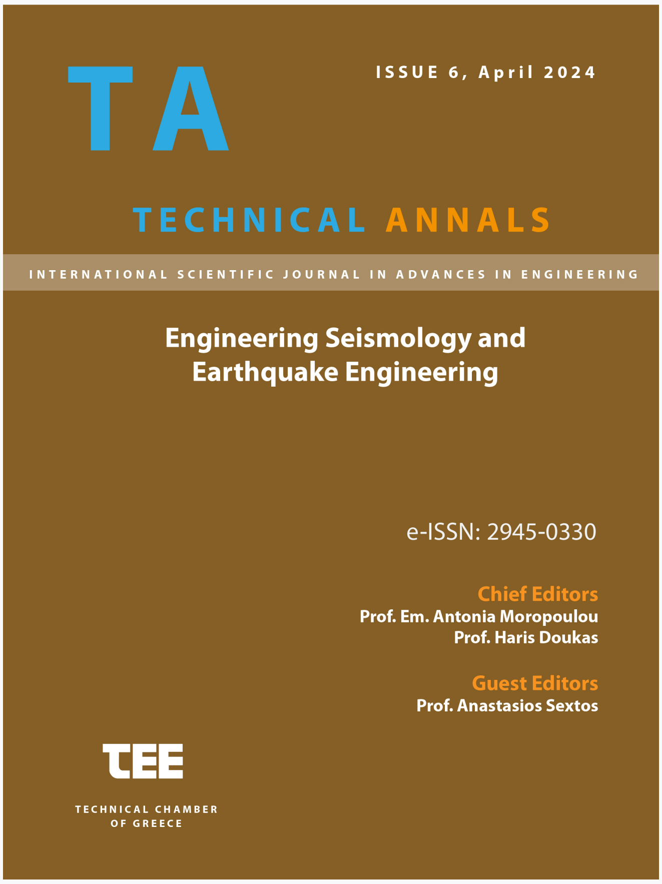
Technical Annals

Vol 1, No 6 (2024)

Technical Annals




# Can We Quickly Retrieve Seismic Source Spectrum Characteristics After a Large Magnitude earthquake? Implementation of a Methodology Based on Coda Wave Analysis

*Ioannis Grendas, Nikos Theodoulidis, Fabrice Hollender, Panagiotis Hatzidimitriou*

doi: [10.12681/ta.36965](https://doi.org/10.12681/ta.36965)

# Can we quickly retrieve Seismic Source Spectrum characteristics after a large magnitude earthquake? Implementation of an approach based on coda wave analysis

Grendas, I.[1][0000-0003-4142-1795], Theodoulidis, N.[1][0000-0002-0169-9197], Hollender, F.[2][0000-0003-1440-6389] and Hatzidimitriou, P.[3][000-0002-9366-1187]

[1]Institute of Engineering Seismology and Earthquake Engineering, Greece
[2]Atomic Energy and Alternative Energies Commission (CEA), France
[3]Aristotle University of Thessaloniki, Greece
grendasioannis@gmail.com, ntheo@itsak.gr,
fabrice.hollender@cea.fr, chdimitr@geo.auth.gr

**Abstract.** After a large magnitude earthquake event, the direct estimation of its Seismic Source Spectrum (SSS) is important to estimate the energy content of the seismic source in broad-band frequency range. This direct knowledge of the SSS, except for the fact that can directly provide information about the Moment Magnitude of the earthquake, constitutes also, in frequency domain, that information, which is required to the Fourier Amplitude Spectra (FAS) simulation of the real-input seismic motion, in several target sites close to the source for which no earthquake recordings exist. In this study, the computation of the SSS of an earthquake is based on a single-station analysis algorithm by applying the spectral factorization method on the coda wave part of a seismic record. An application of this algo-rithm is implemented here for the Mw = 6.1 Cephalonia Island earthquake of 26/01/2014. The corresponding SSS, computed for several stations away from the source, are compared with the average SSS retrieved by standard applied method. The comparison results strongly encourage application and development of this SSS computation approach.

**Keywords:** Seismic Source Spectrum, Coda waves, Near-field motion estimation

## 1 Introduction

Simulation of seismic ground motion or its Fourier Amplitude Spectrum (FAS) at specific sites close to a seismic fault, is significant in understanding the amount of energy that affected the nearby constructions. Realistic simulation is directly related to the knowledge of fault rupture, or in other words of its Source Time Function (STF). In most of large magnitude earthquakes ($M \geq 6.0$), the STF estimation is achieved through relevant time-consuming processes (e.g. the method of Empirical Green's Functions, [1], [2], [3]) that requires selection and combination of several earthquake records quite close to the seismic source, so as to converge to a single-accepted STF solution. In other cases, the STF estimation is impossible to be extracted, since not enough number of earthquake records exist close to the seismic source due to the lack of installed stations. For this reason, to estimate a STF, proper use of remote stations with respect to seismic source, is an issue that requires further research.

