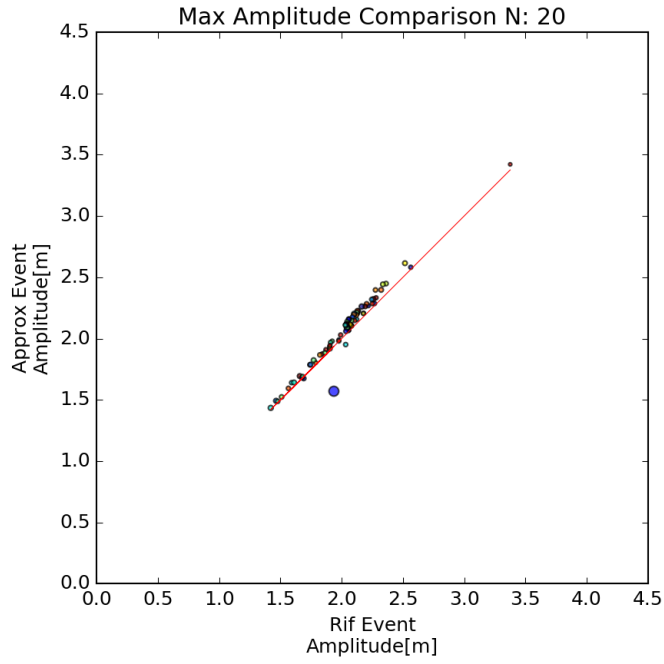

Figure 5.21: Scatter plot representing the approximated minimum values against the reference minimum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.
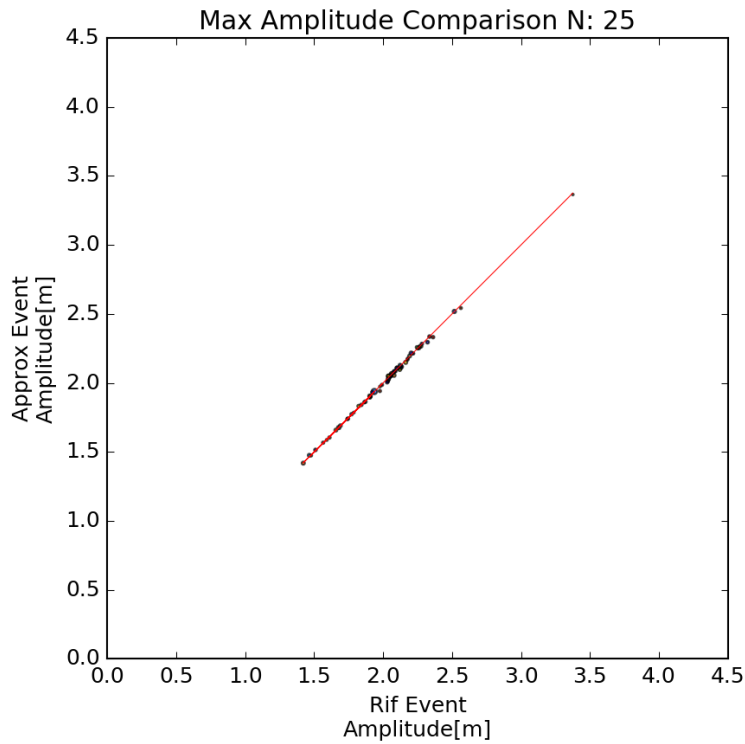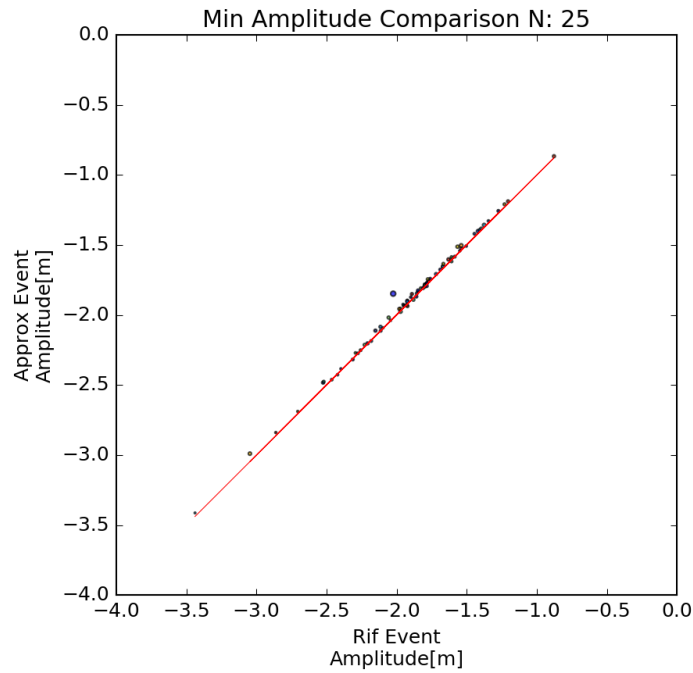
Figure 5.22: Scatter plot representing the approximated minimum values against the reference minimum values at given N. Each circle represents the value associated with a single station, while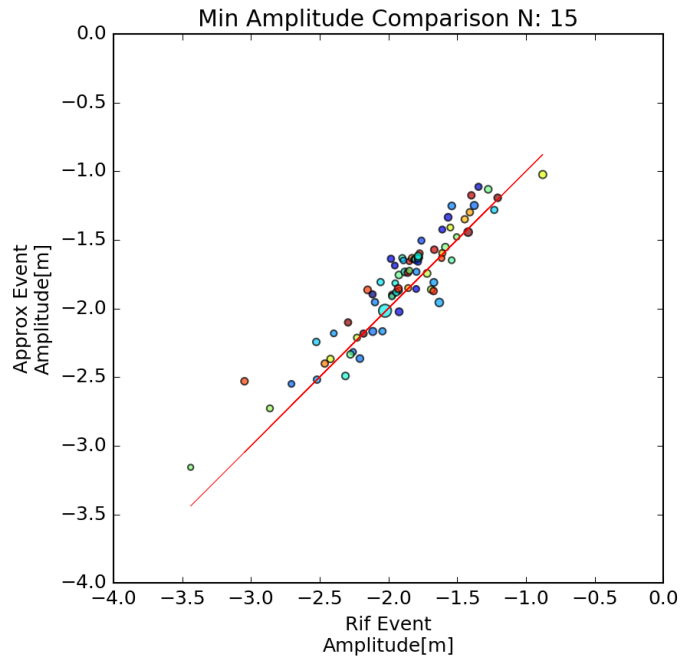 the re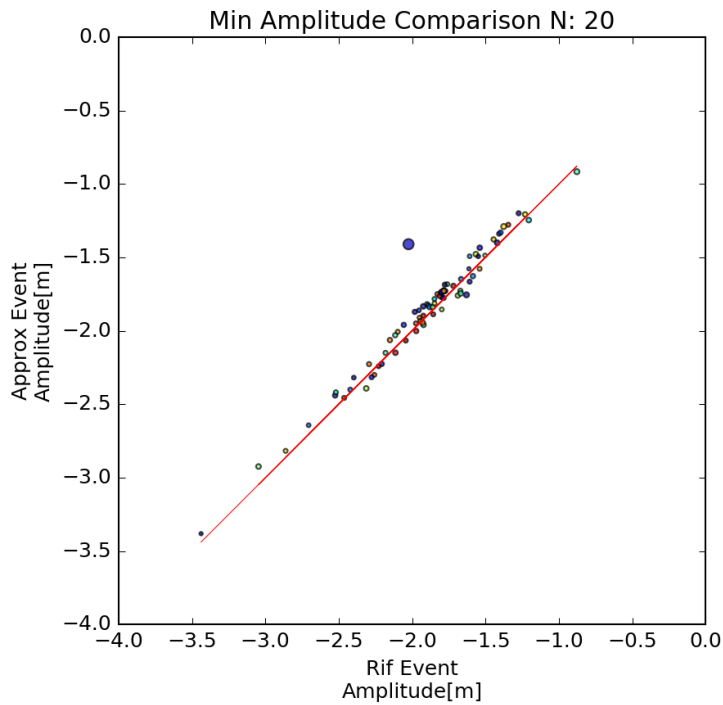d straight line represents the perfect approximation. Both in this figure (N = 25) and in the previous one (N=20), a high accuracy in approximating the reference values is achieved.

By looking at Figure 5.17 to Figure 5.22, we can see that the accuracy in approximating the extreme values for the selected stations increase remarkably at increasing N.

By comparing these results to the ones obtained for the uppermost event in the previous paragraph, we can see that for all given N the accuracy in the approximation is far better than the accuracy in the uppermost case.

In this case, N = 30 has not been taken into consideration as the accuracy in approximating the extreme values at N = 25 is already high (see Figure 5.22 and Figure 5.19).

