Improvements in depth estimation through global Network Cepstral Analysis and Bootstrapped F-Statistics

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Introduction

Source depth determination remains an important problem in seismology. Surface reflections, pP and sP, if accurately picked, can provide precise depth estimates. Unfortunately, depth-phases are prone to phase identification and picking errors. Depth phase amplitudes are dependent on focal mechanisms and path effects, which can lead to large depth errors. To overcome this problem, we propose a new method for robust depth estimation, which doesn't rely on reported phase picks but exploits the information present in the full waveforms.

Some of the techniques used to estimate source depth directly from waveforms, include Cepstral F Statistic (Bonner et all, 2002) and the probabilistic F Statistic/Trace (Herburn, 2008). Both of these methods take advantage of the wavelet coherence in arrays at teleseismic distances. Other methods use beamforming automatically picked phases (Bonner et all, 2002) or time-scale contractions of waveforms (Woodgold, 1999). Bootstrapping statistics have been successfully applied in seismology error parameter estimations by Sandvol and Hear (1994) for waveform inversions.

Methodology

1. Data selection

The proposed method uses broadband waveforms from globally distributed stations for events at teleseismic distances (20° to 90°), and with depths greater than 20 km and magnitudes larger than 5.0mb. These are the conditions where depth phase waves are clearly separated from P waves.

To illustrate the methodology of the procedure, we have selected an event from the Hindu-Kush region (Figures 1, 2, 3).

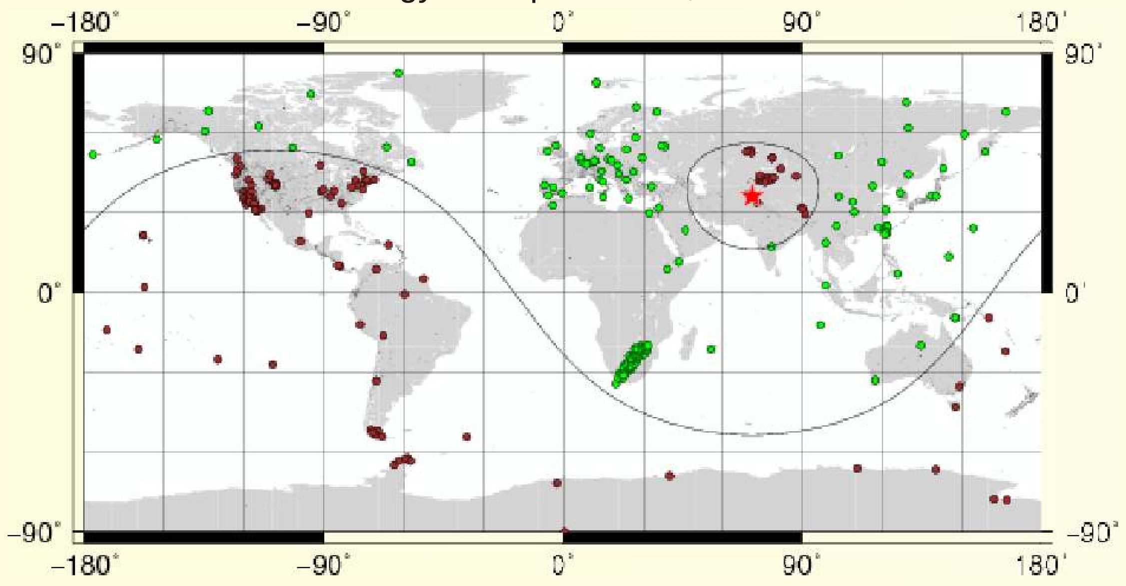


Figure 1. Map of event on the 14th of February 1998, (5.1mb) located in the Hindu-Kush region (red star). The event's depth computed by ISC is 224km, while the Bootstrapped F-Statistic gives a depth of 234km with a confidence interval between 233 and 234km (at 95% confidence). To compute the depth, we used stations with distances between 20° and 90° from the source (142 stations, green circles) but 152 stations were outside of the limits for analysis (red circles).

2. Window selection and envelope computation

For waveforms within the optimal distance range, we selected a window around the predicted P arrival and the largest possible pP moveout (pP-P time of 200 s).

For each time window (Figure 2a), we compute the envelope using the Hilbert transform (Figure 2b), which reduces the complexity of the trace and desensitizes the polarity.