In this short study the applied methodology that uses the coda waves part of an earthquake recording, based on a particular property related to their "generation" natural mechanism, as firstly studied in [4], [5], and [6], seems that can provide Seismic Source characteristic by using remote stations with respect to the Source. Moreover, this methodology can be directly applied to a single earthquake-station record, without requiring the combination of several records of the same earthquake, being also feasible to make the computation in real time, after a few minutes of the earthquake occurrence and its origin time determination.

Except for the STF, its Fourier Amplitude Spectrum (FAS) is an essential information about the characteristics of the amount of seismic source energy releasement per each frequency, albeit it does not directly provide the time domain characteristics of the fault rupture. A methodology where the FAS of an earthquake can be estimated based on a single station analysis, by using the coda wave part of an earthquake record has been introduced in [7]. Moreover, based on this study ([7]), the unique produced wavelet, which corresponds to the minimum phase scenario of the extracted FAS, is similar to the real STF, which is general considered as a simple pulse, corresponding to a point source for low magnitude earthquakes. In large magnitude earthquakes the point source scenario is generally not the expected one, considering that the fault rupture is a relevant complicated function of space and time.

In this study an effort in retrieving the FAS of a large earthquake (Mw = ~6.1), based on this coda wave analysis [7], was implemented using the modified coda wave analysis algorithm developed in [8]. The examined earthquake is the one occurred in western Greece, on Cephalonia Island and it was chosen since its source characteristics were known by other studies and could validate the results extracted by the present research study.

It's worth noting that the coda wave analysis was applied to stations located on non-reference sites after removing their corresponding Site Amplifications Factor, as they were determined by [8], since no records were available by accelerographs located on rock site.

## 2 Methodology

Computation of the Fourier Amplitude Spectrum (FAS) of a seismic source, is based on a single station analysis proposed in [7], applied on the coda waveform of an earthquake record (e.g. Fig.1.). This analysis can be applied in 7 steps (Fig.2.), as defined in [8], plus one more aiming to scale the corresponding FAS of the seismic source. The analysis is based on the following fundamental equation (1) that relates the Power Spectral Density (PSD), $R_{ij}(f, t')$ of a coda wave window, centred at travel time, $t'$, with the corresponding PSD of the Seismic Source, $W_i(f)$, of $E_c$, coda excitation factor, of Attenuation Path, $|A_C(f, t')|^2$ and of Site Amplification Factor (SAF(f)2 = N_j (f)), at a station, j and a source, i ([4], [5], [6]):

$$R_{ij}(f,t') = W_i(f)\cdot E_c\cdot |A_C(f,t')|^2\cdot N_j(f) \tag{1}$$

where:

$$|A_c(f,t')|^2 = \frac{1}{(v_s\cdot t')^2} e^{-\frac{2\pi f t'}{Q_c(f)}} \tag{2}$$

and

$$W_i(f) = \frac{\left|\dot{\Omega}_i(f)\right|^2}{10\pi\rho\beta^5} \tag{3}$$

following the source model given in [9].

The attenuation factor (Eq. (2), [5], [6], [10]), except for the travel time, $t'$, is controlled by the average shear wave velocity, $v_s$ of the total examined area, as well as by the frequency dependent quality factor, $Q_c(f)$ of the coda waves. The PSD of the seismic source, $W_i(f)$, is controlled by its corresponding FAS, $\dot{\Omega}_i(f)$ and is scaled by the average shear wave velocity, $\beta$ and density, $\rho$ close to the fault.

The $R_{ij}(f,t')$ is also controlled by the coda wave excitation factor, $E_c$ ([11]) as following:

$$E_c = \frac{1}{\pi\cdot l} \tag{4}$$

where, $l$ (in meters) is the mean free path factor ([6]), expressing the fractional loss of energy per unit travel distance of the shear waves from the source to the receiver, due to the wave scattering by the lithosphere heterogeneities ([12]). All those scattered waves arrive late in time, after the main seismic motion of the direct P and S-waves, with reduced amplitudes in time, due to the longer travel distances and they actually form the “tail” of the seismograms (e.g. Fig.1.).

The first two steps of the coda wave analysis, refer to the signal pre-processing corrections related to the instrument characteristics, as well as to a suitable Signal to Noise Ratio (SNR) analysis determined in [8], so as to detect the good quality coda wave record which is able to extract the reliable FAS of the seismic source.

