



HAL
open science

Single station estimation of seismic source time function from coda waves: The Kursk disaster.

O. Sebe, Pierre-Yves Bard, J. Guilbert

► To cite this version:

O. Sebe, Pierre-Yves Bard, J. Guilbert. Single station estimation of seismic source time function from coda waves: The Kursk disaster.. Geophysical Research Letters, 2005, 32 (4), pp.L14308. 10.1029/2005GL022799 . hal-00107881

HAL Id: hal-00107881

<https://hal.science/hal-00107881>

Submitted on 19 Feb 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Single station estimation of seismic source time function from coda waves: The Kursk disaster

Olivier Sèbe,^{1,2} Pierre-Yves Bard,¹ and Jocelyn Guilbert³

Received 23 February 2005; revised 11 May 2005; accepted 21 June 2005; published 23 July 2005.

[1] We propose a high-resolution technique for estimating the source time function of a seismic event from only one record. This technique is based on the spectral factorization of the minimum phase wavelet from the most random part of a seismogram: its coda. As the coda non-stationarity is inconsistent with the classical spectral factorization theory, we develop a two-step algorithm: first, the diffuse coda field is whitened to remove the non-stationary attenuation effect; second, the minimum phase wavelet equivalent of the seismic source time function is estimated. Applied to the recordings of the Kursk's wreck, this method gives a source wavelet strikingly similar to the general shape of an underwater explosion, allowing us to infer its depth and yield. Based on the fundamental "random" character of diffusive waves, this approach opens up promising applications for new blind deconvolution methods.

Citation: Sèbe, O., P.-Y. Bard, and J. Guilbert (2005), Single station estimation of seismic source time function from coda waves: The Kursk disaster, *Geophys. Res. Lett.*, 32, L14308, doi:10.1029/2005GL022799.

[2] Recovering the source time function of a seismic event, i.e. the time history of the excitation process inside the earth, is an important goal for seismologists as it provides essential information on the physical mechanism of the source and the local geologic conditions. This goal is not limited to large, destructive events, but is also crucially important as a tool to monitor compliance with the CTBT (Comprehensive Test Ban Treaty), which implies the need to develop high resolution, reliable tools applicable to small magnitude events ($M < 3.5$) that are often sparsely recorded.

[3] The techniques presently used in that aim are based on the analysis of the most energetic and coherent part of the seismic signals, i.e., direct body waves travelling deep in the Earth, and/or surface waves guided along the Earth's surface; they require the processing of several simultaneous recordings obtained at different locations, as well as some a priori information on the inner structure of the Earth, in order to separate propagation and source effects. As small-scale heterogeneities within the Earth are only very poorly known, their resolution is limited to the low frequency

domain, while moderate events emit their maximum energy in the intermediate to high frequency domain.

[4] This paper is intended to illustrate one simple (but dramatic) example of a promising new technique allowing the reliable, high resolution reconstruction of the high frequency source time function from a single recording: paradoxically this is possible by considering the most random part of seismic signal, i.e. its coda.

[5] There exist many seismic events for which it is important to identify and characterize quickly the source phenomena (earthquakes, blasts, volcanoes, ...). This was the case for the dramatic explosion and wreck of the "Kursk" Russian submarine that occurred within the Barents sea on August 12, 2000, and took more than one hundred lives (Figure 1).

[6] While the location and the size of this explosion were easy to determine with usual seismological tools (69.628° North, 37.160° East; equivalent magnitude m_b 3.5) [Koper *et al.*, 2001], its finer characterization (depth, single or multiple explosion, energy) is a much more difficult endeavour. It requires discriminating among different physical phenomena (Figure 2). First, the gas bubble generated by an underwater explosion has an oscillatory motion due to the competition between expanding internal pressure and confining hydrostatic pressure [Cole, 1948]. Moreover, the reflections on both the sea surface and the sea-floor of acoustic waves emitted by the explosion, generate various echoes (Figure 2b), with delay times depending on the explosion depth and the water layer thickness [Wielandt, 1975], all overlapping with the bubble oscillation. A reliable assessment of this kind of source time function requires a high resolution not only in frequency (< 0.5 Hz) but also in time (< 0.02 s) (Figure 2c).