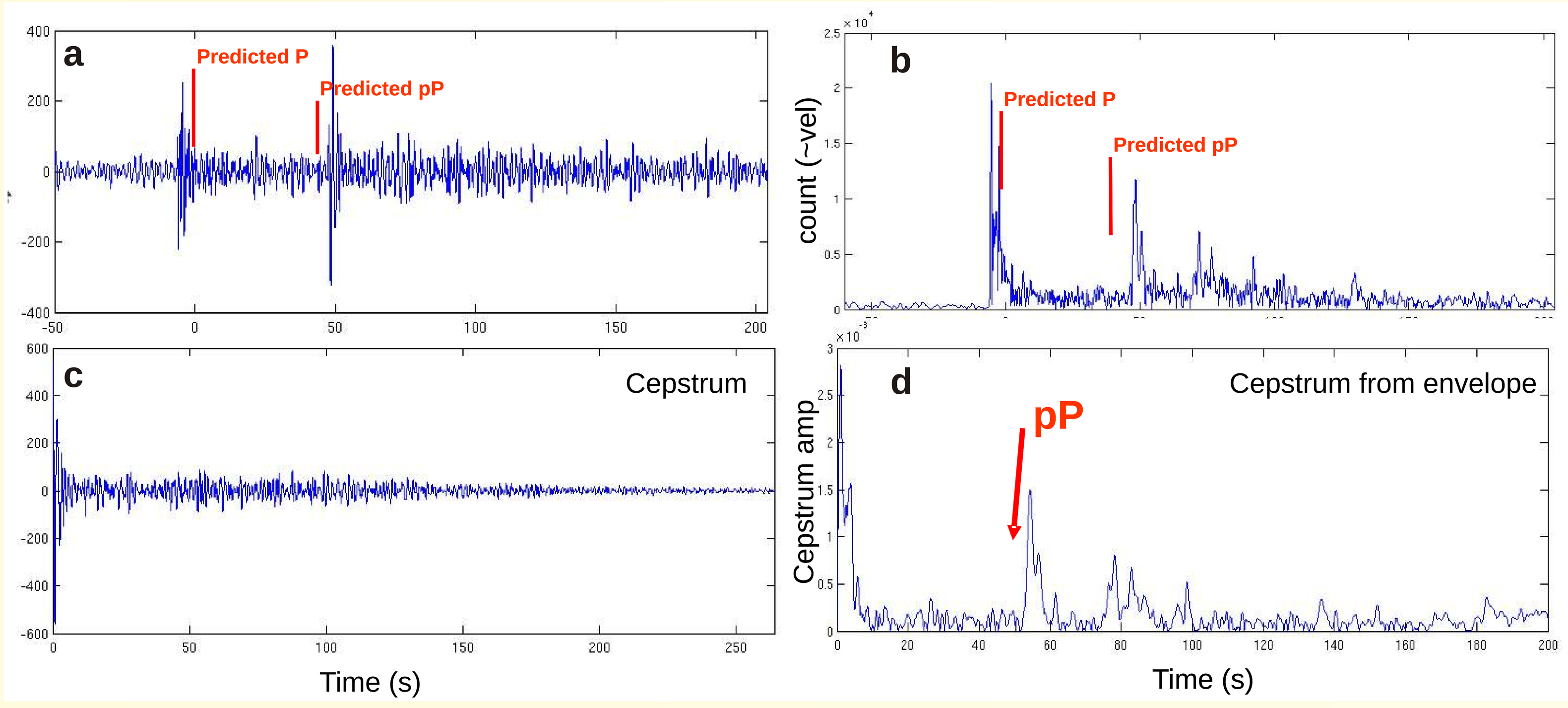


Figure 2. Seismogram from station LBTB (Δ=75°) for the earthquake on 14th February 1998 (5.1mb), a) Filtered signal between 0.5 and 2.5Hz, b) signal's envelope from 2a, c) cepstrum computed from 2a, d) envelope of 2c. In d can be seen than the computed cepstrum from the envelope provides better information about the depth phases, than the cepstrum.

3. Cepstrum

The cepstrum (figure 2c and 2d) is computed from each window and the cepstrum's log spectra is detrended using splines (Bonner, 2002). The cepstrum provides information about the presence of depth phases in the signal. For a detailed description about cepstrum see Buttkus (2000).

4. Time to depth conversion

Cepstra are transformed to depths using the depth-moveout relations predicted by AK135 at the epicentral distances of the stations (Figure 3).