5.1.3 Larger depth event

Figure 5.23 shows the location of the stations that produced the 50 highest and lowest amplitudes for the last deepest event, whose horizontal projection at the
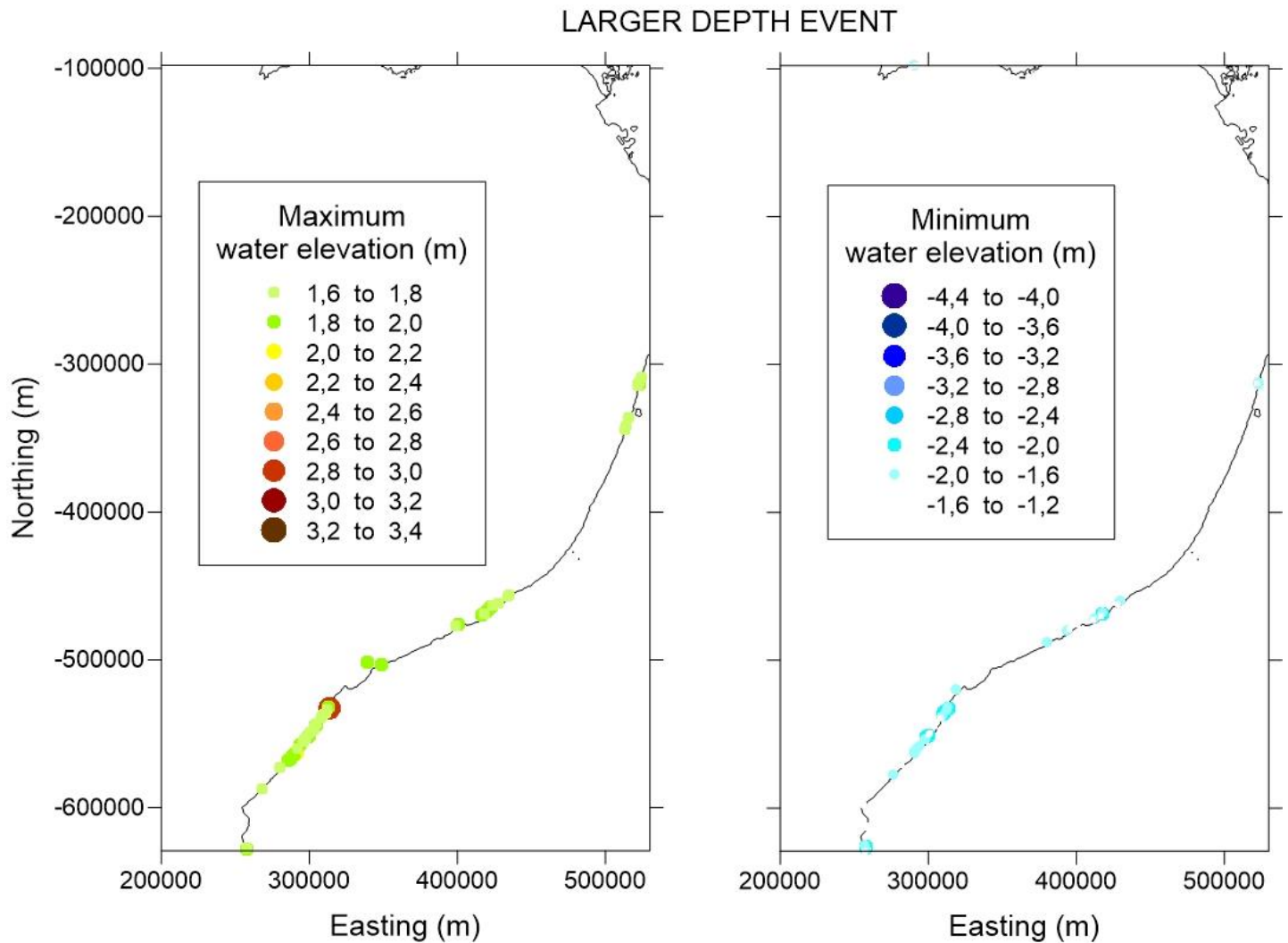

Figure 5.23: On the left, the 50 stations that produced the highest amplitude value within the reference forecast are shown. On the right, the ones that produced the lowest 50 elevation values.

surface is shown in Figure 4.15.

The results in terms of average relative errors are given from Figure 5.24 to Figure 5.26.

MAJOR DEPTH EVENT - TOP 50
Avarage Relative Errors given N

Figure 5.24: The scatter plot shows the relative error, averaged over the available stations, committed at given N, adopting the RANDOM1 selection mode. The straight green line interpolates the relative errors associated with the approximation without building algorithm (green dots). As we can see, for this event, the building algorithm shows a good performance with an overall reduction of the error (purple dots). Almost all the purple dots are below the green line when N is around 20. The ACCURATE selection mode is shown as a comparison (red dots).

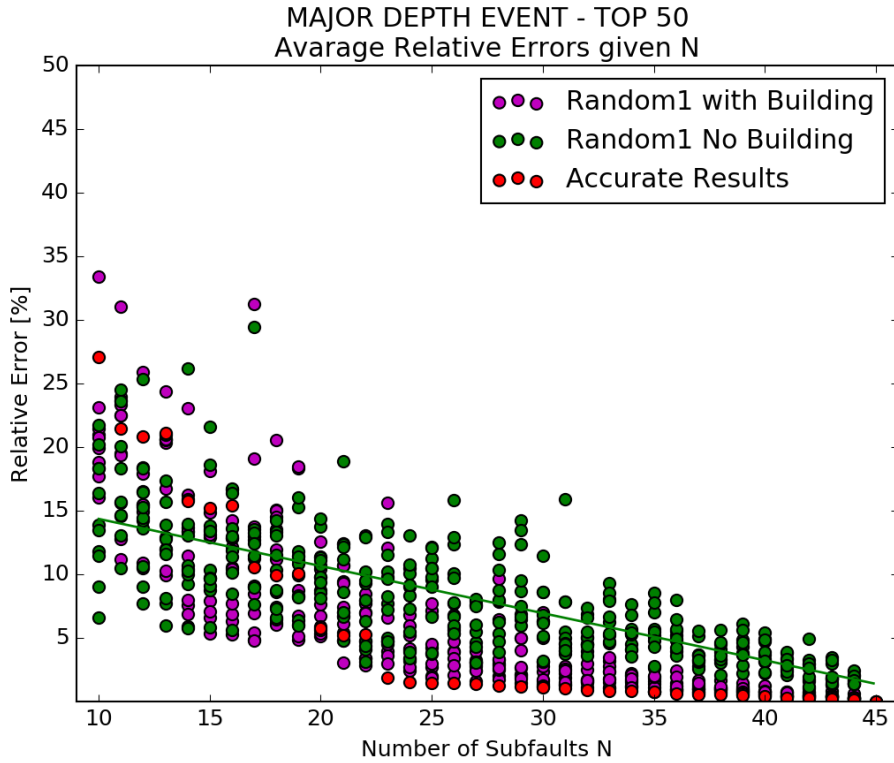MAJOR DEPTH EVENT - TOP 50
Avarage Relative Errors given N

Figure 5.25: The scatter plot shows the relative error, averaged over the available stations, committed at given N, adopting the RANDOM2 selection mode. The straight green line interpolates the relative errors associated

