Review of the paper entitled « *Exploring the potentials and limitations of the time-reversal Imaging of finite seismic sources* », *by Kremers et al., April, 2011*

Kremers and co-authors investigate how to image finite seismic sources and to retrieve source time function by Time-Reversal Method (hereafter referred to as TRM). They first demonstrate, by synthetic tests, that focusing by TRM works fine for a single point source, correctly for multiple point sources but not for finite source simulations. The application of TRM to real data of the Tottori earthquake is a complete failure. Consequently, the conclusions of the paper are very pessimistic on the ability for TRM to image finite seismic sources. They propose some good reasons for that failure but, to my sense, the authors do not put forward the real basic reasons why TRM does not work for their experiments. I will detail later on all my criticisms.

This paper constitutes an interesting and serious piece of work, but I disagree with the conclusions. Actually, my understanding is that the authors missed the « essence » of the interest in TRM, eventhough some of the co-authors are aware for many years, which physical conditions must be fulfilled for getting a good source time function.

First of all, the introduction on TR is very poorly written. Time reversibility and spatial reciprocity are well known in acoustics and in seismology for many decades and are not new by themselves. In that respect, the firstly quoted papers on TR in meteorology, geodynamics and other fields look weird. An historical perspective should have been preferred. The authors, in the introduction, should discuss why TRM has been revived during the last 2 decades and what is really new in the lab experiments made the Fink's group (ESPCI, University Paris 7). The real innovation in the Fink's approach, is that TRM works in strongly heterogeneous, SCATTERING medium and can be experimentally implemented thanks to the development of transducers which can be at the same time recorders and emitters. Even, the focusing is greatly improved when the medium is very COMPLEX : TRM thrives with complexity. The complexity of the seismograms is reflecting the complexity of the medium. By time-reversing complete seismograms obtained in scattering media, the focusing is much better than in a smooth medium. In laboratory, since the forward propagation and the backward propagation are performed in the same real medium (therefore with the same Green's function), the focusing is excellent. Actually, it is not the case for seismic experiments, where the Green's function used during for the back-propagation is approximate because numerical calculations are performed in a virtual model. This basic limitation explains why the first attempt for applying TRM (following McMechan's paper in 1982) were not very successful (2D- case, acoustic case, many theoretical and practical limitations….). Since TRM is primarily interesting in highly complex media, TRM will be successful if and only if numerical computations can reproduce the complexity of the Green's function and are very accurate. With the rapid expansion, during the last ten years, of more and more powerful computers and numerical tools, (such as Spectral Element Methods), Larmat et al. (2006) were able, for the first time by TRM, to calculate at long periods (T>100s) accurate enough Green's function in 3-global models, with complete elastic field, and to obtain good focusing and even source time function for the giant Sumatra earthquake (Dec. 2004). TRM in that case works fine only because the spatial scale of the earthquake is huge (larger than 1000km). But we cannot escape the diffraction limit. The width of the focusing peak is related to the diffraction limit related to the seismic wavelength and the aperture of the array.

Another fundamental advantage of TRM compared with classical beamforming or phase conjugation techniques operating with monochromatic plane waves, is based on the fact that it is possible to back-propagate BROADBAND signals, which makes the focusing more efficient. Finally TRM is very easy to implement since there is a priori assumption on the location of the source in space and time.

In the Kremers' paper, the discussion on the physical limitations of TRM missed most of these basic points. One simple reason why their TRM experiments fail is related to the propagating medium which is dramatically SMOOTH and to the frequency range (0.03-0.5Hz) not well suited for getting details on the fault. Consequently, the authors are only able to retrieve scales of the source of the same order of magnitude of wavelength (approximately 20km). So it is not surprising that the authors obtain very disappointing results. They should get a much better focusing and source imaging in a highly COMPLEX SCATTERING medium, with a high frequency content such that the seismic wavelength be much smaller than the scale of source.

I agree with the authors that, even when all physical conditions are fulfilled, it is not granted to correctly image a finite source. And, one real problem is the absence of SINK as clearly identified by authors. By the way, it can be easily demonstrated that the width of the focusing peak is due to the interferences between the converging and the diverging waves. Even with very favourable conditions (complex scattering medium, broadband signal), as mentioned by the authors, the waves after focusing (though diverging and decreasing with increasing distance) continue to propagate and affect the focusing on the other parts of the fault. Consequently, it is necessary to get rid of, or minimize the diverging waves (by numerical calculations, by using synthetic seismograms). It will be necessary to implement an iterative process in order to get useful information of the rupture history.