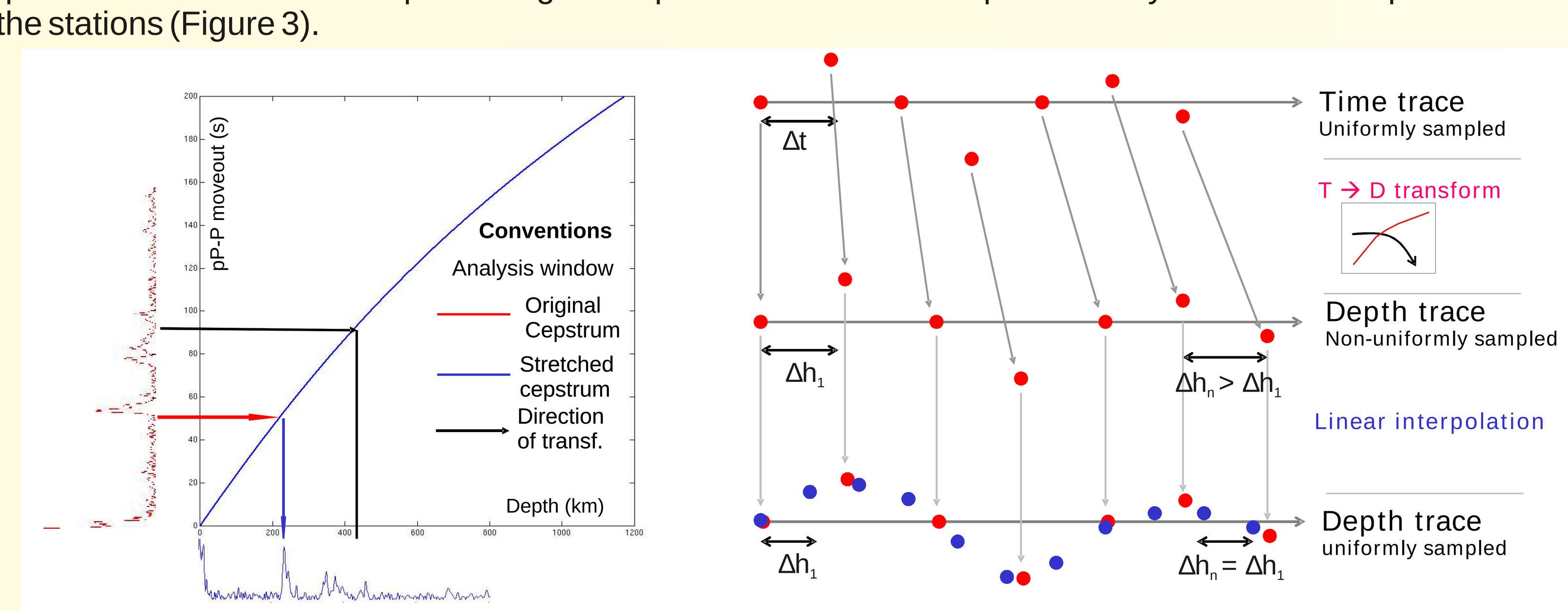


Figure 3. Procedure for time to depth conversion used in this method. a) conversion of the LBTB trace (original cepstrum in red and the depth cepstrum in blue, b) resampling applied to the cepstrum to produce even distributed depths.

5. Bootstrapped F-Statistic

The F-Statistic/Trace is computed as the power of the stack of cepstra divided by the average over all subset of cepstra of the power of the difference between the stack of cepstra and the individual cepstra (Heyburn, 2008). To compute each bootstrap F-Statistic (2000 bootstraps), we take subsets from the population of the cepstra. The event depth is found in the second peak (Figure 4a) for each Bootstrapped F-Statistics. The confidence interval (95% confidence level) and variance are computed from the empirical distribution of depths (Figure 4b).

