Subject offered for a contract starting october 2016

SUBJECT TITTLE: A quantitatively error-controllable methodology for inverting seismic data

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Financing: Doctoral contract with or without teaching assignment

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Seismology has greatly contributed to our knowledge of the structure of the Earth's interior (deep or shallow) and its dynamic processes (e.g., mantle convection, thermal history, etc.). Amongst all accessible observables on the Earth's surface, seismic signals are and will continue to be our primary source of information on the Earth's interior. With seismic data of increasing quantity and quality, seismologists can unveil more and more of the Earth's internal structure, regionally and globally. However the model resolution not only depends on the data but also on the tools that make it possible to extract the information from seismic waves. For instance, one of the most powerful methods for extracting information on the Earth's interior has been seismic tomography, which minimises the misfit of observed and synthetic travel-time data that have been calculated using ray theory. The shortcoming of ray theory, as a high frequency approximation, is that the Fresnel zone of a propagating signal is collapsed to the ray path, which causes a large part of the Earth to be poorly sampled even with many sources and stations. More realistic finite-frequency Fresnel zones, on the other hand, have a certain volume and seismic waveforms and provide information on the Earth's inner structure in a much larger volume.

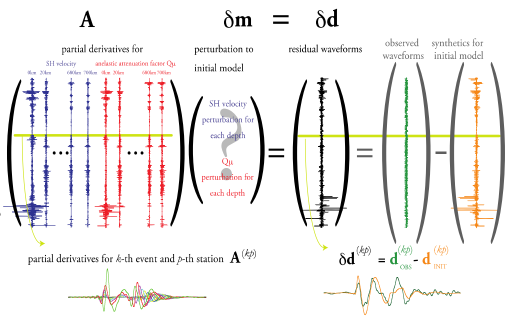

Figure 1 (modified from Fuji et al. 2010): Schematic illustration of waveform inversion. We take the waveform difference **δd** between observed and synthetic data forward modelled for an initial model as data to invert for. Unknown is the perturbation to the initial model **δm** and thus we calculate partial derivatives **A**.

One of the most cited papers from IPGP (Tarantola 1984), that describes this technique, has led seismologists to develop seismic waveform inversion techniques that are not solely based on travel times. A waveform inversion can be based on any set of physical parameters that control seismic wave propagation, and permits to infer their distribution inside the Earth. However, it remained theoretically and numerically challenging to include parameters such as anisotropy (e.g., Bodin et al. 2014), anelastic attenuation (e.g., Belahi et al. 2015) both in forward waveform modelling and in inversions. For example, in practice, due to high computational cost, waveform inversion schemes that are used in the industry, so far use the acoustic approximation. That is why seismologists have struggled enormously for decades to push such limitations in order to extract as much information as possible from recorded seismic waveforms without misinterpretation.

Waveform inversion thus tries to fit the synthetic waveforms to the observed waveforms, normally by minimising least square misfit. Fig. 1 schematically resumes waveform inversion processes. We invert waveform difference between observed and synthetics calculated for an initial model, locally searching model modification based on partial derivatives. Obviously, synthetics and partial derivatives are calculated with a certain forward modelling scheme. Hence, the success of the methodology depends heavily on i) the accuracy of forward modelling of synthetic data; and ii) the efficiency of the inversion scheme. These two axes are equally important for conducting waveform inversion and to obtain accurate models but in reality, people have been working separately on the two subjects.

The inversion community has kept updating the capacity of waveform inversion technology by rearranging the objective function to be minimised or by proposing different parameterisations in order to concur several technical problems known as local minima or cycle skipping (e.g., Plessix 2006; Virieux & Operto 2009; Wang et al. 2013; Borisov et al. 2015). Fig. 1 illustrates the least square waveform inversion scheme. While the partial derivative matrix $\mathbf{A}$ can be fully calculated for regional datasets even up to high frequencies (e.g., Fuji et al. 2010; Konishi et al. 2014), global waveform inversion with dense array data needs some asymptotic assumption of the Hessian matrix $\mathbf{A}^T\mathbf{A}$ (e.g., French et al. 2013). Even more dense datasets are being acquired for land and sea exploration geophysics experiments where we have a tremendous number of sources and receivers: seismologists in industry normally impose more rough assumption (e.g., Sirgue et al. 2010). However, in any cases, the gradient $\mathbf{A}^T\delta\mathbf{d}$ is calculated with the given forward modelling scheme. We again observe that forward modelling accuracy heavily controls the quality of obtained model using waveform inversion.

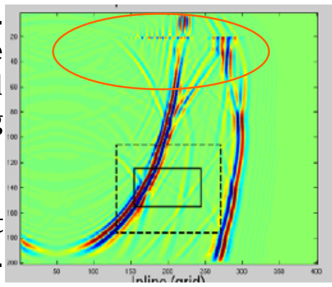

Figure 2 (modified from Yuan et al. 2016): Snapshot of elastic wavefield calculated with staggered grid finite difference scheme. Around the water-rock discontinuity, we can clearly observe numerical dispersion (in the red circle)..

There have been many forward modelling methods proposed that improve the accuracy and/or efficiency of seismic wavefield simulations. In exploration seismology, finite difference methods are widely used. However, the discontinuity treatment is limited to the numerical gridding. Fig. 2 shows one of typical problems that we could have with finite differences. Under the strong contrast of media (e.g., water-rock interface), FD scheme will create a huge degree of numerical errors if we do not optimise the operators (Fuji et al. 2016). On the other hand, family members of finite element methods enjoyed their increasing popularity especially in global seismology, since they can treat interfaces in a more sophisticated manner. Some studies compare these various methods in terms of accuracy and efficiency in forward modelling (e.g., Hirabayashi 2006) but no studies have explored the impact of the different methods onto models obtained during waveform inversion. Here in this PhD project, we propose to explore the impacts on waveform inversion results in order to develop an ensemble of strategic waveform inversion engine that controls the degree of errors in the obtained model.

The Ph.D. candidate will work at Laboratoire de Sismologie, under the supervision of N. Fuji and A. Mangeney. We will take advantage of synergy with R.J. Geller's group in University of Tokyo for optimally accurate operators, H. Chauris' group in École des Mines de Paris for inversion schemes, R. Martin and S. Chevrot's group in GET of Toulouse for staggered grid and boundary condition problems, and R.-E. Plessix' group in Shell (Holland) for 3D elastic formulation so that we can take benefit of inputs from them in terms of codes, theoretical supports, etc.