with the approximation without building algorithm (green dots). As we can see, for this reference event with RANDOM2 selection mode, the building algorithm shows a good performance with an overall reduction of the error (purple dots). Almost all the purple dots are below the green line when N is around 20. The ACCURATE selection mode is shown as a comparison (red dots).
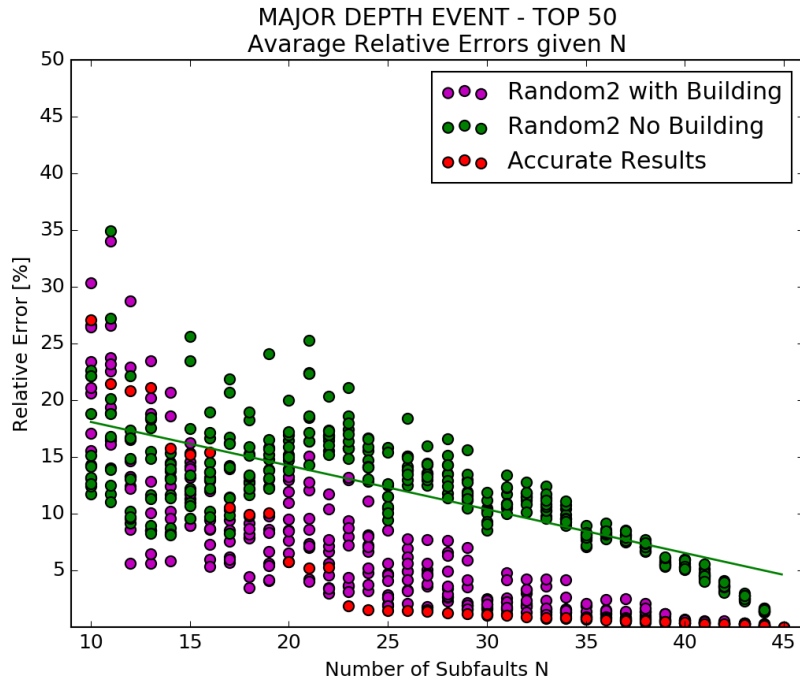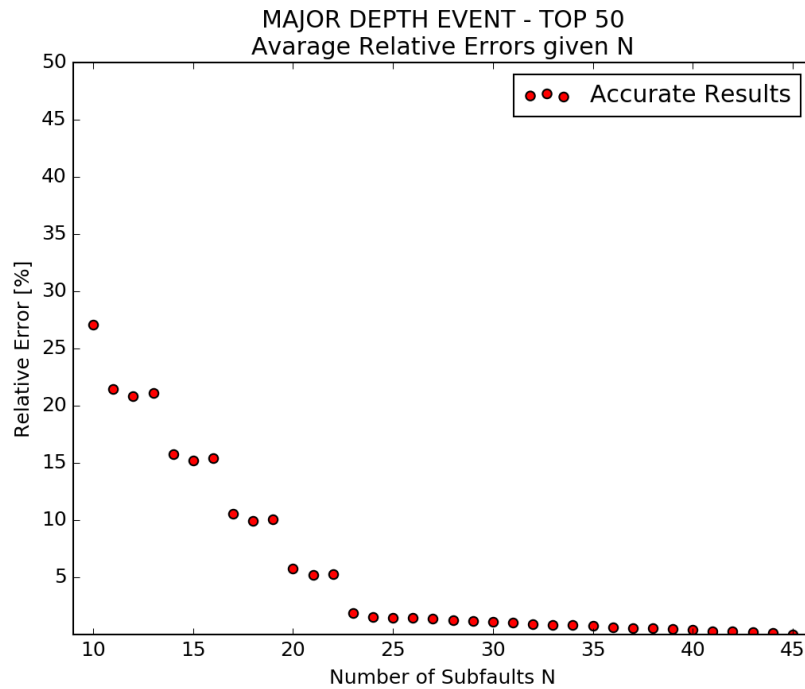

Figure 5.26: Results obtained adopting the ACCURATE selection mode and the building algorithm for the stations available in these analyses. When N gets around 25, the average relative error over the whole signal flattens under 5%.

Both RANDOM1 and RANDOM2 selection modes present lower relative errors when the building procedure is applied (see Figure 5.24 and Figure 5.25).

The results obtained with the ACCURATE selection mode are the best ones, as can be seen in Figure 5.24 and Figure 5.25. In fact, Figure 5.26 shows that the error flattens under 5% when N approaches 20.

The overall results obtained for this large depth event are the best ones compared to the results obtained with the other two cases. The comparison is straightforward by looking at Figure 5.26 (deepest event), Figure 5.16 (reference event at middle depth) and at Figure 5.4 (uppermost event).

By looking at the scatter plots from Figure 5.27 to Figure 5.32 and comparing them with the ones obtained for the other two events, one remarkable feature appears clearly: the more we move down the fault, the bigger accuracy is reached in approximating the reference results, at fixed N.

Figure 5.27: Scatter plot representing the approximated maximum values against the reference maximum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.
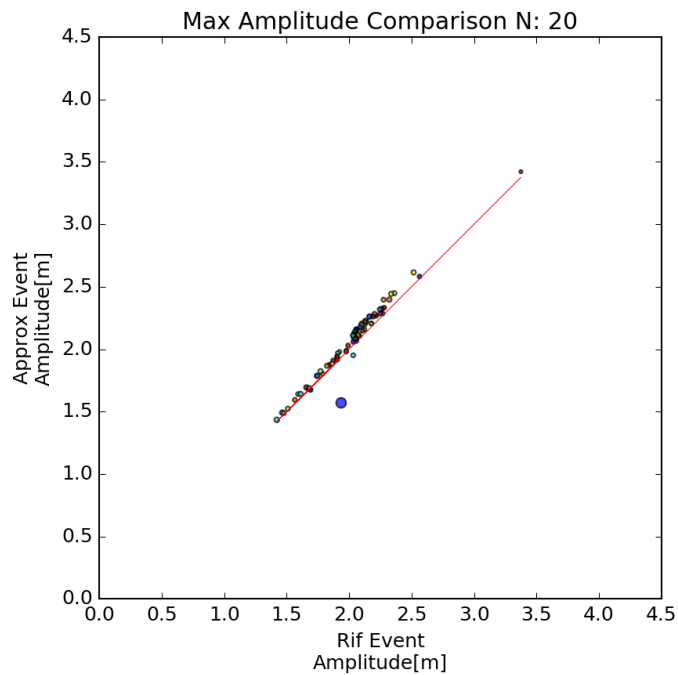
Figure 5.28: Scatter plot representing the approximated maximum values against the reference maximum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.
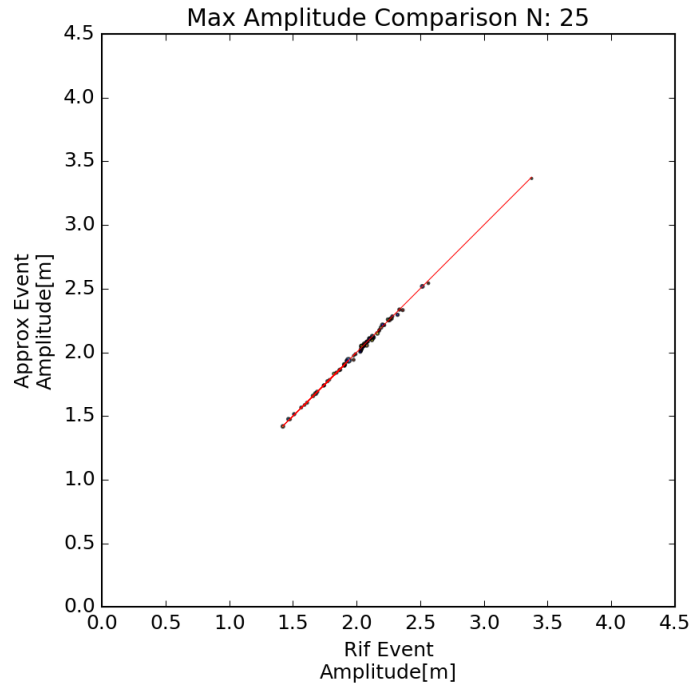
Figure 5.29: Scatter plot representing the approximated maximum values against the reference maximum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.
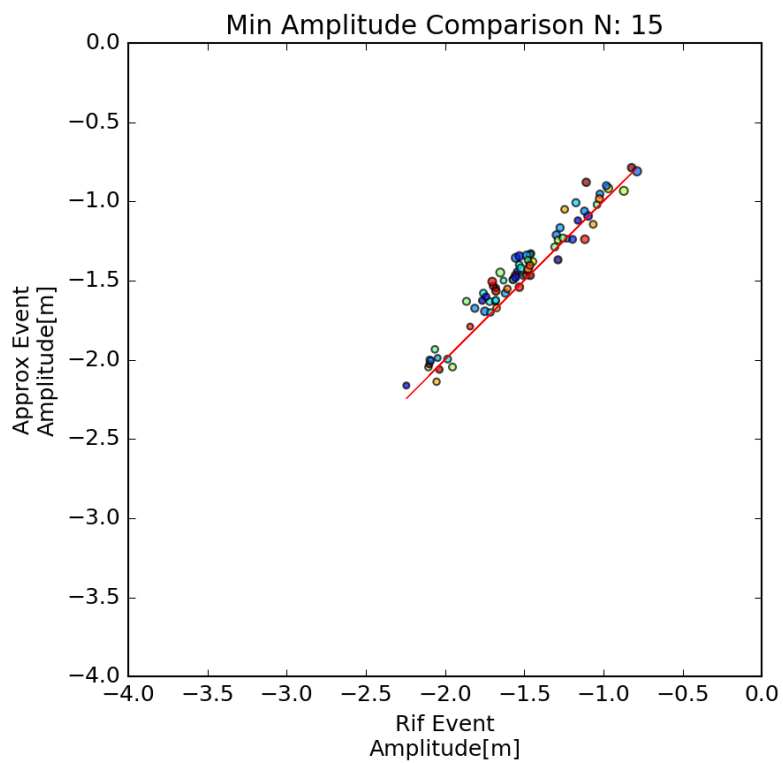
Figure 5.30: Scatter plot representing the approximated minimum values against the reference minimum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.
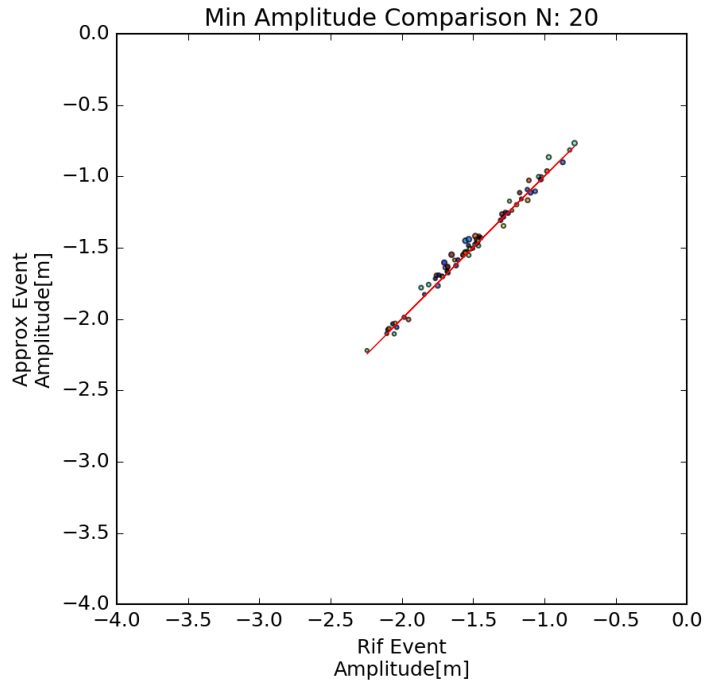
Figure 5.31: Scatter plot representing the approximated minimum values against the reference minimum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.
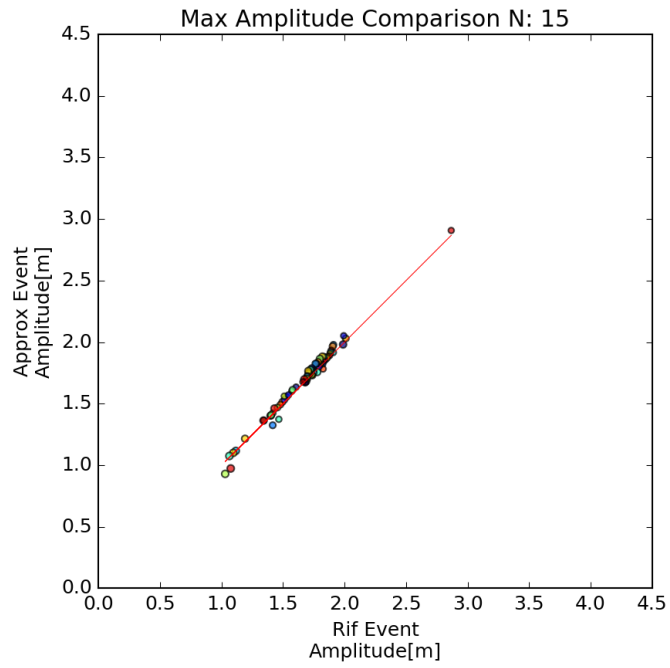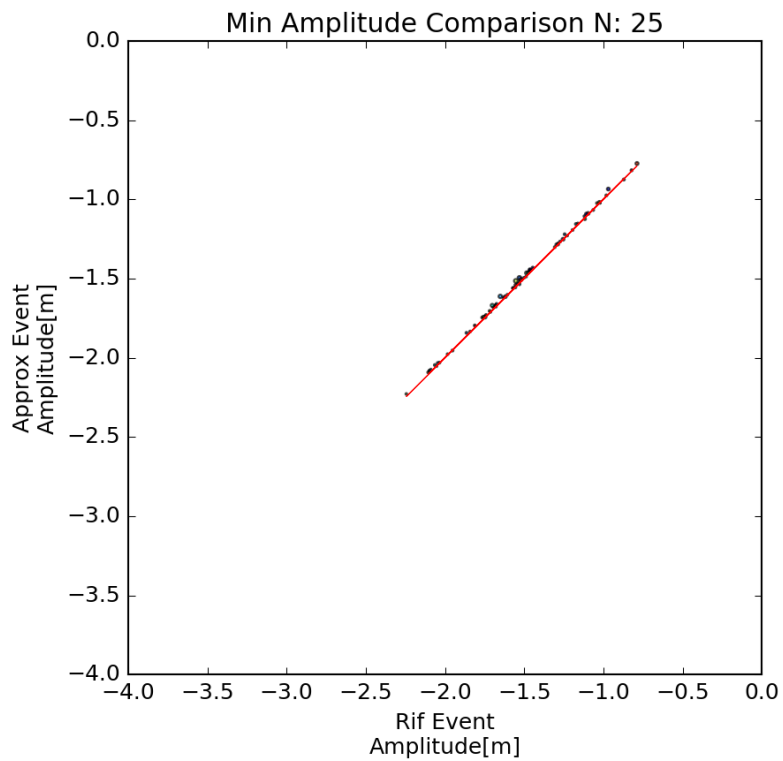

