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REPORT

PhD thesis dissertation - Influence of velocity model uncertainty in earthquake source inversions

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This PhD thesis dissertation describe new approaches to investigate source properties of earthquakes by: (1) introducing a simple approach to efficiently account for uncertainty of the velocity model in source inversions; and, (2) developing a Bayesian inversion method with self-adapting parameterization of fault slip. These methods are first applied to conduct moment tensor inversions of the 25 April 2012 Corinth Gulf earthquake and of the 2016 Kumamoto sequence. The self-adapting fault slip inversion approach is then applied to the mainshock of the 2016 Kumamoto earthquake sequence. The source inversion of earthquakes is fundamentally an ill-posed problem, such that multiple source models can often explain the data equally well. In addition, imprecise knowledge of the velocity model can significantly bias point-source or finite-fault estimates. These models are essential to capture the physics of earthquake ruptures and it is thus essential to evaluate the associated uncertainties. This work thus constitutes an important contribution to provide more reliable source models with accurate posterior uncertainty estimates. While the technical developments presented in this study are significant, the applications presented in the manuscript sometimes lack discussion regarding the implications in terms of tectonics or earthquake physics.

Chapter 1 is a general introduction chapter to the representation of earthquake sources and Bayesian inversion methods used in this thesis. It describes basic concepts related point-source approximation, finite-fault source representation and parameterization of earthquake sources. It also introduces the Bayesian approach for simple linear Gaussian problems along with Monte-Carlo methods (Metropolis-Hastings and Parallel tempering methods). This chapter is clear and well written, and it reviews the main literature relevant to the thesis.

Chapter 2 describes one of the main product of the thesis – an approach to efficiently compute approximate covariances describing prediction uncertainties due to imprecise knowledge of the velocity model. Prediction uncertainty is first studied by generating Green's functions for randomly perturbed 1-D velocity models. Assuming that Earth model uncertainties mainly translates into time-shifts of the Green's functions, various approximations are proposed to compute prediction error covariances. Tests on synthetic and actual datasets show that accurate posterior uncertainty estimates can be obtained using an approximate time-averaged auto-covariance assuming a random uniform distribution of time-shifts. This approach is interesting given that previously proposed methods rely either on diagonal covariances or by means of more expensive calculation to compute partial derivatives or velocity model perturbations. This chapter is very well written and the work presented in it has been published in Geophysical Journal International. I only have a couple of comments on this part of the manuscript. First, although equation 2.31 is convenient to define bounds of the uniform time-shift distribution, it is unclear if this empirical relationship is valid for other reference velocity models. In addition, Earth model uncertainty might vary as a function of depth and I wonder if equation 2.31 still holds when $\sigma_M(z)$ is not constant. My second comment is related to the relationship between the proposed approximate prediction covariance and the Green's function covariance matrices. In this study, the covariance matrix is estimated directly from the observed waveforms (e.g., using equation 2.21). It would have been interesting to incorporate a discussion on the limit of that approximation and if it is generally a valid assumption.

Chapter 3 is an application of the approach developed in the previous chapter to the centroid moment tensor inversion of foreshocks and aftershocks of the 2016 Kumamoto earthquake sequence. Results show that foreshocks are mostly right lateral strike-slip events while aftershocks are normal dip-slip events. Most events involve a small CLVD component remaining within posterior uncertainties. However, a couple of events contains large CLVD component that might reflect complexities in the rupture process, possibly involving a combination of strike-slip and dip-slip mechanisms. To study such complexities, moment tensor solutions are decomposed into two double-couple sources assuming that the main principal stress axis of subsources are within 20°. The geometry of the activated ruptures is finally determined by analysis of (1) moment tensor solutions, (2) orientation of the surface fault traces, (3) relocated cluster geometry and (4) the relative location of the hypocenter and centroid. This chapter is in very good shape and has been published in Earth, Planets and Space. As a minor remark, it would have been interesting to account for uncertainty in moment tensor solutions in the decomposition of moment tensor solutions. Another minor remark is that the maximum main axis difference of 20° is not really justified in that chapter. I wonder if there is any rationale behind this choice as static and dynamic stress fields might differ significantly. Finally, I didn't really understand how the geometry of the activated ruptures was determined. Is it a manual process or is there some kind of optimization to determine the orientation of each fault plane? Is it assumed that each earthquake occurs on a different fault?

Chapter 4 presents another main product of the thesis – a Bayesian fault slip inversion algorithm with automated self-adapting parameterization. The chapter starts by explaining the basic principles of the method. The approach relies on a non-linear parameterization, inverting for a self-adaptive slip distribution along with the spatial distribution rupture velocity, rise time, peak time and hypocenter location. These are parameterized using two systems of control points with spline interpolations enforcing zero slip magnitude on the fault edges. The problem is solved using a Bayesian sampling approach combining the reversible jump MCMC algorithm and the parallel tempering approach. The method is applied to the 2016 Mw=7.1 Kumamoto earthquake using a two fault geometry (composed of the Hinagu and Futagawa segments). Results show dominant strike-slip motion on the Hinagu segment while the Futagawa segment has a significant dip-slip component. The analysis of posterior model ensembles reveals large uncertainties in the deep part of the Hinagu segment while larger variability is noticed in the northeastern portion of Futagawa segment. This chapter is very interesting and constitute a significant piece of work. I have a few minor questions on this part of the manuscript. First, I would be curious to know what is the impact of the zero-slip constrain on the fault edges (in particular at the free surface). Given that the Kumamoto rupture reached the surface, wouldn't it be more meaningful to avoid any non-zero slip constrain at the free surface (or alternatively enforce a non-zero slip value from field and geodetic observations)? This comment is particularly motivated by the fact that there is a long-standing discussion regarding a possible deficit of shallow-slip for large strike-slip earthquakes. It is thus important to understand if such a deficit is observed for the Kumamoto mainshock and how the depth variation of slip potency is affected by the interpolation scheme employed in this study? My second question is how the maximum likelihood solution on Figure 4.5 is obtained? The reason I am asking is that the most likely model sample in the posterior ensemble is usually a poor estimate of the so-called Maximum A Posteriori (MAP). Finally, although I enjoyed the uncertainty analysis detailed in this chapter, we are left a bit hungry for more. In particular, it would be very interesting to investigate correlation between model parameters (e.g., spatial correlation of slip; correlation between rupture velocity, rise time and peak time, etc.). Posterior ensemble could also allow to address relevant scientific questions probabilistically. Beyond the technical aspects that are very well addressed in this study, we are sometimes missing what are the important scientific questions in the context of the application examples that are presented.

Concluding remarks: This is a very interesting and solid piece of work bringing new approaches to constrain the source properties of earthquakes along with reliable posterior uncertainties estimates. The thesis is very well-written and easy to read. I thus have no hesitation in recommending that this thesis should be submitted for oral examination.

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