[7] Some attempts have been made to take advantage of the very specific peculiarities of the spectral shape of such underwater explosions to infer details of the Kursk disaster. Koper *et al.* [2001] estimated the depth and the yield of the explosion from the location of spectral troughs, while Guilbert [2004] emphasized the use of cepstral analysis to improve the time resolution. However, neither of these techniques could offer an unambiguous estimate of the actual source time function, because of the trade-off between the different physical phenomena: echo, bubble oscillation, possible multiple explosions and crustal propagation effects such as attenuation.

[8] Considering the limitations when interpreting only the direct body waves, we thus decided to work with the late part of the recordings (Figure 1), classically called "coda" after Aki [1969]. Coda waves are due to the scattering of primary waves on crustal heterogeneities, which redirect them in all directions (such as light within fog). Such a choice may look strange at first glance since coda waves are

¹Laboratoire de Géophysique Interne et Tectonophysique, Université Joseph Fourier, Grenoble, France.

²Also at Commissariat à l'Énergie Atomique—Department of Analysis and Surveillance of Environment—Laboratoire de Détection et de Géophysique, Bruyères le Châtel, France.

³Commissariat à l'Énergie Atomique—Department of Analysis and Surveillance of Environment—Laboratoire de Détection et de Géophysique, Bruyères le Châtel, France.

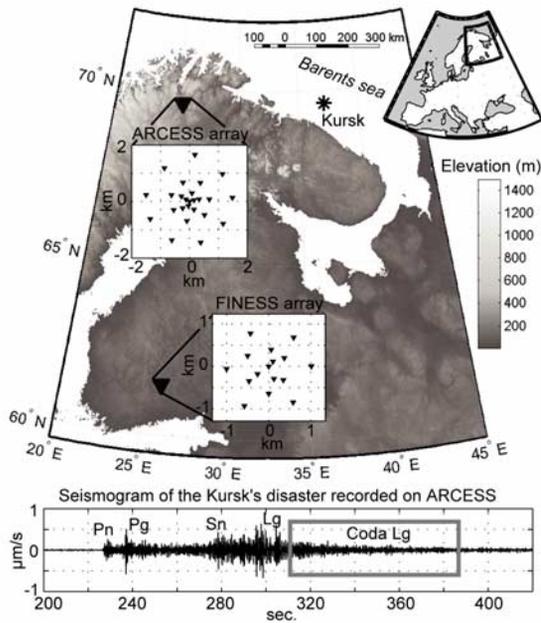


Figure 1. The Kursk's explosion seismogram recorded by the central station of the ARCESS. Among the different seismic phases of seismograms, we focus our study on their apparently most random part: Lg coda waves (rectangle).

quasi-random and non-stationary, while we look for a high-resolution estimate of the source time function.

[9] The signal processing community has developed several deconvolution techniques allowing ones to represent a random signal as the convolution of an uncorrelated stationary random process with a deterministic signal. Our work has thus consisted mainly of adapting some of these signal processing techniques to the particular case of coda waves, using the randomness of scattering on distributed crustal heterogeneities compared to the finite duration deterministic source wavelet. As seen in Figure 1, coda waves are indeed not stationary since their amplitude is decreasing with time: increasing travel times correspond to longer and longer paths, with diffraction on an increasing number of scatterers. This apparent “attenuation”, classically characterized in seismology by a “Coda Q” quality factor denoted Q_c , introduces both a non-stationarity and a correlation which must be removed. However, current seismic source studies based on coda waves [Aki and Chouet, 1975; Mayeda and Walter, 1996; Rautian and

Khalturin, 1978] allow one to extract only the spectral characteristics but not their time dependence. On the other hand, present approaches to correct for the non-stationary apparent attenuation still follow Aki and Chouet's initial developments based on simple narrow band-pass filtering: their resolution power is not high enough to allow the reconstruction of all the details of the source time function of complex events.