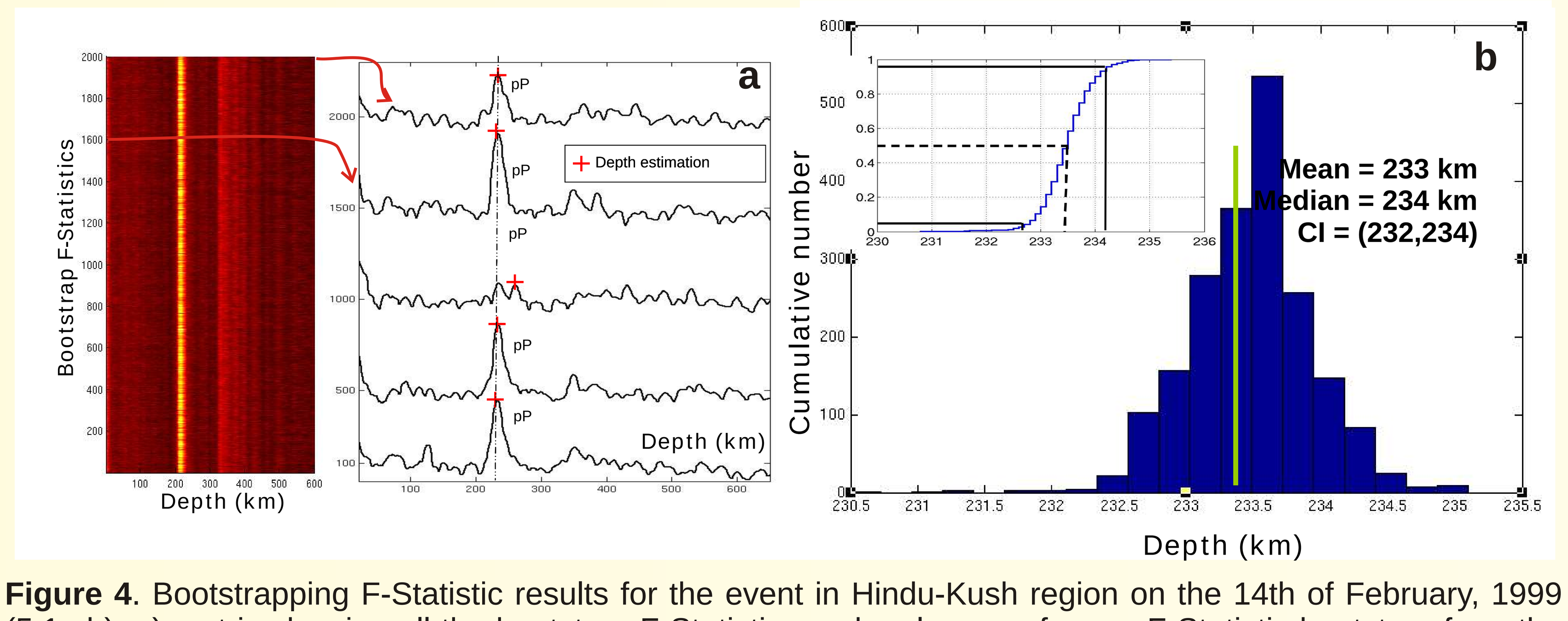


Figure 4. Bootstrapping F-Statistic results for the event in Hindu-Kush region on the 14th of February, 1999 (5.1mb), a) matrix showing all the bootstrap F-Statistics and a closeup of some F-Statistic bootstrap from the matrix, b) empirical distribution of depths computed from Bootstrapping F-Statistics.

Data

To evaluate the performance of our methodology, we analyzed 31 events (Figure 5) from the southeastern Carpathians in the Vrancea seismic zone (Romania). The seismicity in the area consists of crustal and intermediate-depth clustered earthquakes with moderate magnitudes (Tagui et al, 2009). The intermediate-depth earthquakes in the area occur between 60 and 180km depth (Bonjer, 2007). Events from the zone are routinely located and reported by the Romanian Seismic Network, with stations at local distances, which assures a good depth estimation. The selected events span 7 years (2000-2007) and have magnitudes greater than 4.0mb.

Broadband waveforms from stations at teleseismic distances for the 31 events were fetched from the IRIS waveform repository. For the Bootstrapped F-Statistics depth estimation, waveforms recorded at distances between 20° and 90° were used. An automatic quality control was applied to reject abnormal traces.

To establish the influence of the waveform quality on the depth estimation, each trace was ranked manually from 0 (no visible signal) to 3 (clear signal). The best possible score for an earthquake due its ranked waveforms is 3N (N: number of used stations)