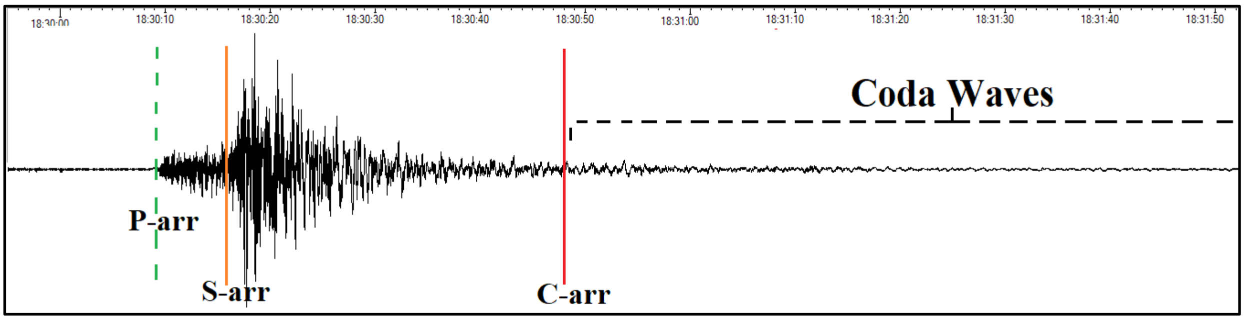



**Fig. 1.** An example of an earthquake record, where the P, S and Coda wave arrival times are depicted, in green, orange and red vertical lines, respectively.

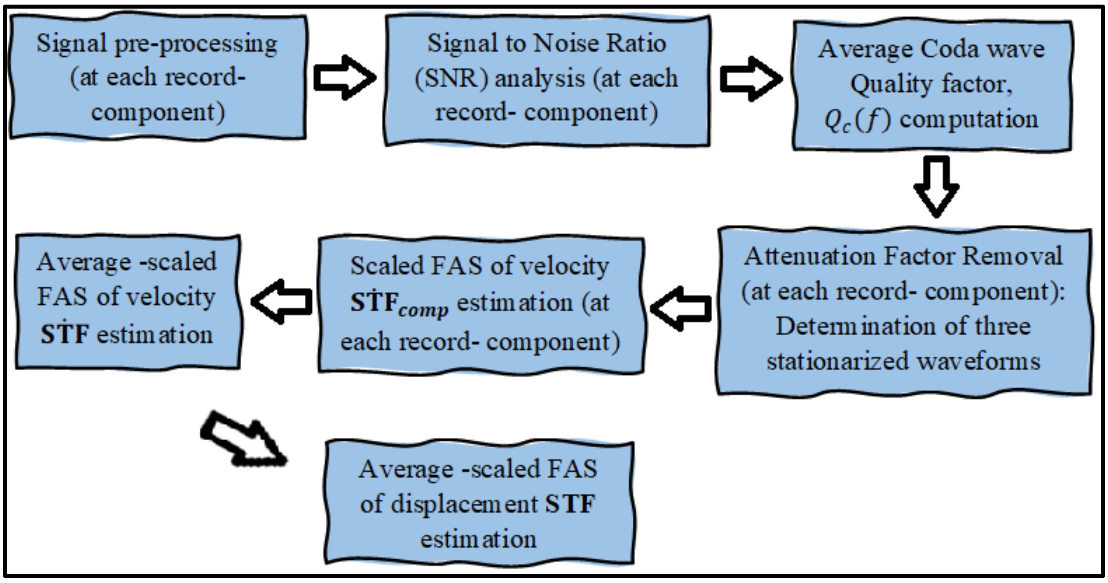



**Fig. 2.** The flowchart of the 7 steps applied by the examined coda wave analysis, for the estimation of the average – scaled by the mean free path factor, $FAS[\mathrm{STF}^{sc}]$ (in displacement) (modified by [8])

In the third step the common for the three components (EW, NS and vertical one) frequency dependent coda wave Quality factor, $Q_c(f)$ is estimated, as well as its standard deviation, based on the process introduced in [5] and analytically explained in [13]. In the fourth step the frequency dependent and distance dependent attenuation factor is removed in time domain by each component of the source-site coda wave record, based on the deconvolution ([14]) of all the progressive in time, $t'$ minimum phase wavelets, $A_c(t,t')^{min}$ (Eq. (2)), as analytically explained in [8]. By this way the three component coda wave records (e.g. Fig.3., top) are "corrected" for the attenuation factor and three stationarized waveforms are "created" (e.g. Figure 3, bottom). These three waveforms are directly reduced to the source, but they are still scaled by the constant mean free path factor (Eq. (1) and (4)).

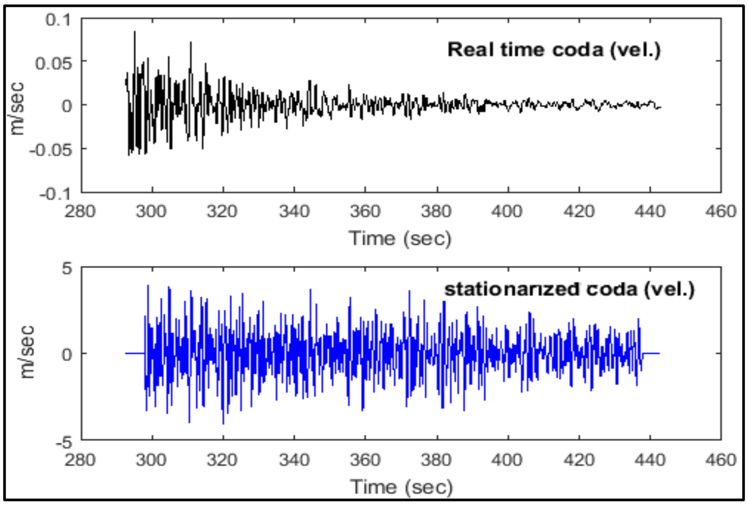



**Fig. 3.** An example of a real coda waveform (top) and of the corresponding corrected for the attenuation factor, stationarized coda waveform (bottom).