[10] The first step of our work is to improve the procedure for correcting this apparent attenuation. The second step is then to use spectral factorization techniques [Claerbout, 1976] to recover the power spectrum of the source wavelet, and then to assign a phase in order to reconstruct the source function in the time domain.

[11] Rather than correcting for coda attenuation for discrete frequency values, we performed a global correction over the whole spectrum by non-stationary deconvolution. According to Sato and Fehler [1998] and Tregoures and Van Tiggelen [2002] the coda waves field attenuation A_c follows a general algebro-exponential formula which is equal to (1) for a layered medium in diffusive regime (heterogeneous crust overlying a homogeneous mantle) [Margerin et al., 1998]:

$$|A_c(t, f)| = \frac{1}{(tt^*)^{1/2}} e^{-\frac{t}{Q_c(t)}} \quad (1)$$

where f is frequency, t is lapse time ($t > 2t_s$ where t_s is the S wave arrival time), t^* is transport mean free path and Q_c the frequency dependent “coda Q” made up of intrinsic attenuation Q_i^{-1} and a frequency dependent term Q_{cr}^{-1} linked to the leakage of the energy from the crust to the mantle [Margerin et al., 1998]. For a multi-scale distribution of crustal heterogeneities such as exponential model, $t^*(f)$ can be considered as frequency independent [Ishimaru, 1978] since the studied frequency band (>1 Hz) corresponds to the domain where $ka \gg 1$ (with a correlation distance $a > 1$ km) [Gusev and Abubakirov, 1996]. We classically estimate Q_c in northern Norway by filtering the coda in 12 narrow band pass with central frequencies regularly and geometrically spaced between 0.3 and 20 Hz, followed by a fit to the formula $Q_c(f) = Q_0 f^{\alpha}$. The time domain coda signals corrected for attenuation are then estimated through a nonstationary deconvolution with causal filters $|A_c(t, f)| e^{-i\varphi(f, t)}$ reconstructed from the spectral amplitude $|A_c(t, f)|$ where the phase $\varphi(f, t)$ is derived from the causality assumption [Aki and Richards, 1980].

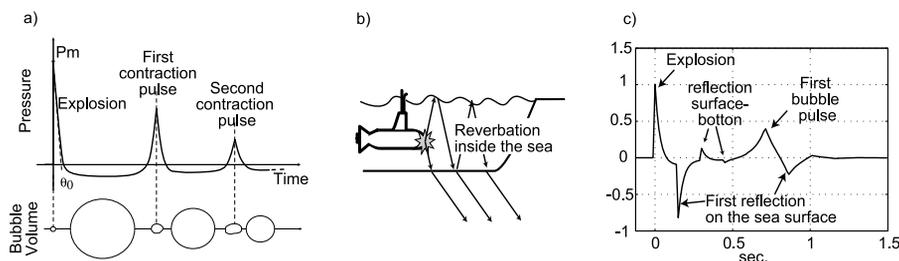


Figure 2. (c) The theoretical source time function of an underwater explosion is made up of (a) the convolution of the bubble oscillation history and (b) the reverberation inside the water layer. This theoretical source time function has been computed using a bubble oscillation period of 0.72 s, an amplitude decay ratio of 0.5 between the first and second pulse, and a depth of 121 m.

