PbAS - A 4D centroid-based method for location of complex waveform seismic events

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Abstract

Conventional Back-Projection Imaging (BPI) methods determine the origin time of an event from the peak of the Maximum Brightness Function curve, however, this assumption might not be completely valid for long duration seismic events composed of continuous bursts of energy, which may produce non-pronounced peaks on the curve due to varying levels of noise and waveform complexity. For such adverse conditions, an adaptive centroid of the energy could be considered a better alternative to describe the origin (x_0, y_0, z_0, t_0) of these events.

Here we propose the *Brightness PDF-based Amplitude Stacking (PbAS)* method, a 4D-Centroid location method derived from the Back-Projection Imaging family, able to compute simultaneously the spatial and temporal location of a wide variety of seismic sources. We generate 100 model realizations by perturbing an initial layer-cake velocity model. For each model we perform the event location using a conventional BPI method and PbAS method. The PbAS method produced lower dispersion results and exhibited a better capability to handle higher levels of velocity uncertainty compared to the conventional BPI method. Furthermore, this centroid based method is not as dependent on discretization as most conventional BPI methods, which enable the PbAS method to achieve enough resolution without excessive mesh refinement.

Introduction

Location of seismic sources has always been a major goal in seismology and several approaches have been developed over the years to yield results with high accuracy and computational efficiency. In the last century, conventional earthquakes have been generally located by methods which require picking of arrivals and minimization of time residuals (Thurber and Kissling, 2000); however, there are other seismological phenomena which generate complex waveforms with no distinguishable phases that demand the use of other methods which are able to handle both the dynamic and kinematic wave properties (Wang et al., 2016). Recently, *Reverse Time Imaging* (RTI) and similar methods have risen as powerful tools to perform such tasks successfully thanks to the advances in theory and computing power; nonetheless, there are still some procedures such as robust sensitivity analyses, real-time monitoring and others that make RTI impractical unless computer clusters are available. Consequently, faster but less accurate methods known as *Back-Projection Imaging* (BPI), part of the RTI group, can efficiently estimate source locations with acceptable resolution, for a large variety of seismic events and in a wide range of applications including: location of tremor events in the northern Cascadia subduction zone (Kao and Shan, 2004), real-time earthquake location (Baker et al., 2005) mapping earthquake rupture planes (Kao and Shan, 2007), delineating complex distribution of earthquake aftershocks accounting for the contribution of multiple seismic phases (Liao et al., 2012).

In practice, BPI methods assume the origin time t0 as the time when the *Maximum Brightness Function (MBF)* curve reaches its peak. For conventional seismicity, the presence of a clearly larger amplitude arrival will generally dominate the brightness function and, in consequence, the origin time; but that might not be a proper assumption for more complex events characterized by long duration bursts of energy with no defined amplitude maxima. Subsequently, here we introduce a 4D location method that we called Brightness PDF-based Amplitude Stacking (PbAS), able to jointly determine an adaptive spatiotemporal centroid of a large variety of seismic signals, which could sometimes be considered a more reasonable location coordinates and origin time estimation than using only the largest arrivals. Finally, to measure the impact of velocity uncertainty on the outcomes, PbAS and a conventional BPI method are compared by implementing a Monte Carlo algorithm which randomly samples velocity models according to given velocity PDFs (they represent the large uncertainty [±25%] usually expected in real life applications).

Back-Projection Imaging (BPI)

BPI is a simplified form of RTI in which recorded traces are backpropagated from their respective stations toward the original event source, however, amplitude changes due to wave propagation effects are ignored, as well as polarity changes due to earthquake radiation patterns (Beskardes et al., 2018). Therefore, BPI can handle kinematic and dynamic information, without solving the wave equation, which makes it computationally efficient and sufficiently accurate for practical cases. BPI can be considered analogous to Kirchhoff migration method in active seismic (Trojanowski and Eisner, 2016).

Conventional BPI methods are based on time-shifting and stacking of observed seismograms according to travel-time tables computed for a given velocity model. In this work, we used the 3D Fast Marching Method (Sethian and Popovici, 1999), which solves the Eikonal equation to obtain the required travel times. Stacking is then carried out according to *eq. 1*:

$$F(\mathbf{r},t) = \frac{1}{N}\sum_{i=1}^{N} \left| u_i\left(t + ttt_i(\mathbf{r})\right)\right|, \quad (Eq.1)$$

Where *F(**r**, t)* is the brightness function, also called image or energy function, u_i is the normalized seismogram (trace) recorded on station *i* =1,…,N; $ttt_i(\mathbf{r})$ represents the travel-time volume in the i^{th} station and t is the initial time of the time-window under evaluation. Once the brightness function is constructed, the spatiotemporal location of the source can be determined. The conventional method follows a grid-search that determines the grid-point coordinates and timestep with the maximum stacked energy (Gajewski et al., 2007). This method is referred to as *Maximum Amplitude Time Function* (MATF) from here forward.