Figure 5.32: Scatter plot representing the approximated minimum values against the reference minimum values at given N. Each circle represents the value associated with a single station, while the red straight line represents the perfect approximation.

5.2 Top 2 stations

In the previous paragraph, we have seen that the stations presenting extreme elevation are well approximated when the seismic event is at middle/large depth, with N around 20, while bigger N are required if the seismic event is located in the upper fault.

Hence, in this section we propose a further comparison between the uppermost event and the one at largest depth, to focus on the performance of the building algorithm for these two cases.

Only one station is considered for each of the two events, i.e. the station that produced the maximum forecasted value. The two events and the associated stations are shown in Figure 5.33.
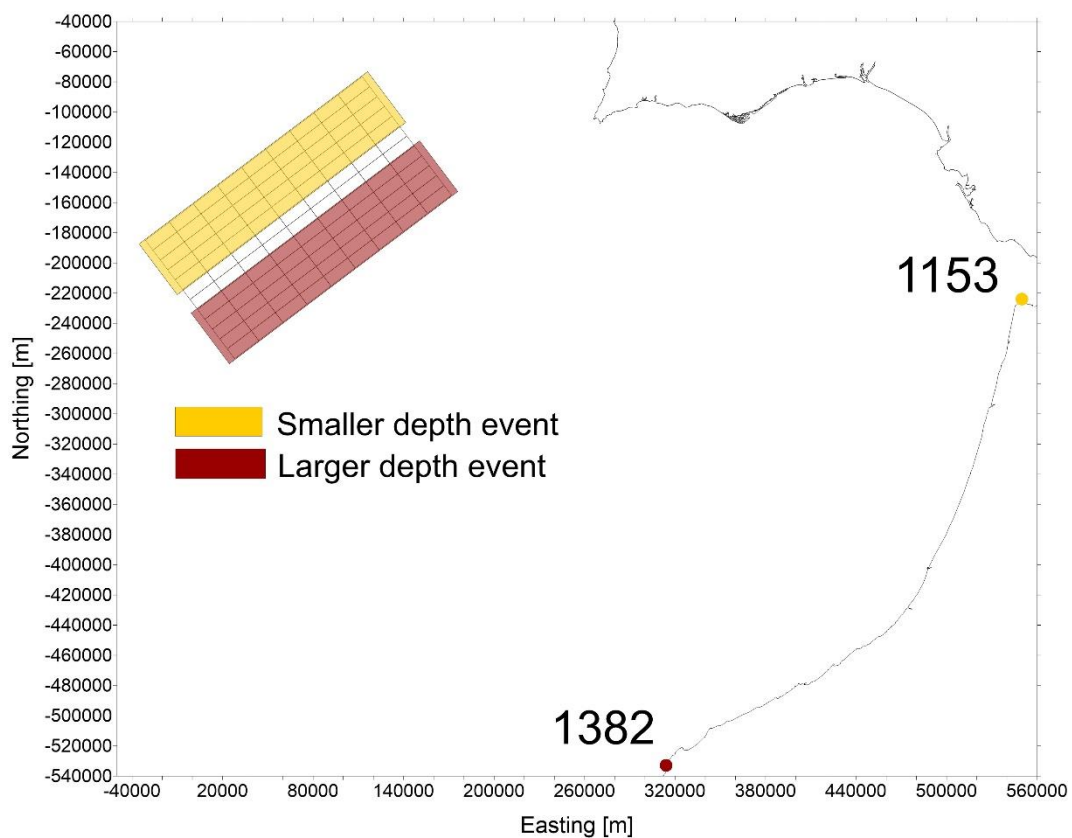
Figure 5.33: Horizontal projection of the two events, located at different depth over the GBF fault surface. For each of these two events, a single station, presenting the respective maximum elevation, has been chosen and shown in figure. The 1153 station for the uppermost event and the 1382 station for the deepest one.