In the fifth step of the coda wave analysis algorithm (Figure 2) the scaled FAS of the $S\dot{T}F$ (in velocity) at each horizontal component $FAS[S\dot{T}F^{sc}_{comp}]$) is extracted (e.g. Figure 4a), being uncorrected for the low frequency noise effect, related to the SNR process. Finally, at the sixth step the two horizontal components STF (in velocity) are cumulatively combined in terms of energy according to the following formula:

$$FAS[S\dot{T}F^{sc}] = \sqrt{FAS[S\dot{T}F^{sc}_{EW}]^2 + FAS[S\dot{T}F^{sc}_{NS}]^2} \quad (5)$$

concluding to the average, scaled by the mean free path factor, $FAS[S\dot{T}F^{sc}]$ (in velocity). It's worth noting that the standard deviation of each $FAS[S\dot{T}F^{sc}_{comp}]$), is considered in the average $FAS\left[S\dot{T}F^{sc}\right]$ computation, based on the propagation error method.

In the seventh step (Fig.2.), the average, scaled by the mean free path factor, $FAS[\mathrm{STF}^{sc}]$ in displacement is determined after dividing by the frequency dependent, 2πf, factor (f ≠ 0) (e.g. Fig.4b). Here it must be clarified that this $FAS[\mathrm{STF}^{sc}]$ refers to the good quality part of the coda waves in frequency domain defined after the suitable Signal to Noise Ration process and it is still affected by the low frequency noise. In general, in case that the minimum phase wavelet corresponding to $FAS[\mathrm{STF}^{sc}]$ is wished to be computed, this low frequency noise effect must be corrected in an extra step, to a low frequency plateau (e.g. Fig.4b), as it is normally expected for the STF which must be a positive wavelet representing the moment rate in time.

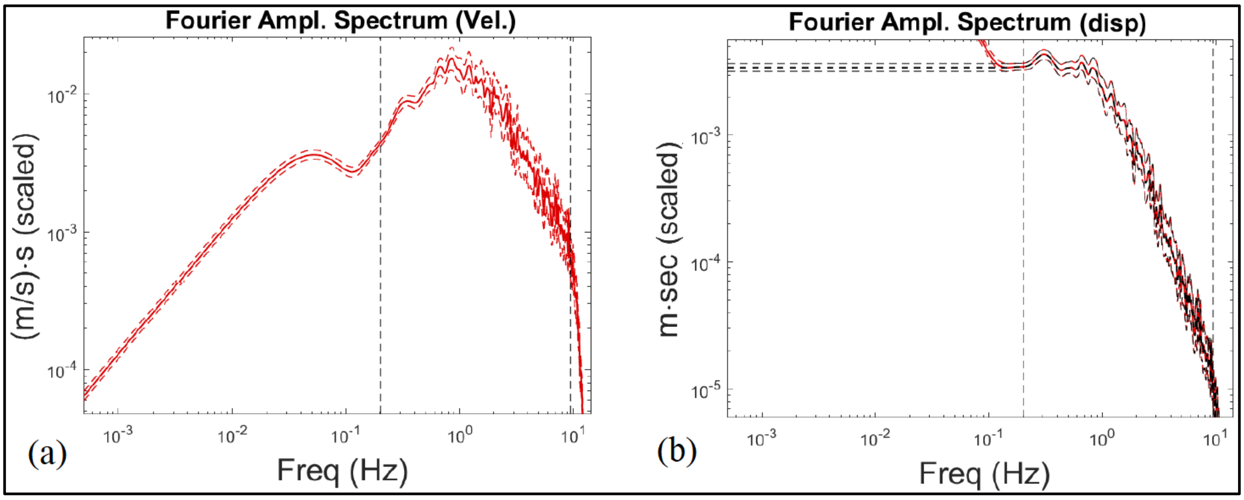



**Fig. 4.** (a) An example of a 〖FAS[(STF)˙〗_comp^sc]) (Eq. (5)), in velocity (for the EW component) and of its standard deviation, for the ML = 4.3 earthquake of 20190117_214639. Between the vertical dashed lines, the reliable frequency range is defined based on the already applied SNR process (b) An example of a FAS[(STF) ^sc] (in displacement) (Eq. (5)). In horizontal black dashed line, the low frequency plateau correction on the non-reliable frequency part, is depicted.