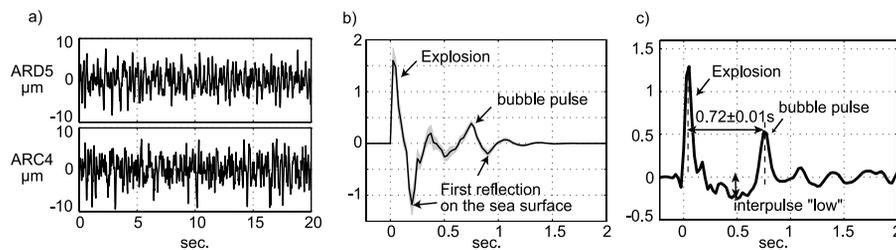


Figure 3. (a) The first 20 seconds of the stationarized coda window on 2 distinct stations of the ARCESS array. Despite the small inter-station distance (about 3 km), signals are highly incoherent. (b) Minimum phase estimates of the source time function (black curve = average curve from the 25 ARCESS array recordings; grey zone corresponds to average \pm one standard deviation). The main characteristics of an underwater explosion, i.e., bubble oscillation and underwater reverberations, appear clearly. (c) The bubble pressure history, obtained after removing the effect of the multiple echoes inside the sea.

[12] We can then assume that the autocorrelation of this whitened and stationary coda signal reflects the information on the source wavelet: the Fourier transform of this autocorrelation function can be interpreted as the Fourier spectrum of the source function. Its frequency resolution Δf no longer depends neither on the number of frequencies used in the band-pass filtering process, nor on the type of filter that is used. It is directly proportional to the duration T_w (exceeding 3s in this study) of the autocorrelation window used to calculate the source: $\Delta f = k/T_w$. The longer it is, the better the resolution and the higher the quality of the estimated source spectral amplitude. As for the scale factor k , it is related to the kind of autocorrelation weighting window (e.g., equal to 1 for a box window).

[13] To obtain the source time function, one then needs to assign a phase to this spectral amplitude. In this study, we adopted the minimum phase assumption commonly used in seismic exploration [Robinson, 1967], even if it is not always true [Barrodale et al., 1984]. This assumption was carefully checked by Sèbe [2004] through an extensive parameter study of the differences between the theoretical source function shape and its minimum phase equivalent. We showed that an underwater explosion could be considered at least to the first order as a minimum phase wavelet. The phase can then be estimated with the Bode-Bayard relationships, through the Hilbert transform of the logarithm of the spectral amplitude [Claerbout, 1976; Kolmogorov, 1939; Oppenheim and Schaffer, 1975]. The physical meaning of this minimum phase property is that the corresponding wavelet is, among all the causal waveforms having the same assigned spectral amplitude, the one with the faster energy release.

[14] This processing was thus applied to the Kursk explosion recordings obtained at the ARCESS array, located in Norway 530 km away from the wreck, and consisting of 25 stations located within a circle of about 3 km radius. After correcting for the instrument response, a 40 s long window is selected in the coda, corresponding to a crustal travel path of at least 100 s (i.e., exceeding 3000 km). The length of this coda is limited by the requirement to have a signal to noise ratio larger than 2 over the whole frequency band [0.3–20 Hz]. At each station, this window is then corrected for the non-stationary coda attenuation, as displayed in Figure 3a, and the source time wavelet is reconstructed. Figure 3b displays the average (plus minus one standard deviation) of the wavelets retrieved from each

recording, and compares it with the theoretical source function [Barrodale et al., 1984] of an underwater explosion with appropriate parameters. The striking agreement between theoretical and experimental curves provides good evidence of the possibility to reconstruct accurately, even at distances larger than 500 km, the source function with a time resolution as small as 0.0125 s, and to clearly distinguish the initial pulse of the explosion, and its reverberations at the sea surface and bottom. The very small standard deviation also supports the robustness of the technique, even at high frequencies where coda recordings are highly incoherent (Figure 3a).

[15] This source function allows a very precise estimate of the depth of the vessel at the time of the explosion, from an analysis of the delays and polarities of echoes. Surface reflections are associated with an echo having the same polarity as the initial pulse, while bottom reflections correspond to an inverse polarity. Considering that sound velocity in the Barents sea is around 1470 m/s [Fofonoff, 1985], the measured delay time of 0.165 ± 0.0125 s provides a depth estimate of $0.165 * 1470/2 = 121$ m, with an uncertainty of about 9 m. Knowing this depth, it was then possible to construct the reverberation filter associated with the surface and bottom echoes [Wielandt, 1975], and to deconvolve the wavelet from this filter to derive the actual source time function of the explosion. The final wavelet (Figure 3c) is very similar to the theoretical one (Figure 2a), with one secondary peak and a clear inter-pulse “low”, which allows an accurate estimate of the bubble oscillation period (0.72 s).