In next sections, we will see how the maximum of each station has been approximated, using the building algorithm with ACCURATE selection mode.

5.2.1   Smaller depth event

In Figure 5.34 the gradual approximations of the reference signal, produced at station 1153 by the uppermost event, are shown. We can see that with N = 10, the target signal is poorly approximated even with the ACCURATE selection mode with building algorithm applied. The first oscillations are poorly matched and the maximum value is in this case underestimated.

Figure 5.34: Three different approximations of the target signal at station 1153 for three different values of N. The approximation is obtained by using the ACCURATE selection mode with the building algorithm.

By looking at Figure 5.34, we can see that the target signal becomes well approximated at increasing N, and for N = 20, the approximation gives suitable values of the peaks of the signal.

In the following, three different graphs are given, showing how the maximum value of the reference station has been approximated at given N by means of the various

selection mode either with or without the building algorithm. The graphs are shown

from Figure 5.35 to Figure 5.37.
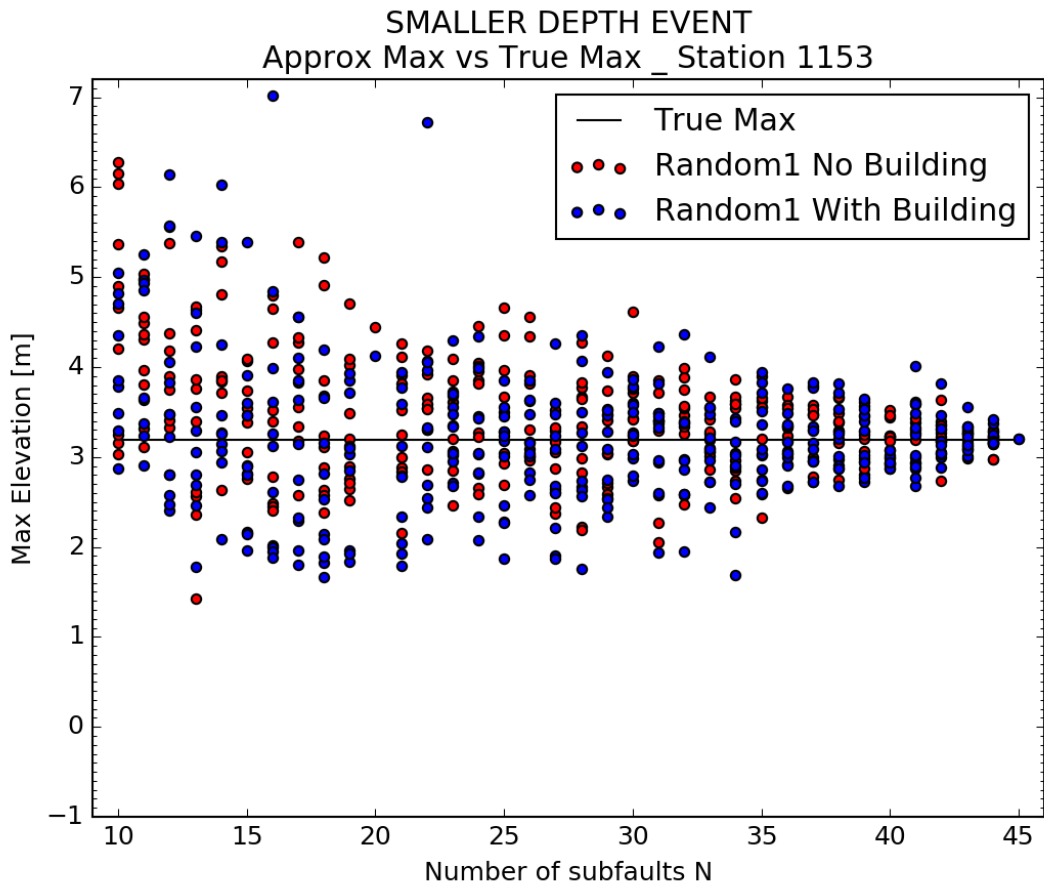
Figure 5.35: This graph focuses on the maximum value of the recorded reference signal. The straight black line represents the target value. The approximated values obtained by the RANDOM1 selection mode with the building algorithm (blue dots) and without the building algorithm (red dots) are shown.

Figure 5.36: This graph focuses on the maximum value of the recorded reference signal. The straight black line represents the target value. The approximated values obtained by the RANDOM2 selection mode with the building algorithm (blue dots) and without the building algorithm (red dots) are shown.

Figure 5.37: This graph focuses on the approximation of the maximum value of the recorded reference signal. The straight black line represents the target value. The approximated value is obtained by using the ACCURATE selection mode with the building algorithm (purple dots).

By looking at Figure 5.35, we can see that, for this uppermost event with RANDOM1 selection mode, the building algorithm slightly improves the approximation of maximum but the approximated values keep being spread around the reference even at larger values of N. The maximum value is better approximated with the RANDOM2 selection mode (see Figure 5.36) where the building algorithm shows remarkable improvements when applied. The ACCURATE selection mode, together with the building algorithm applied, presents the best results as happened in the previous more general cases. As is shown in Figure 5.37, the approximated maximum value is constrained within half of a meter around the reference value, for N > 25. Some inaccuracies are still present at higher values of N.