## 3 Data

The data used in this study refer to the coda wave part (e.g. Fig.1.) of five, 3-component, seismic records, corresponding to the $M_w$ = 6.1 (±0.2) ($M_L$ = 5.8) earthquake occurred in western Greece (Cephalonia island, 26/1/2014, GMT: 13:55:43, Lat: 38.1522o, Long: 20.3912o, Depth: ~15 km, as given by the Seismological Station of Aristotle University of Thessaloniki and confirmed in [15]) (Fig.5.). The examined earthquake records correspond to the accelerograph stations: PRE2, MSL1, PAT4, KAC1 and ZAK2, which belong to the Institute of Engineering Seismology and Earthquake Engineering (ITSAK). These recordings were selected in this study, since they were the only ones that included coda wave records appropriate to be analyzed and were not interrupted by the occurrence of other local earthquake recordings. Regarding the characteristic of the examined Seismic Source of the Cephalonia earthquake the fault process of this earthquake was related to the Cephalonia Transform Fault zone ([16]), as it is indicated in [17] and was dominated mainly by a dextral strike slip motion (Figure 5). Also, based on the rupture process study of this earthquake which was carried out in [15], the fault strike lies on NNE-SSW direction, and its plane is steeply dipped to the East (Fig.5.).

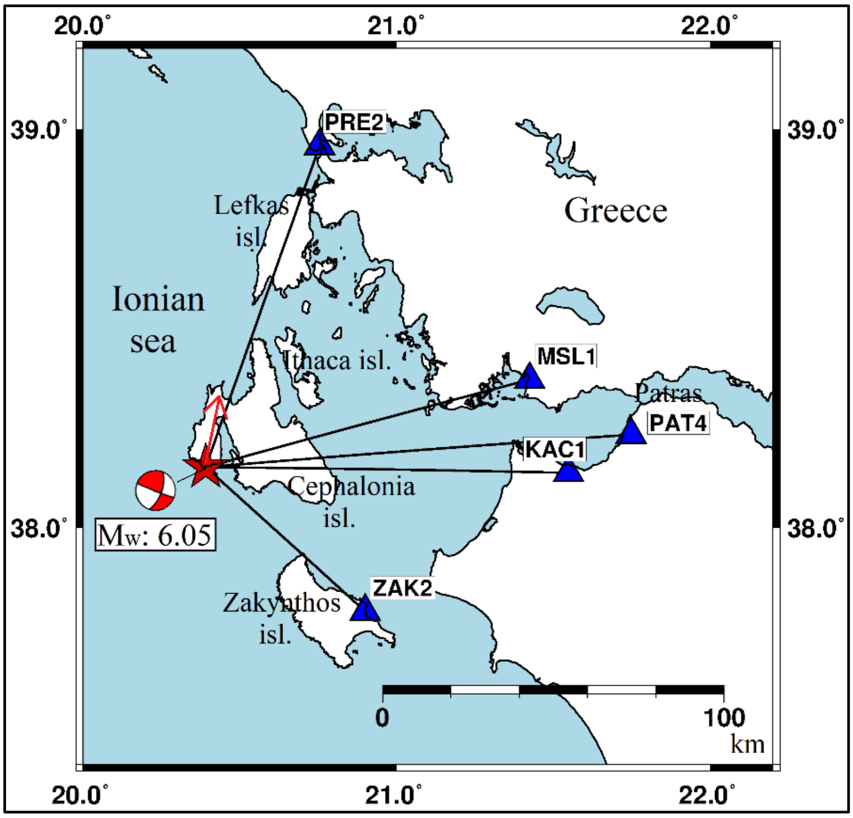



**Fig. 5.** The examined area (western Greece). In red asterisk the location of the Cephalonia earthquake is depicted ([15] and Seismological Station of Aristotle University of Thessaloniki), as well as its focal mechanism ([17]) and the rupture direction (red arrow). The location of the five examined stations (Institute of Engineering Seismology and Earthquake Engineering), are presented in blue triangles

## 4 Results

Based on the coda wave analysis mentioned above, the scaled Fourier Amplitude Spectra, $FAS\left[S\dot{T}F^{sc}\right]$ (Eq. (5), e.g. Figure 4a), in velocity, of the $M_w$ = 6.1, Cephalonia earthquake, for the horizontal component, were determined for the five examined stations (Fig.5.). Then the corresponding scaled $FAS[\mathrm{STF}^{sc}]$ in displacement were computed by dividing the $FAS\left[S\dot{T}F^{sc}\right]$ ], with 2πf ($f \neq 0$). Finally, these $FAS[\mathrm{STF}^{sc}]$ results were divided by the coda excitation factor, $E_c$ (Eq. (4)), based on Eq. (1), so as to be scaled. The mean free path value, $l$ (Eq. (4)) was considered equal to 253 km, as it was determined in [8], examining plethora of low to moderate magnitude earthquakes in this area (western Greece) and scaling the computed $FAS[\mathrm{STF}^{sc}]$ with the extracted ones by a Generalized Inversion Technique application for the same dataset ([18]). Except for the average value of $l$, its standard deviation range, in logarithmic scale (88 km

– 727 km), which was also determined in [8], was considered in order to take into account the statistical uncertainties at the $FAS$[STF] estimation. In Figure 6 the unscaled $FAS$[STF] results of the examined earthquake, for the five examined station, are presented. It's worth noting that these $FAS$[STF] are also corrected for the corresponding known frequency dependent average Site Amplification Factors (SAF(f)), as they were computed in [8]. The correction was achieved in frequency domain by dividing the $FAS$[STF] with the corresponding SAF(f).