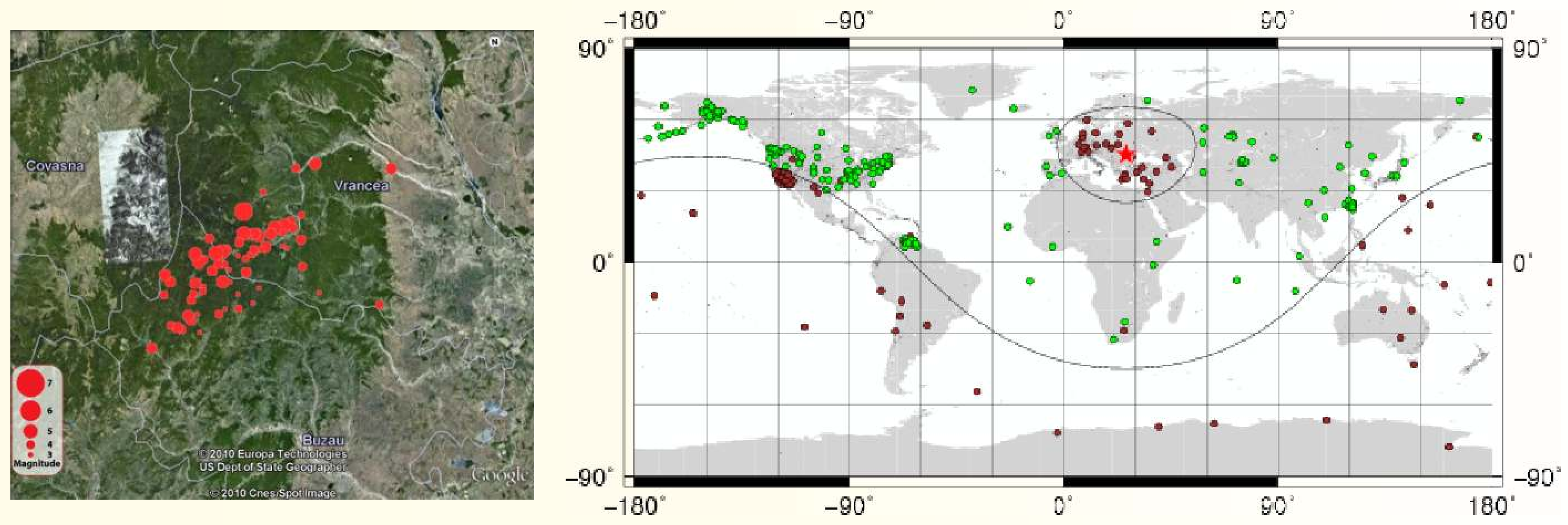


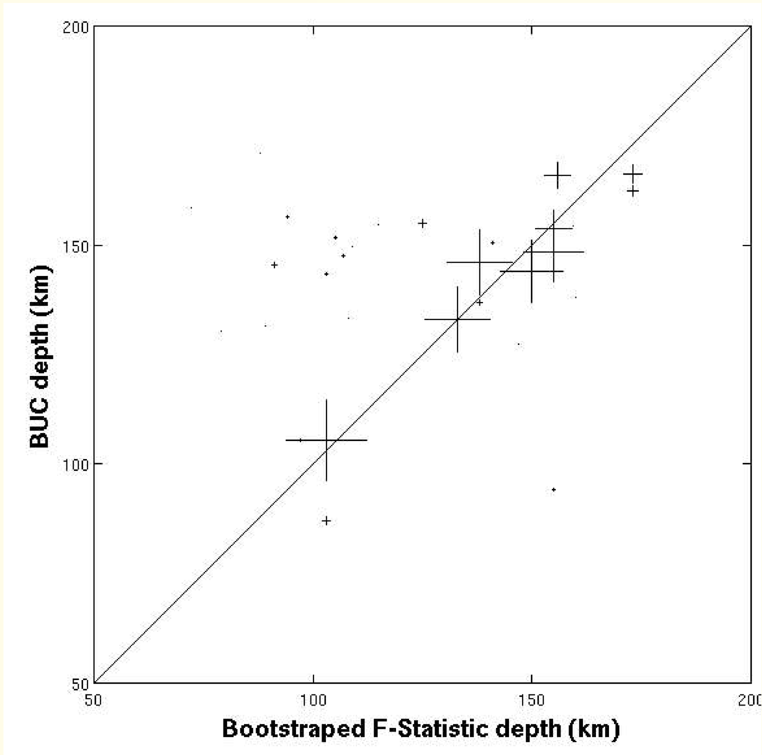
Figure 5. Events in the Vrancea area (2000- 2007) used to test the Bootstrapped F-Statistics depth estimation (Left). The red star on the right map indicates the event on the 27th of October 2004 (5.8Mw, 5.6mb). The event's depth computed by the Romanian Seismic Network (with stations at local distances) is 105.3 km, while the Bootstrapped F-Statistic gives a depth of 103 km with a confidence interval between 100 and 108 km (at 95% confidence) and a standard error of 3.0 km . To compute the depth, we used stations with distances between 20° and 90° from the source (157 stations, green circle).

Results

The range of depth estimations using the Bootstrapped F-Statistic is in agreement with the expected depths for the Vrancea area (60 to 180km; Bonjer, 2007).