5.2.2 Larger depth event

The last event, considered for these analyses, is the deepest event available as shown in Figure 5.33. Figure 5.38 shows how the target signal have been approximated at given N with the ACCURATE selection mode and the building algorithm.
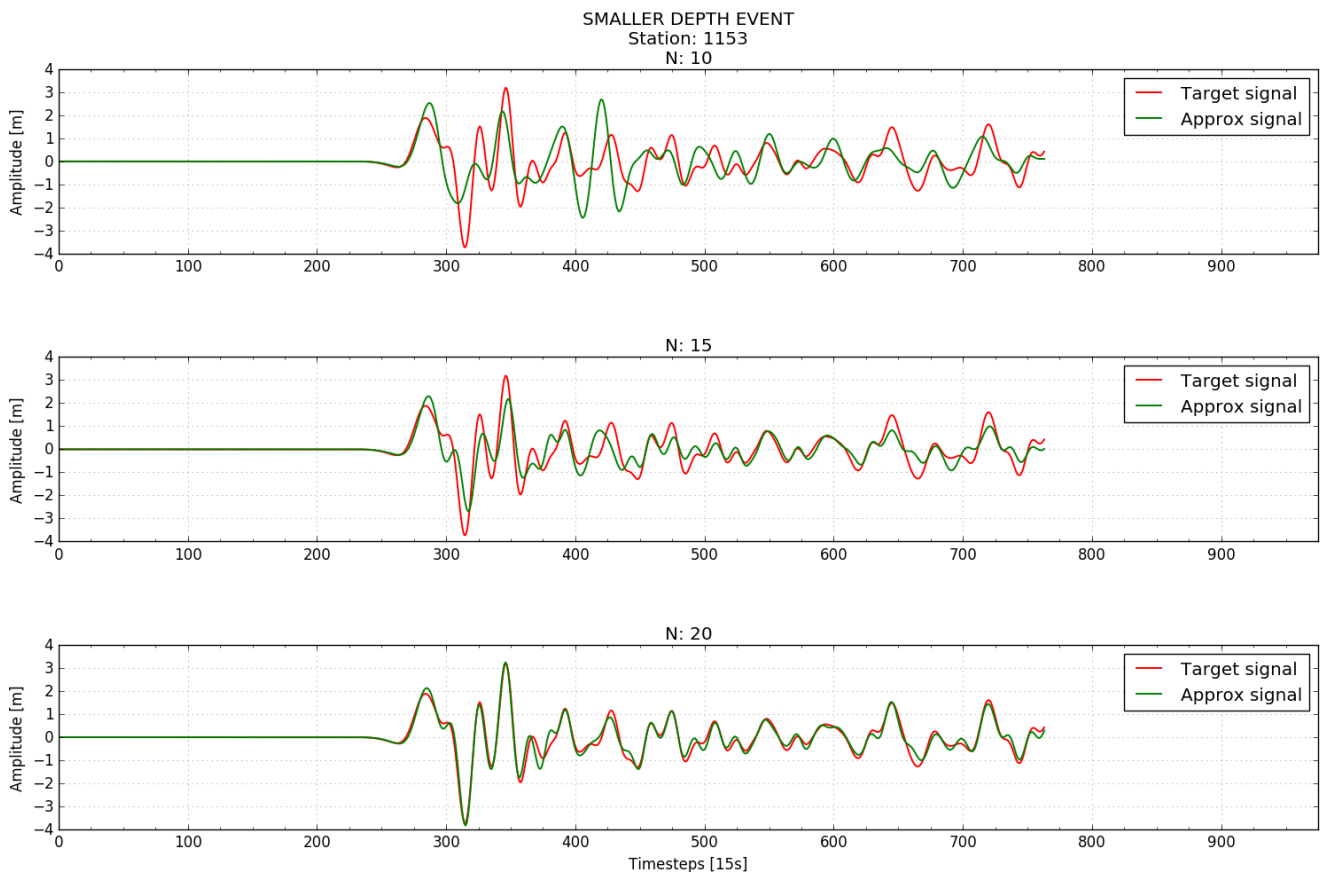
103
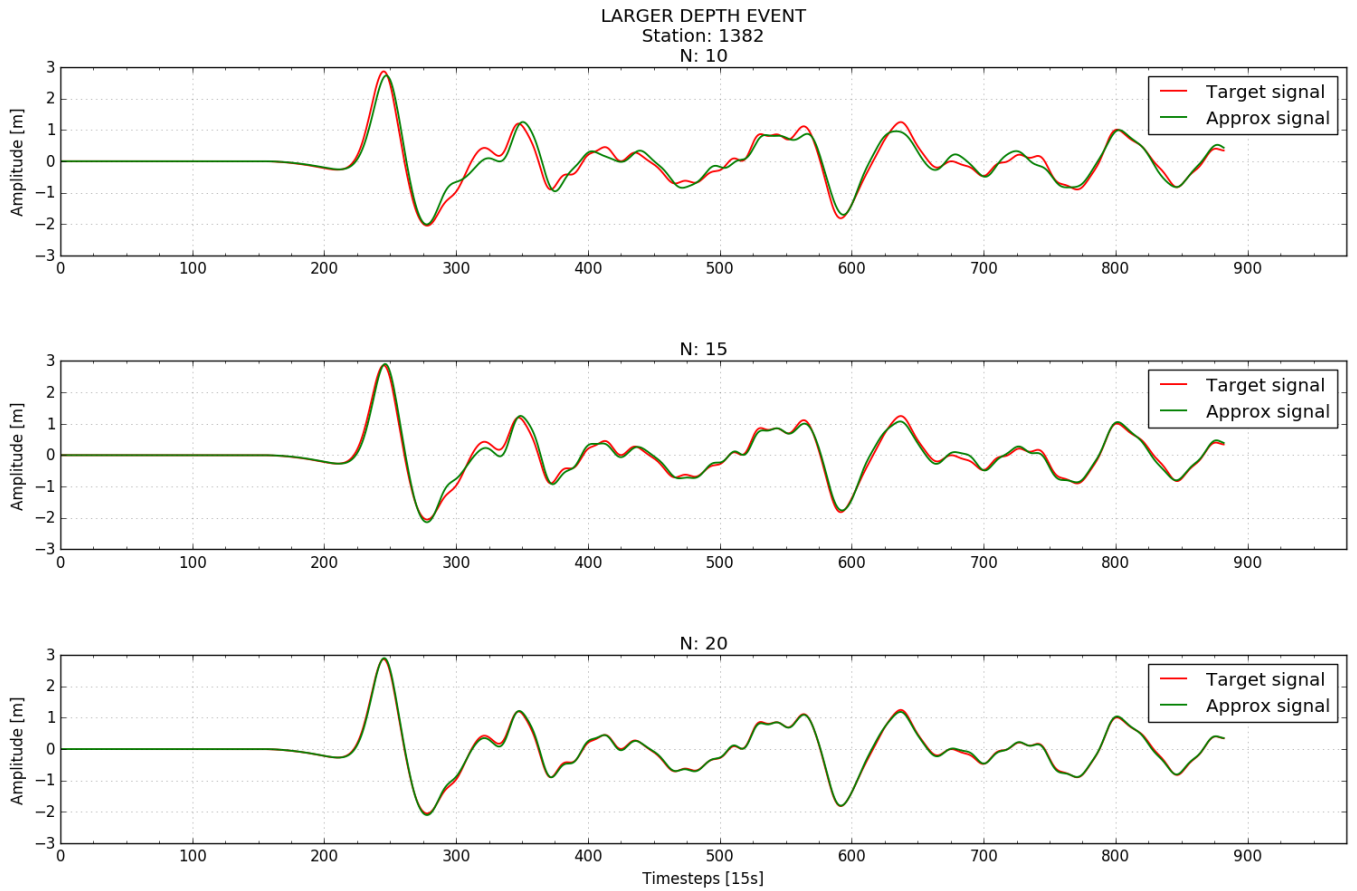
Figure 5.38: Three different approximations of the target signal at station 1382 for three different values of N. The approximation is obtained by using the ACCURATE selection mode with the building algorithm.

By looking at Figure 5.38, we can see that the signal for this largest depth event is already well approximated at N = 10, with some smaller inaccuracies along the whole signal. At increasing N, the performance gives smaller and smaller relative errors and the reference signal is almost perfectly recovered at N = 20.