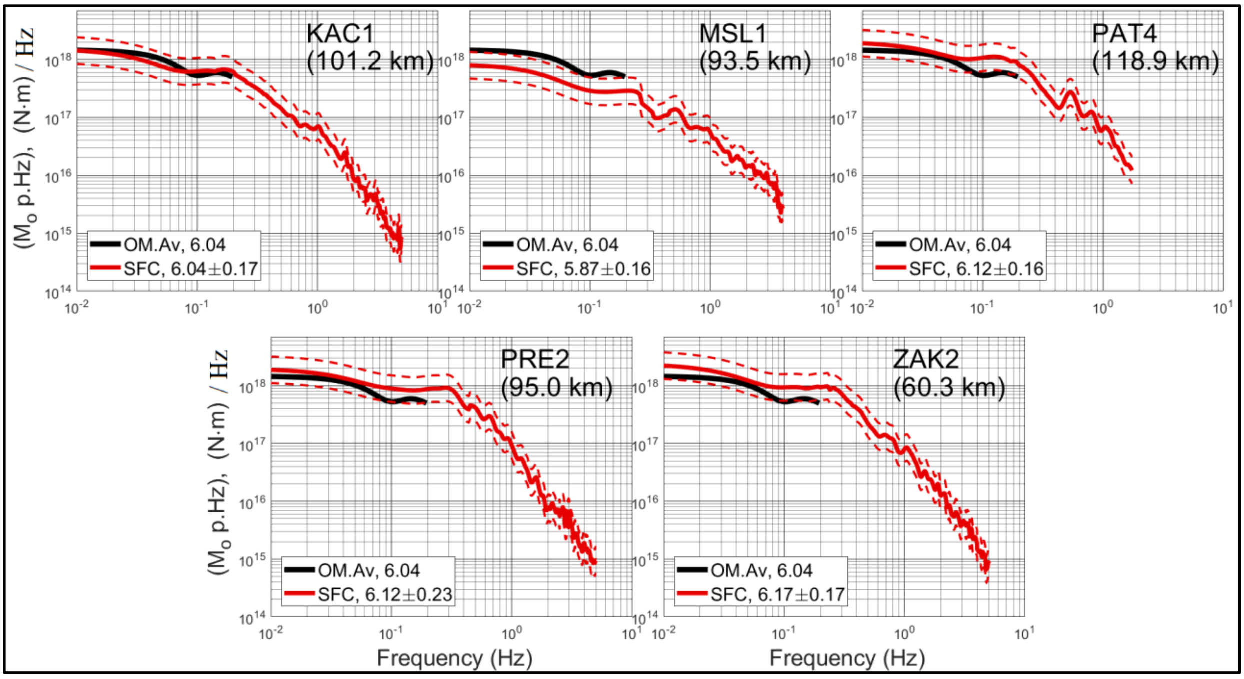



**Fig. 6.** The examined area (western Greece). In red asterisk the location of the Cephalonia earthquake is depicted ([15] and Seismological Station of Aristotle University of Thessaloniki), as well as its focal mechanism ([17]) and the rupture direction (red arrow). The location of the five examined stations (Institute of Engineering Seismology and Earthquake Engineering), are presented in blue triangles

The moment magnitudes, $M_w$, separately extracted by each one $FAS$[STF] (Figure 6), are quite close to the $M_w$ = 6.04±0.20, determined in [15], [17] and by the Seismological Station of Aristotle University of Thessaloniki, while their average, $M_w$= 6.08±0.20 (Figure 7a) and its standard deviation indicate reliable results regarding the scaling of the $FAS$[STF]. Moreover, a quite good agreement is presented between all the $FAS$[STF] and their standard deviation range at each station, with respect to the corresponding average $FAS$[STF] extracted by an alternative methodology performed in [15], up to 0.2 Hz, which is the higher frequency limit of their computation. Also, the results by the coda wave analysis gave Fourier Amplitude information in higher frequencies up to ~5 Hz, where in Figure 7a, it seems that they satisfactorily agree between each other. This result also supports reliability of the examined $FAS$[STF] estimation approach, although corresponding information in higher frequencies do not exist by other methodologies to compare.

Finally, in this study an effort was made in retrieving the Source Time Function wavelets, of the examined earthquake, at each station, based on the computed $FAS$[STF] (Fig.6.) and on the minimum phase scenario, as proposed in [7]. The results presented in Fig.7b, confirm that the minimum phase scenario in large magnitude earthquake like the examined one, ($M_w$ = ~6.1) does not satisfactory simulate how the energy releases in time (Fig.7c). However, as it is presented in Fig.7d, based on the total energy release computations of Fig.7c, the 95% of the total energy release by the minimum phase STF wavelets (average ~12.5 sec), is in good agreement with the actual fault-rupture duration (~12.1 sec) estimated in [15]. This indicates that the minimum phase scenario could reveal this important information of the seismic source.