Two of the main disadvantages of grid-searching methods like MATF are: first, their results are dependent upon grid discretization thus to gain accuracy could demand high computational cost; and second, the origin time is determined by the global maximum of the curve, however, such a curve can sometimes develop several peaks or a plateau (as in *fig.1*) due to varying levels of noise, complex waveforms, long duration events, different geometries of receivers, and other factors; consequently under unfavourable conditions, these methods lose stability and reliability in their solutions. Later, (Anikiev et al., 2014) proposed a 3D centroid method to overcome the discretization dependency. In that study, the image function is transformed into a *Probability Density Function* (PDF), used to compute the spatial centroid; nonetheless, the origin time is still determined by the peak in the MBF curve. Here, we have adapted this method to a 4D version able to successfully localize the centroid of either the total energy or the largest amplitude arrival by signal enhancement and noise suppression.

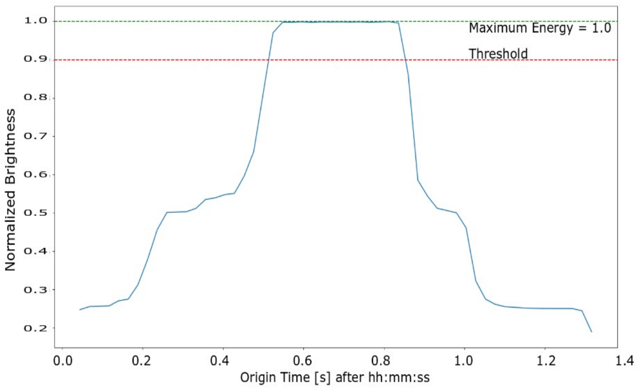


Figure 1 *– Normalized Maximum Brightness Function curve for a square recording array. This curve displays the maximum energy value in volume per timestep and allows to visually identify events as peaks due to coherent summation of signals (amplitudes) above a given threshold; however, even with the idealized conditions of this synthetic experiment, it was not unusual for the curve to produce a challenging large plateau with no clear peaks, therefore, high uncertainty.*

Methodology

Brightness PDF-based Amplitude Stacking (PbAS) computes the 4 variables *(x_0, y_0, z_0, t_0)* at once. First, the origin time (*eq. 2*) makes use of the MBF, *max_r(F(**r**, t))*, to calculate a time weighted average.

$$t_0 = \sum_{i=1}^{nt}\left(t_i * \max_{\mathbf{r}}\left(F(\mathbf{r},t)\right)^{n_{exp}}\right), \quad (Eq.2)$$

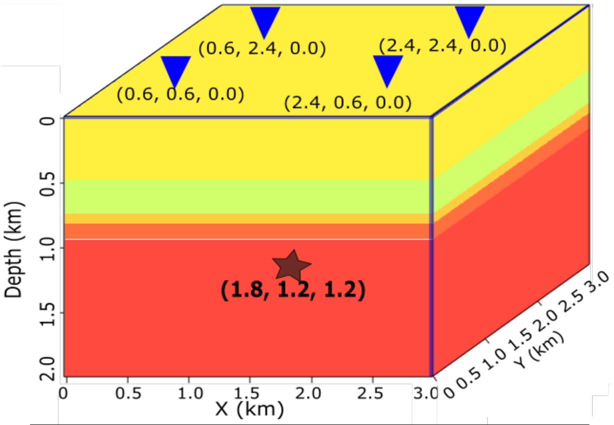
Where n_{exp} is an adaptive parameter used to either highlight strongly impulsive events while suppressing noise or compute a regular centroid, which is useful for complex events such as tremors that have no distinguishable seismic phases and may last from minutes to weeks (Obara, 2002). On the other hand, *eq. 3* must be solved for the spatial location r_0.

$$r_0 = \sum_{j=1}^{nr}\left(r_j * \sum_{i=1}^{nt}\left(NmaxF(t_i)^{n_{exp}} * P(\mathbf{r},t_i)\right)\right), \quad (Eq.3)$$

Where r_j is the position vector for each grid point and *P(**r**,t_i)* is the transformation of the brightness function into a *PDF*, whose main objective is noise suppression to highlight the most likely candidates.

Assessment of velocity uncertainty

To evaluate the performance of the proposed methodology in realistic conditions, we performed a sensitivity analysis for media P-wave velocities. From real sonic logs and VSP data we built a 3D layer cake velocity model in which forward modelling and backpropagation were conducted (*fig.2*). From P-velocity data, a histogram and PDF estimation was fitted for each layer, then such velocity distributions were fed to a *Monte Carlo* algorithm that randomly sampled the model space in a hundred realizations, and each of them was used to backpropagate the synthetic data. Finally, results reflect the effect of velocity uncertainty on spatiotemporal location for the two location methods under consideration.