From Figure 5.39 to Figure 5.41, the scatter plots focusing on the maximum reference value are shown.
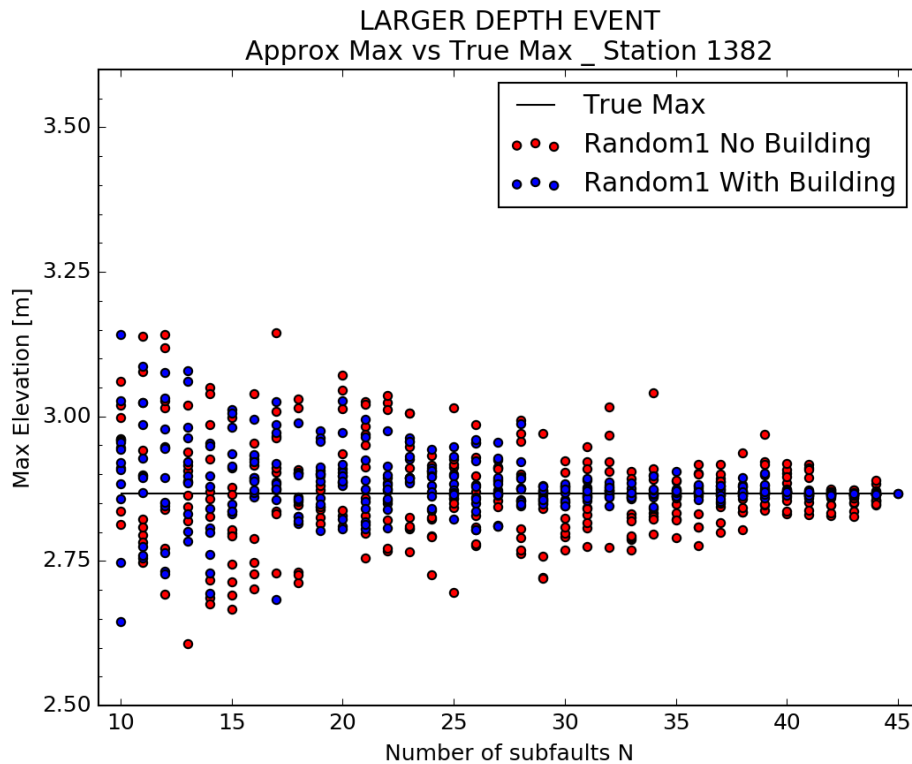
Figure 5.39: This graph focuses on the approximation of the maximum value of the recorded reference signal considered for this event. The straight black line represents the target value given by the reference forecast for this station. The approximated values obtained by using the RANDOM1 selection mode with the building algorithm (blue dots) and without the building algorithm (red dots) are shown.
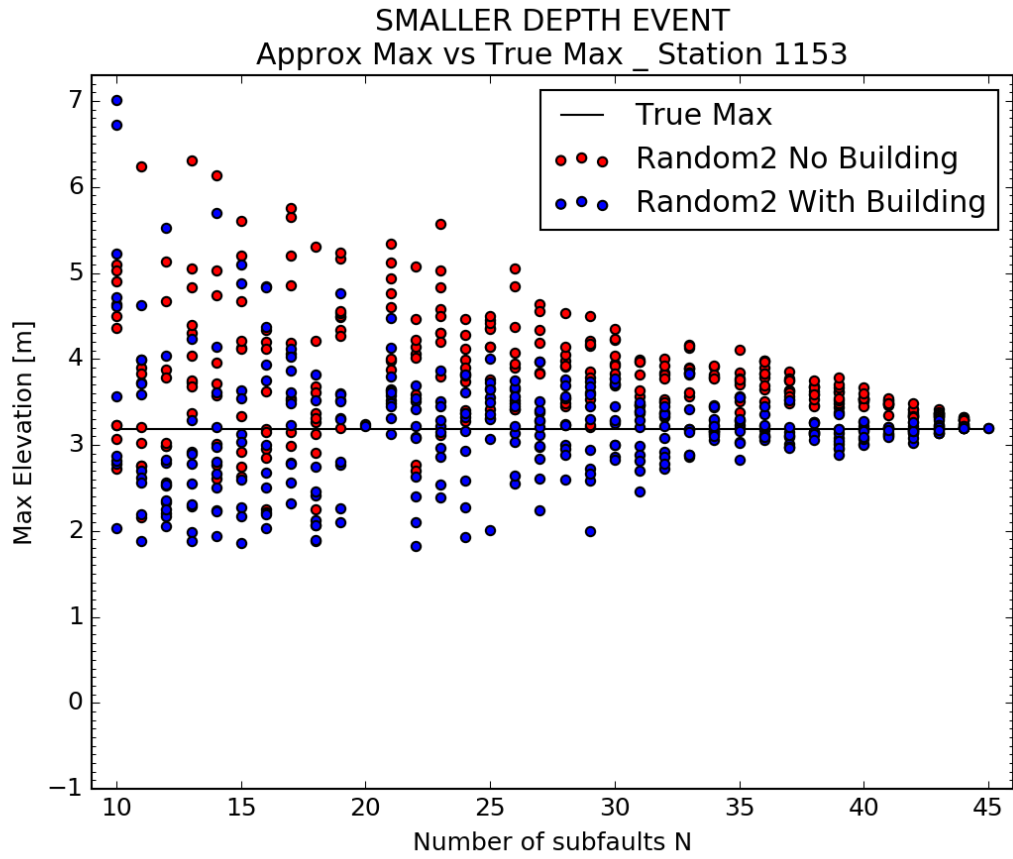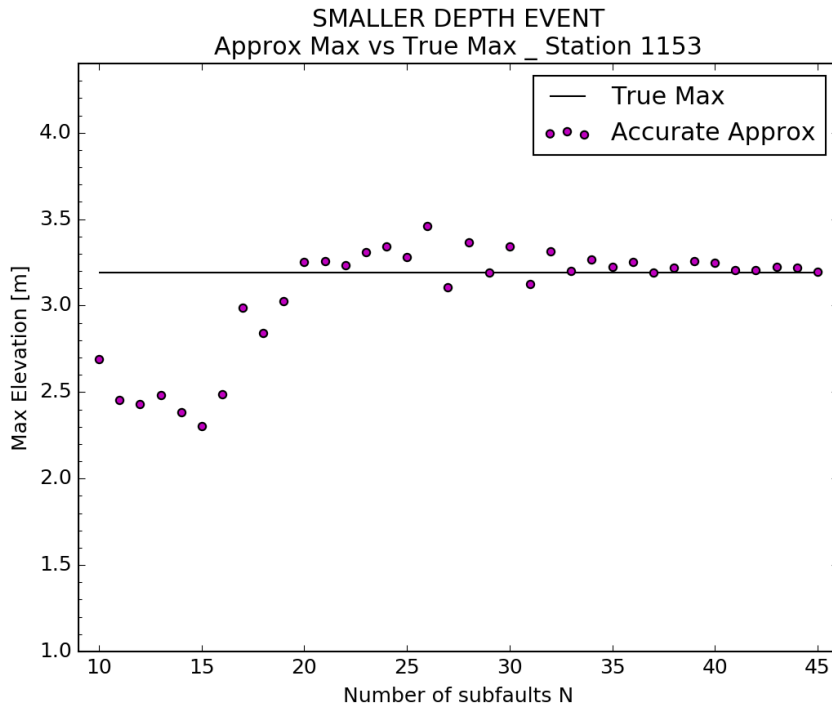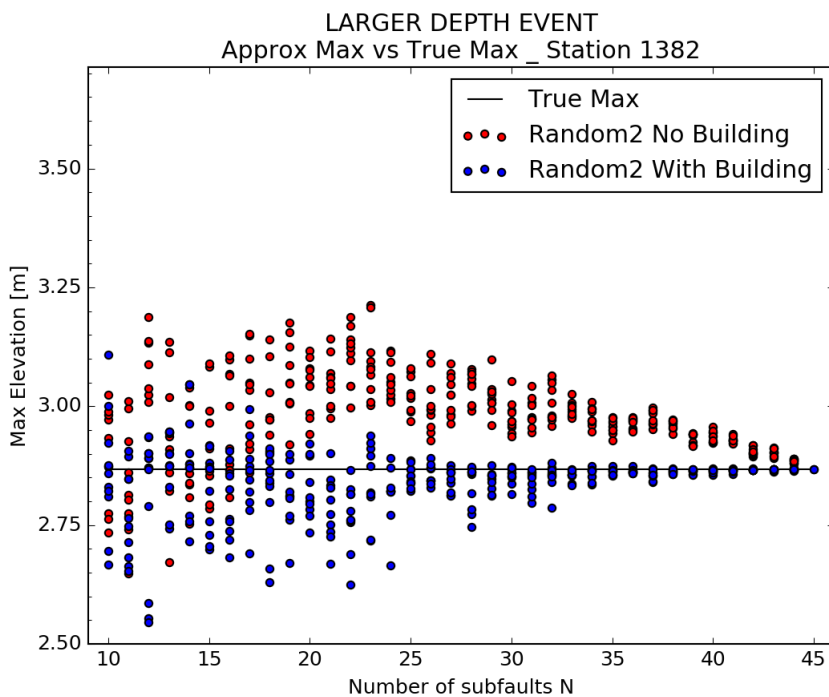

Figure 5.40: This graph focuses on the approximation of the maximum value of the recorded reference signal considered for this event. The straight black line represents the target value given by the reference forecast for this station. The approximated values obtained by means of the RANDOM2 selection mode with the building algorithm (blue dots) and without the building algorithm (red dots) are shown.
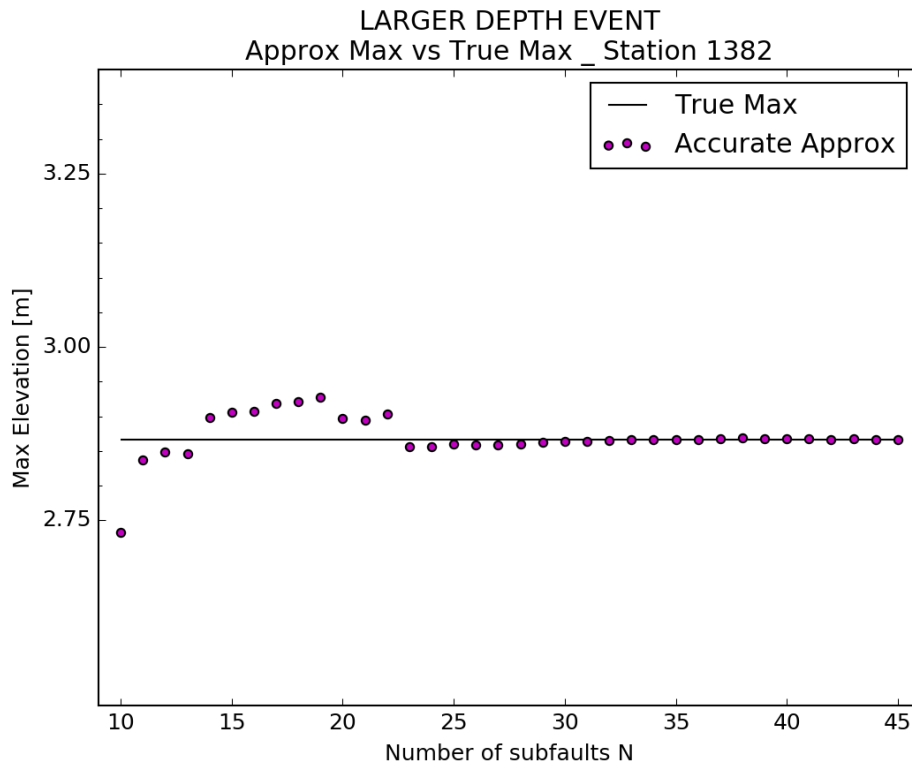
Figure 5.41: This graph focuses on the approximation of the maximum value of the recorded reference signal considered for this event. The straight black line represents the target value given by the reference forecast for this station. The approximated value is obtained by adopting the ACCURATE selection mode with the building algorithm (purple dots).

By looking at graphs from Figure 5.39 to Figure 5.41, we can see that performances for this event give in general smaller errors with respect to the ones achieved for the uppermost event, as can be seen by comparing these plots with those from figures from 5.35 to Figure 5.37.