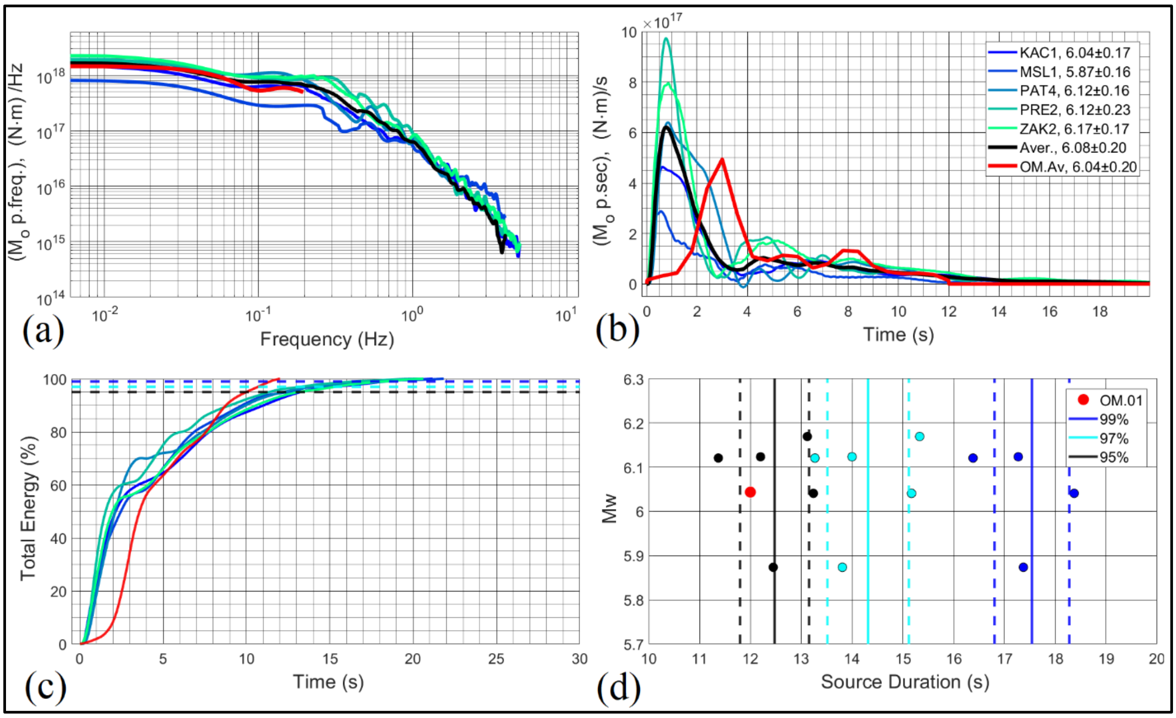



**Fig. 7.** (a) The $FAS$[STF] of the examined earthquake computed in this study (Fig.6.), for each one of the five stations (multi-color lines), their average one (black line) and the $FAS$[STF] (red line) computed by [15], using Other Methodology (O.M.). (b) The corresponding to each $FAS$[STF] of Figure 7a, minimum phase wavelets (c) The total energy release of each minimum phase wavelet of Figure 7b (d) The duration of each minimum phase wavelet of Fig.7b, corresponding to 95%, 97% and 99% of the total energy release of Fig.7c.

## 5 Conclusions

In this study an application of the Spectral Factorization of Coda waves (SFC) methodology, proposed in [7], was applied for a large magnitude earthquake, Mw = ~6.1, in Cephalonia Island 9 (26/1/2014), aiming at retrieving the Fourier Amplitude Spectrum (FAS) of its Source Time Function (STF). Five FAS[STF]s were computed for five accelerograph stations located in western Greece, recorded the earthquake in epicentral distances from ~60 km to 120 km. These FAS[STF]s results are in satisfactory agreement with the corresponding FAS[STF]s determined in [15] at least up to ~0.2 Hz, the upper frequency limit of the latter. Moreover, the computed seismic moment magnitudes determined separately by these FAS[STF]s, as well as their average ($M$w= 6.08□}0.20), are in very good agreement with the corresponding magnitude determined in [15], [17] and by the Seismological Station of Aristotle University of Thessaloniki. In general, the FAS[STF]s of this study exhibits a satisfactory agreement between each other, providing information up to ~5 Hz. This agreement and stability of the results is encouraging to assessing reliably and rapidly seismic source properties based on coda waves.