Specific Comments :

Introduction : it must be rewritten differently, starting with the history of TRM (Parvulescu, 1961 ; Fink, 1992….) ; the importance of scattering, broadband signal, and very weak attenuation; first attempts in Seismology (McMechan, 1992), and first implementations at the global and regional scales in 3D tomographic models for the complete elastic field (Larmat et al., 2006, 2008). By the way, the application of TRM to Geodynamics is not granted since the Navier-Stokes equation has non-linear terms which cannot be time-reversed.

I do not understand what is meant by « while being mathematically rigorous , the adjoint method…». TRM and Adjoint Tomography have many similarities but different objectives. TRM so far is primarily used for studying seismic sources, whereas adjoint tomography (Claerbout, 1968 ; Tarantola, 1984, …) is devoted to 3D-structure. Kawakatsu & Montagner (GJI, 2008) proposed a simple way to obtain the moment tensor by TRM.

Synthetic experiments : The existence of ghosts is a well known phenomenon due to the fact that only incomplete wavefield is rebroadcast. But, if the medium is strongly scattering, and if the time window is long enough (beyond the Heisenberg time), ghost waves do not significantly affect the focusing.

The seismograms shown in figure 2 do not present complexity because the 1D model of figure 1 is very smooth. Consequently, we cannot expect a sharp focusing.

No complex heterogeneity => no good focusing.

The multiple sources can be separated provided that their distance is not small compared with the dominant wavelength.

The increase in the number of stations or the use of station arrays, have the same effect as increasing the number of secondary stations due to scattering but it is not as efficient as a complex medium. The weighting of adjoint sources enables to give more weight to isolated stations and to get a better radiation pattern, but basically does not change anything on the quality of the focusing.

Application to real data (Tottori earthquake) : A necessary though not sufficient condition of success for TRM is the accuracy of Green's functions. This point is not detailed, since no real and synthetic seismograms are displayed, but I suspect that the information conveyed by real seismograms in a limited frequency range (0.03-0.5Hz) is very poor. The predominance of surface waves is effectively a problem but probably reflects the simplicity of the medium (real at long periods ?). It should be interesting to see some seismograms in order to assess their complexity.

Discussion : it must be rewritten. The reasons of failure are explained and some of them are correct. But they are not due to TRM by itself but to the poor chosen physical conditions under which TRM is used. TRM cannot give magic results if there is no sufficient information in data !

Yes, there is **incomplete information** in the seismograms. But only because the propagating medium is too simple and has no intrinsic complexity. In a highly scattering medium with a lot of coda waves, all information on the 3D structure is included in seismograms and used by TR. However, in that case, we must bear in mind that the numerical problem for getting an excellent Green's function becomes very difficult and even impossible.

Effectively, the seismograms are (consequently) dominated by **surface waves**, and the vertical resolution is very poor. A way to improve the depth resolution is to binarize the whole seismograms or to only time-reverse body waves time window (since there is no information in scattered waves).

Yes, the **missing sink** is a real issue and is related to the diffraction limit. In order to turn around this problem, an iterative procedure must be implemented. The consequence is that, in the period range used by the authors (2-30s), it is very difficult to get small slip, but synthetic calculations must enable to improve the lateral resolution along the fault. Larmat et al. (GRL, 2006) were able to get the source time function for Sumatra-Andaman earthquake (see their figure 4) by using the empirical Green's function provided by a previous earthquake at the same location. Even this additional step is insufficient but constitutes a first step towards an iterative procedure.

The **lack of prior information** is the strength of TRM provided that an excellent Green's function of the medium is numerically available. When waves are re-broadcast in the medium, no information is needed on the location of the source. But when the location in time and space is obtained, it can be used for calculating synthetic seismograms and to go forward for getting source images in time and space.

In conclusion, this paper presents an interesting investigation on the limitations of TRM but its conclusions are too pessimistic because the authors did not correctly analyzed the physical reasons of failure of their experiments. The paper must be greatly improved, since it miss all important points which makes TRM innovative and attractive. This paper deserves publication with major revision. Actually, we are still far from a practical implementation of TRM but this investigation is an important step which should motivate further studies.

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