By looking at Figure 5.39 we can see that, even adopting the RANDOM1 selection mode, the approximated maximum value lies between no more than 30 cm from the reference value, even at small values of N. The improvements given by the application of the building algorithm are remarkable both in the RANDOM1 and the RANDOM2 case, shown in Figure 5.40, where some underestimation occurs with the building algorithm applied.

Figure 5.41 shows the approximated maximum values obtained using the ACCURATE selection mode, which turns out to be the best approximation. As we can see from the figure, the approximated values get closer and closer to the reference one when N approaches 20.

As a conclusion for these paragraphs, we can highlight some meaningful features by comparing the performances for the uppermost event and the deepest event. In both cases the results obtained on using the ACCURATE selection mode are better than the ones obtained using the RANDOM1 or RANDOM2 selection modes, proving that a careful arrangement of the available subfaults better exploits the information, that can be extracted from a certain area.

By comparing the two events, we can see that all the approximation procedures give lower errors for the event at depth, while the uppermost event is not always well approximated at lower values of N (see Figure 5.34 and Figure 5.35). This result is remarkable as it suggests that different values of N are needed at different depths to achieve the same degree of accuracy in approximating the reference forecast.

Aiming at optimizing real-time forecasting procedure, from the application of the building algorithm done so far, we learned that the optimal resolution in terms of unitary sources should change along the fault plane and should likely decrease at depth with respect to the upper fault areas.

6   Results and discussion

The main objective of this work is to explore a possible optimization of the real-time tsunami forecasting production, based on pre-computed scenario databases, proposing a new real time processing achieving the same accuracy of traditional methods but with less time costs.

The study has been conducted on the database MSDB produced in the frame of the European project TRIDEC as an experimental set of scenarios to be used by the Portuguese Tsunami Warning Systems. MSDB contains a wide number of tsunami wave propagation scenarios, generated by an arrangement of evenly-spaced unitary seismic sources covering the five seismogenic faults most relevant for Portugal. The key idea leading to the construction of MSDB was to use these elementary seismic sources as Green's functions, to produce real-time approximate solutions for the linear shallow-water equations, concerning a certain unknown tsunamigenic event. The analysis of this thesis has been limited to the Gorringe Bank Fault (GBF).

Within Chapter 3, we analysed water elevation fields and the associated waveform signals at specific locations, highlighting remarkable features that shaped the strategy of this thesis work: sources at depth induce water elevation fields with content of longwaves larger than surface sources, and the waveforms associated with deep unitary sources present higher cross-correlation values and lower relative differences between each other, than signals induced by the surface sources. Thus, considering the GBF tessellation where the unitary sources are arranged as a matrix with rows containing cells at the same depth and columns containing cells at increasing depth, we decided to seek for an optimal resolution by working along the rows.

Within Chapter 4, a seismic event of reference has been defined, located over the GBF surface, with Mw 8.1 and it has been associated with a reference forecast. It turned out that as many as 45 unitary sources are needed to cover the reference event fault, and hence that each waveform is a synthesis of 45 waveforms. Then, a

building algorithm has been designed to produce approximated forecasts of the tsunami waveform records, to understand how much information can be obtained through the exploitation of only a limited number (less than 45) of elementary sources solutions. Different configurations have been tested, by varying the number of subfaults. In addition, we have also considered two more reference solutions by shifting the reference event upward and downward over the GBF.

We obtained two remarkable results, in terms of both physical properties of the considered seismic area and of numerical and computational advantages.

From a physical point of view, we can state that an evenly-spaced arrangement of unitary sources over the considered fault is not suitable for an optimised forecasting procedure. In fact, concerning the reference events at middle and larger depths, we managed to approximate the associated reference forecast within a 5% average relative error (see Figure 4.13 and Figure 4.22), by using only half of the available subfaults, provided that a strategically designed building algorithm is adopted. This is based on results presented in Chapter 3. A higher number of unitary sources, instead, has been necessary to reach the same level of accuracy for the uppermost reference event (see Figure 4.18).

Coherently, we suggest that a proper tessellation of the seismic area should present higher resolution in the upper part of the fault and lower resolution at depth. The focus on the stations with extreme elevations, presented in Chapter 5, strengthens this suggestion (see Figure 5.4, Figure 5.16 and Figure 5.26).

From a practical point of view, we achieved remarkable results in terms of time optimisation. Producing a single reference forecast, by accessing the database for all the available unitary sources (45), has required more than one minute. The building procedure instead has required, on average, no more than two seconds to produce an approximate forecast, starting from half of the subfaults available and reaching a 5% relative error for the events located at middle and larger depth (see Figure 4.14 and Figure 4.23).

We saved therefore about half a minute, by paying a suitable 5% relative error price over the accuracy of the forecast. Moreover, computational time can be further

optimised with respect to the time required for data access, demonstrating the success of this strategy resulting in an overall benefit for the real-time tsunami forecasting practices.

Beyond these results, some worth-investigating issues are still open. In future works, the performances of the building strategy should be evaluated also for seismic events with different magnitudes over the Gorringe Bank fault. Then, the tests should be enlarged, taking into consideration other seismic faults of relevant interest for Portugal, such as the Horseshow Abyssal Plain area, the Marques the Pombal area and other potential tsunamigenic sources available in the database and well known to the scientific community (e.g. Omira et al., 2009). We believe however that the technique devised here will be proven to be validly beneficial also for more general cases, such as the seismogenic areas of the subduction zones in the Pacific Ocean, Indian Ocean, etc., that are highly tsunamigenic and are the most relevant target areas of regional and national tsunami warning systems.

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Appendix A

Here the Decision Matrices (DM) proposed for the NEAM area are presented. As described in the introduction, the DM is a simple tool providing essential guidelines to adopt within an occurring tsunami hazard.

The essential parameters of the new seismic event are required, i.e. epicentral location and estimated magnitude. Then, following these tables, the operator is supported in the decision-making process with simple guidelines.

The area affected by a certain tsunami threat is defined in the Decision Matrixes agreed by the ICG/NEAMTWS, per three different spatial ranges shown in Table A.1.

Tsunami Range	Mediterranean	NE Atlantic
Local	< 100 km	< 100 km
Regional	100 km to 400 km	100 to 1000 km
Basin	> 400 km	> 1000 km

Table A.1: Within the DM application, the geographical areas subject to the tsunami hazard are defined, according to their distance with respect to the epicentre location.

Examples of the DM proposed for the North-eastern Atlantic and Mediterranean area are shown in Table A.2 and Table A.3, respectively.

NE Atlantic Area							
Depth	Mw	Location	Potential	Type of bulletin	Geographical indication		
					Local	Regional	Basin wide
≤ 100 km	5.5 to 6.5	Coastal distance in ocean ≤ 40 km	Weak potential of local tsunami	Information	Advisory	Information	Information
	6.5 to 7.0	Coastal distance in ocean	Potential of local destructive tsunami	Information	Advisory	Information	Information
	7.0 to 7.5		Potential of local destructive tsunami	Advisory	Watch	Advisory	Information

Depth	Mw	Location	Potential	Type of bulletin	Local	Regional	Basin wide
	7.5 to 7.9	≤ 100 km	Potential of regional destructive tsunami	Watch	Watch	Watch	Advisory
	≥ 7.9		Potential of basin wide destructive tsunami	Watch	Watch	Watch	Watch
≥ 100 km	≥ 5.5	Coastal distance in ocean ≤ 100 km	Null potential	Information	Information	Information	Information

Table A.2: This table provides the Decision Matrix suggested for the North-eastern Atlantic area. The required information concerns the location and the magnitude of the new seismic event (indicated on the left). Depending on the initial parameters, the potential damage is estimated and the consequent message is proposed, accordingly to the target area.

Mediterranean Area							
Depth	Mw	Location	Potential	Type of bulletin	Geographical indication		
					Local	Regional	Basin wide
≤ 100 km	5.5 to 6.0	Coastal distance in ocean ≤ 40 km	Weak potential of local tsunami	Information	Advisory	Information	Information
	6.0 to 6.5		Potential of local destructive tsunami	Advisory	Watch	Advisory	Information
	6.5 to 7.0	Coastal distance in ocean ≤ 100 km	Potential of regional destructive tsunami	Watch	Watch	Watch	Advisory
	≥ 7.0		Potential of destructive tsunami basin wide	Watch	Watch	Watch	Watch
≥ 100 km	≥ 5.5	Coastal distance in ocean ≤ 100 km	Null potential	Information	Information	Information	Information

Table A.3: This table provides the Decision Matrix suggested for the Mediterranean area. The required information concerns the location and the magnitude of the new seismic event (indicated on the left). Depending on the initial parameters, the potential damage is estimated and the consequent message is proposed, accordingly to the target area.