Formation	1	2	3	4	5
Top [m]	0	460	720	820	920
P-Vel [m/s]	3195	2900	3250	4275	4430

Figure 2 *– Layer cake model. A 4-station recording array is used in this synthetic experiment. (x, y, z) Locations of receivers and source, together with P-velocity values and formation tops are indicated.*

Location and origin time results

The absence of a clear peak on the MBF curve *(fig.1)* impacts negatively the results of MATF, while PbAS appears to be more robust to this adverse scenario. Upper panel in *fig.3* shows the estimated origin time histograms for both methods; MATF (left side) exhibits a Gaussian-like behaviour with data well distributed around the true solution, however it is important to mention that if bins are chosen narrower, the discretization dependency problem will be easily appreciable. On the other hand, PbAS does not experience such a difficulty because results are a continuous distribution of data closer to the true value.

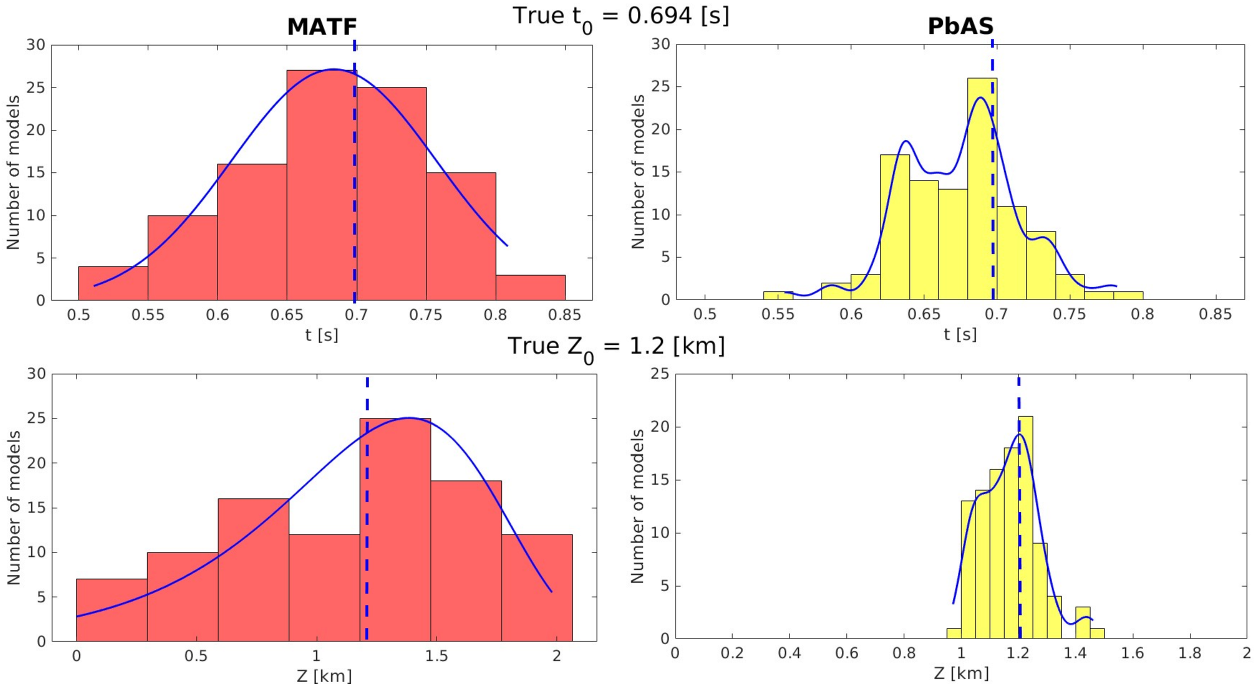


Figure 3 *– Spatio-temporal Location. Origin time in upper panel: MATF (left) and PbAS (right). Vertical axis shows the number of realizations or velocity models with which a given origin time was obtained (horizonal axis). Spatial location (Z-depth) in the lower panel. MATF (left) and PbAS (right). Horizontal axis shows the calculated depth. Dashed lines represent the true values used in the forward modelling.*

The outcome for Z or depth (lower panel) shows the main difference between both methods; while MATF shows a high dispersion and fails to distinguish artefacts from true sources due to incorrect velocities, PbAS is more robust to velocity uncertainty and its results exhibit a clearer tendency toward the true value (1.2 km). Notice that this recording geometry was intentionally used to highlight the difficulties MATF and similar methods may experience while introducing a centroid-based method (PbAS) as a solution to this issue; but then again multiple peaks can be produced on the MBF curve from other factors especially by the waveform complexity and noise level in the data.

Conclusions

Two notorious disadvantages of grid-search based BPI methods including MATF are: the spatiotemporal localization is restricted to the grid nodes (discretization) thus it may result in overall efficiency loss, and they need a clear peak in the maximum brightness curve to work at their best. We propose the new a centroid-based PbAS method that showed to produce more consistent results in the presence of multiple peaks on the maximum brightness function.

Results indicate that incorrect velocity models may displace the maximum energy grid point, affecting any location method. Besides, MATF shows a much higher dispersion on the origin time and estimated depth than the PbAS method.

Sometimes, defining t0 based on the peak of the MBF curve may not be truthful, especially for long duration events comprised of continuous bursts of energy. Therefore, there is a need for different criteria to describe more complex events, among which the energy centroid rises as a good alternative.

Acknowledgments

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