The scatter plot in Figure 6 shows a comparison between the local network depth (y-axis) and the estimation using the Bootstrapped F-Statistic (x-axis). Events with a high score (good quality and a large number of traces) are represented as big crosses. For events with a high score, the Bootstrapped F-Statistics and the Romanian network depth estimations are well-correlated. Therefore, our method has shown to produce accurate depths if the quality requirements are met.

Depth estimation for events with a low score (no visible signals) present scatter in Figure 6. However, some of these results are in agreement with the Romanian network depth estimations, likely due to depth-phase coherence in the waveforms.



To investigate the influence of magnitude to the depth estimation, we first compare the magnitude against the standard error from the empirical depth distribution (Figure 7a). We also compare the magnitude against the difference between the Romanian network depths and the Bootstrapped F-Statistics (y-axis) depths (Figure 7b). For events with magnitudes greater than 4.8mb and a good event score, the standard error (<40km) and depth mislocation (<10km) are small.

Events with magnitude less than 4.8mb and a low score (poor quality signals) resulted in large standard errors. The large values in the standard error or the confidence interval occur when there is a wide dispersion in the empirical depth distribution.

Figure 6. Comparison of the Bootstrapped F-Statistics for the 31 events in the Vrancea area (2000-2007), with magnitudes ranging from 4.0mb to 5.6mb. The size of the crosses represents the score for the event, where the largest crosses represent the highest scoring events and vice versa.

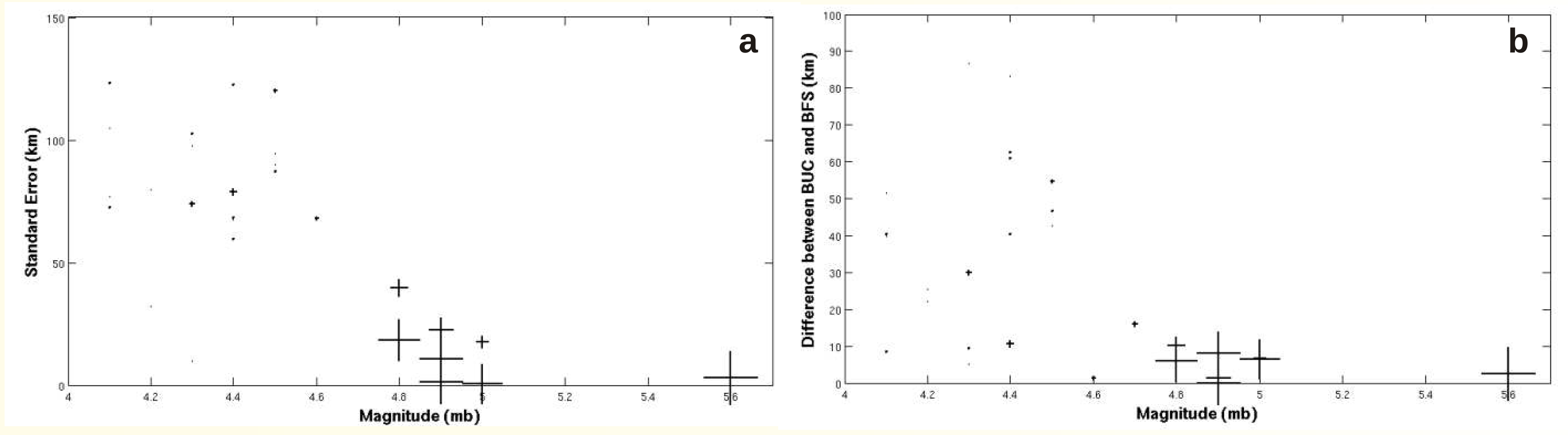


Figure 7. Estimated parameter comparisons for the Vrancea events, a) comparison of event magnitude and the computed standard error from the Bootstrapped F-Statistics b) comparison of event magnitude and the difference between the local network and the Bootstrapped F-Statistics depth estimations. The size of the crosses represents the score for the event, where the largest crosses represent the highest scoring events and vice versa.

Conclusions

— Depths can be estimated directly from the waveforms with few assumptions about the source.
— The envelope provides a better trace to be processed by cepstrum method for estimate depth.
— For magnitudes larger than 4.8mb, the depth estimation with the Bootstrapped F-Statistics is robust.

For further information

Please contact juan@isc.ac.uk. More information on this and related projects can be obtained at www.isc.ac.uk web-page.

Acknowledgments

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