Finally, an effort in retrieving the minimum phases STF wavelets was implemented. Based on the results it can be concluded that the minimum phase scenario does not satisfactorily agree with the STF estimated in [15]. Consequently, it seems that the methodology applied in this study cannot accurately estimate STF of complex seismic sources (e.g. M ≥ 6.0). However, based on the estimated minimum phase STF wavelets, it results that their duration which corresponds to 95% of the total energy release (11.5-13.1 sec), is in very good agreement with the respective STF duration (~12.1 sec) estimated in [15]. After all, it can be concluded that the methodology applied in this study can reliably and quickly estimate important properties of the seismic source, even for large magnitude earthquakes. Consequently, estimation of strong ground motion in the near field can be greatly supported by the methodology applied in this work.

## Acknowledgments

This work was funded by the SIREAT (KE 2.027) project. Pr. Pierre-Yves Bard has greatly contributed to understanding the theoretical background of the applied methodology.

## References

1. Courboulex F, Santoyo MA, Pacheco JF, Singh SK. The 14 September 1995 (M = 7.3) Copala, Mexico, earthquake: a source study using teleseismic, regional, and local data. Bull Seism Soc Am 1997;87–4:999–1010.
2. Roumelioti Z, Benetatos C, Kiratzi A. The 14 February 2008 earthquake (M6.7) sequence offshore south Peloponnese (Greece): source models of the three strongest events. Tectonophysics 2009;471–3:272–284.

3. Vallée M. Stabilizing the empirical Green function analysis: development of the projected Landweber method. Bull Seism Soc Am 2004;94–2:394–409.
4. Aki K. Analysis of the Seismic Coda of Local Earthquakes as Scattered Waves. J Geophys Res 1969;74:615–31.
5. Aki K, Chouet B. Origin of coda waves: Source, attenuation, and scattering effects. J Geophys Res 1975;80:3322–42. https://doi.org/10.1029/JB080i023p03322.
6. Sato H. Energy propagation including scattering effects single isotropic scattering approximation. J Phys Earth 1977;25:27–41. https://doi.org/10.4294/jpe1952.25.27.
7. Sèbe O, Guilbert J, Bard P-Y. Spectral factorization of the source time function of an earthquake from coda waves, application to the 2003 rambervillers, France, earthquake. Bull Seismol Soc Am 2018;108:2521–42. https://doi.org/10.1785/0120170038.
8. Grendas I, Theodoulidis N, Bard PY, Perron V, Hatzidimitriou, P., Hollender F. Can site effects be estimated with respect to a distant reference station? Performance of the spectral factorization of coda waves. Geophys J Int 2022;230:1–28.
9. Vassiliou MS, Kanamori H. The energy release in earthquakes. Bull Seismol Soc Am 1982;72:371–87.
10. Sato H, Fehler MC, Maeda T. Seismic wave propagation and scattering in the heterogeneous earth. Vol. (496). Berlin: Springer; 2012.
11. Herraiz M, Espinosa AF. Coda waves: A review. Pure Appl Geophys PAGEOPH 1987;125:499–577. https://doi.org/10.1007/BF00879572.
12. Aki K. Scattering and attenuation of shear waves in the lithosphere. J Geophys Res 1980;85:6496–504. https://doi.org/10.1029/JB085iB11p06496.
13. Margerin L, Campillo M, Shapiro NM, Van Tiggelen B. Residence time of diffuse waves in the crust as a physical interpretation of coda Q: Application to seismograms recorded in Mexico. Geophys J Int 1999;138:343–52. https://doi.org/10.1046/j.1365-246X.1999.00897.x.
14. Margrave GF. Theory of nonstationary linear filtering in the Fourier domain with application to time-variant filtering. Geophysics 1998;63:244–59. https://doi.org/10.1190/1.1444318.
15. Sokos E, Kiratzi A, Gallovič F, Zahradník J, Serpetsidaki A, Plicka V, et al. Rupture process of the 2014 Cephalonia, Greece, earthquake doublet (Mw6) as inferred from regional and local seismic data. Tectonophysics 2015;656:131–41. https://doi.org/10.1016/j.tecto.2015.06.013.
16. Scordilis EM, Karakaisis GF, Karacostas BG, Panagiotopoulos DG, Comninakis PE, Papazachos BC. Evidence for transform faulting in the Ionian sea: The Cephalonia island earthquake sequence of 1983. Pure Appl Geophys PAGEOPH 1985;123:388–97. https://doi.org/10.1007/BF00880738.
17. Karakostas V, Papadimitriou E, Mesimeri M, Gkarlaouni C, Paradisopoulou P. The 2014 Kefalonia Doublet (Mw6.1 and Mw6.0), central Ionian Islands, Greece: Seismotectonic implications along the Kefalonia transform fault zone. Acta Geophys 2015;63:1–16. https://doi.org/10.2478/s11600-014-0227-4.
18. Grendas I, Hollender F, Theodoulidis N, Hatzidimitriou P. Spectral decomposition of S - waves in investigating regional dependent attenuation and improving site amplification factors: A case study in western Greece. Bull Earthq Eng 2022:1–25. https://doi.org/10.1007/s10518-022-01459-z.