[16] Estimating the event size from source wavelet amplitude requires the knowledge of an amplitude scaling factor in the coda filter, i.e., l^* , which is not available in the present case. However, for underwater explosions, an indirect estimate is still possible through the Willis formula [Cole, 1948], describing the relationship between the yield, the depth (i.e., the confining pressure) and the gas bubble oscillation period. Accounting for the correcting term tied to the closeness of sea bottom [Cole, 1948], the measured 0.72 s oscillation period is associated with a yield estimate equivalent to 4000 Kg of TNT (also equivalent to a moment magnitude between 3.5 and 4). This yield estimate is very similar to what has been already obtained through other means [Koper et al., 2001; Marshall and Bowers, 2002; Savage and Helmberger, 2001], using the information carried by direct waves.

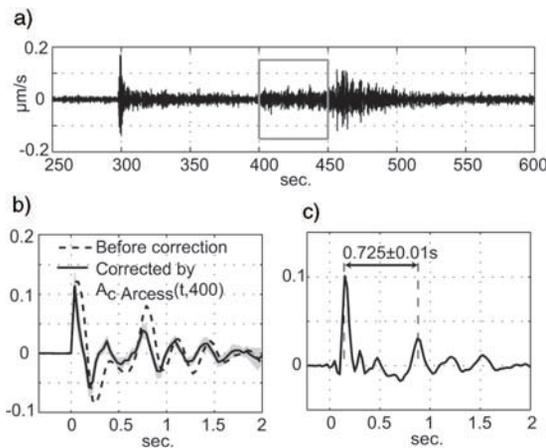


Figure 4. The source time function obtained from the records on the FINESS array located more than 1000 km away from the explosion. (a) The analysed S wave window. (b) Comparison between the minimum phase wavelet obtained without attenuation correction (dashed line) and after correction by the attenuation filter calculated from the ARCESS at the arrival time t_s on the FINESS array (Black). The attenuation correction allows us to reveal the impulsiveness of the explosion and the presence of the reverberation inside the sea. (c) The bubble pressure characteristics obtained after removing the reverberation effects.

[17] In order to check the robustness of this technique, we applied a similar processing to the FINESS array recordings, at a distance exceeding 1000 km from the wreck. The low signal to noise ratio in the coda led us to use another scattered waves train, the phase S_g , (Figure 4a); the similarity between the derived source time function (Figures 4b–4c) and the previous one (Figure 3c), confirms the efficiency and robustness of the approach.

[18] The example of the Kursk explosion recordings was chosen because of the very good constraints on the location and yield obtained with independent techniques. From these striking and robust results, we may conclude that the combination of the now classical Aki's idea of a quasi-random scattered wave field in the seismic coda, and advanced signal processing techniques, allows one to obtain fast, high resolution information on the source even for low magnitude seismic event, from a single recording, without any a priori information on the crustal properties. Beyond very promising applications in seismology like the quasi-real time estimation of the source time function, this technique may also prove useful for detailed investigations on any kind of diffuse wave field, opening new fields of application for all blind deconvolution methods.

[19] **Acknowledgments.** We thank J. L. Lacoume (LIS, University of Grenoble) for enlightening discussions and NORSAR for making the data available. This work was supported by both CNRS and CEA, through a Ph.D. fellowship.

References

- Aki, K. (1969), Analysis of the seismic coda of local earthquakes as scattered waves, *J. Geophys. Res.*, *74*, 615–631.
- Aki, K., and B. Chouet (1975), Origin of coda waves: Source, attenuation, and scattering effects, *J. Geophys. Res.*, *80*, 3322–3342.
- Aki, K., and P. G. Richards (1980), *Quantitative Seismology: Theory and Methods*, W. H. Freeman, New York.
- Barrodale, I., N. R. Chapman, and C. A. Zala (1984), Estimation of bubble pulse wavelets for deconvolution of marine seismograms, *Geophys. J. R. Astron. Soc.*, *77*, 331–341.
- Claerbout, J. F. (1976), *Fundamentals of Geophysical Data Processing*, Blackwell, Malden, Mass.
- Cole, R. H. (1948), *Underwater Explosion*, Dover, Mineola, N. Y.
- Fofonoff, N. P. (1985), Physical properties of seawater: A new salinity scale and equation of state for seawater, *J. Geophys. Res.*, *90*, 3322–3342.
- Guilbert, J. (2004), Le cepstre: Définition et exemples d'utilisation en hydroacoustique et en sismologie, in *Traitement du Signal Pour Géologue et Géophysiciens, Techniques Avancées*, pp. 191–199, Ed. Technip, Paris.
- Gusev, A. A., and I. R. Abubakirov (1996), Simulated envelopes of non-isotropically scattered body waves as compared to observed ones: Another manifestation of fractal heterogeneity, *Geophys. J. Int.*, *127*, 49–60.
- Ishimaru, A. (1978), *Wave Propagation and Scattering in Random Media*, Elsevier, New York.
- Kolmogorov, A. N. (1939), Sur l'interpolation et l'extrapolation des suites stationnaires, *C. R. Acad. Sci.*, *208*, 2043–2045.
- Koper, K. D., T. C. Wallace, S. R. Taylor, and H. E. Hartse (2001), Forensic seismology and sinking of the Kursk, *Eos Trans. AGU*, *82*, 39, 45–46.
- Margerin, L., M. Campillo, and B. Van Tiggelen (1998), Radiative transfer and diffusion of waves in a layered medium: New insight into coda Q, *Geophys. J. Int.*, *134*, 596–612.
- Marshall, P., and D. Bowers (2002), The sinking of the “Kursk”, *Discovery Mag.*, *24*, 48–50.
- Mayeda, K., and W. R. Walter (1996), Moment, energy, stress drop, and source spectra of western United States earthquakes from regional coda envelopes, *J. Geophys. Res.*, *101*, 11,195–11,208.
- Oppenheim, A. V., and R. W. Schaffer (1975), *Digital Signal Processing*, Prentice-Hall, Upper Saddle River, N. J.
- Rautian, T. G., and V. I. Khalaturin (1978), The use of the coda for determination of the earthquake source spectrum, *Bull. Seismol. Soc. Am.*, *68*, 923–948.
- Robinson, E. A. (1967), Predictive decomposition of time series with application to seismic exploration, *Geophysics*, *32*, 418–484.
- Sato, H., and M. Fehler (1998), *Seismic Wave Propagation and Scattering in the Heterogeneous Earth*, Springer Verlag, New York.
- Savage, B., and D. V. Helmberger (2001), Kursk explosion, *Bull. Seismol. Soc. Am.*, *91*, 753–759.
- Sèbe, O. (2004), Déconvolution aveugle et sismologie: Estimation de la source sismique et des effets de site, Univ. Joseph Fourier, Grenoble, France.
- Tregoures, N., and B. Van Tiggelen (2002), Generalized diffusion equation for multiple scattered elastic waves, *Waves Random Media*, *12*, 21–38.
- Wielandt, E. (1975), Generation of seismic waves by underwater explosions, *Geophys. J. R. Astron. Soc.*, *40*, 421–439.

P.-Y. Bard and O. Sèbe, Laboratoire de Géophysique Interne et Tectonophysique, Université Joseph Fourier, F-38041 Grenoble cedex 9, France. (osebe@obs.ujf-grenoble.fr)

J. Guilbert, CEA-DASE-LDG, BP12, F-91680 Bruyères le Châtel, France.