2014 Source Inversion Validation (SIV) Workshop Report

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The 2014 Source Inversion Validation (SIV) workshop was held in Palm Springs in conjunction with the SCEC annual meeting. The workshop was invitation-only and had on average approximately 25 participants, although up to 35 people attended at certain times.

Martin Mai began the workshop by summarizing the current SIV benchmarks. The Green's function benchmark, which includes both point-source and finite-fault forward tests, has 5-8 participating groups. There are plotting tools on the SIV website that make it easy to compare waveforms and misfits between the submissions.

The first inversion benchmark, a simple dynamic rupture with no noise, has 10 submitted solutions from 5 groups. M. Mai remarked that many people have been using this benchmark to test and calibrate their codes, but they are not necessarily all submitting solutions to the website.

The second inversion benchmark includes two kinematic ruptures in a 3D heterogeneous Earth; the first part of this benchmark has 6 submissions; the second, which includes Green's function noise, has 1 submission.

The third benchmark is a recent addition to the SIV tests. It is a teleseismic rupture in California with synthetics at 52 global sites. Regional and local synthetics will be added soon.

The main points of discussion regarding M. Mai's talk were:

- *L. Meng said a teleseismic array should be included in this benchmark so that backprojection could be done; this is possible because the source does radiate high frequencies.*
- *Green's function results are still not all in agreement, because those modelers whose codes gave very disparate results are no longer participating in SIV, and have not updated their results. Those modelers who had consistent forward solution submissions are the modelers who went on to submit solutions to benchmarks. To help get more forward-model submissions with more agreement, W. Ellsworth suggested that more instructional*

information for modelers on the forward tests could be given (e.g. how to set up some of the standard codes).

Next, Thorne Lay gave a talk on strategies to improve reliability of teleseismic inversions. The main strategies were 1) data increases, 2) using an independent constraint on rupture velocity to condition the inversion, 3) joint inversion, for example with tsunami data, and 4) improvements to the Green's functions. In particular, including tsunami data improves the resolution at shallow depths. Linearizing the tsunami data is "dicey", but with appropriate filtering and windowing it can be included in a joint inversion with seismic and GPS data. One inversion example Th. Lay discussed that was particularly interesting was a 2012 Costa Rica earthquake where the rupture occurred under a peninsula, so in this case there was data right over the source, which is usually not the case for large subduction-zone earthquakes.

The key discussion points regarding Th. Lay's talk were:

- *R. Archuleta asked about the effects of HR-GPS and any other HF-data in the inversion when combing teleseismic and tsunami data, since these data may see a very different physical process.*
- *M. Denolle asked how to best determine the weights for the different data set, and if there is an approach to assign these weights automatically. Th. Lay responded that weights are based on experience, and are case dependent.*
- *B. Shaw made a comment regarding the need to define/quantify the epistemic uncertainties in these source-inversion results.*

Frantisek Gallovic gave a talk about inverting data from the L'Aquila earthquake. He discussed how smoothing could be used to suppress Green's function artifacts; however, smoothing also introduces its own artifacts on the solution, for example, temporal spreading of slip rates at large hypocentral distances. In some inversions he saw multiple peaks in in the slip-rate function, but interpreted these as likely artifacts. F. Gallovic also presented a preliminary inversion of the 2014 M6 Napa earthquake, which seemed to be a much more simple rupture compared to L'Aquila.

Questions on F. Gallovic talk were:

- *Th. Lay asked about the effects of topography and related seismic scattering on the Green's functions, and how this will affect the source inversion. F. Gallovic responded that the data are still more complicated to full include this aspect.*
- *W. Ellsworth asked how we (The SIV group) can better formalize the quality of the source-inversion results*
- *R. Harris asked to all participants if inelastic effects of ground-motion should be included in the inversion.*

Sarah Minson gave a talk about approaches to make inversions more robust to error – and for source inversions the important source of error is not really observational error, it is Green's function error. Green's function errors scale with the source, so bigger earthquakes don't help to mitigate their effect. Furthermore, these errors are highly correlated, so more data can only get you so far. Looking

at intra-time series correlation and station-to-station correlations can help to give a measure of how much data power there really is.

Question and comments on S. Minsons's talk were:

- *R. Burgmann pointed out the different complementary datasets can help because then the Green's function errors may not correlate.*
- *W. Ellsworth suggested to apply cross-validation and jack-knifing to better understand the uncertainties.*
- *R. Harris was discouraged by the results shown by S. Minson, in the sense that the uncertainties are very large, and commented "We should be able to do better!".*

Next Lingseng Meng gave a talk on ideas to merge back-projection and source inversions. Back-projection could be used as guidance for rupture velocity or to determine the spatial extent of the rupture. It could also be used to constrain the rise time, as backprojection is sensitive to high frequency radiation. Conversely, perhaps finite-fault inversions could be used to constrain back-projection, or a two-step hybrid approach could make a unified model to fit both low and high frequencies. Or a "joint" inversion of both could be achieved by minimizing the mismatch of peak location at each time step.

Olaf Zielke gave a short presentation discussing the SIV teleseismic benchmark. Building on suggestions at last year's SIV workshop, this new benchmark is for a M7.8 strike-slip earthquake on the Southern San Andreas fault. Teleseismic synthetics have already been calculated. O. Zielke requested that models send in requests for additional synthetics so that modelers using different techniques can participate.

M. Mai commented that we need a hierarchy of tests so that we can formalize weight choices between different datasets. It is well-recognized that the number of data points is not necessarily proportional to the information content of the data. Is there is a way to assess the information content of the data a-priori?

In the afternoon session, M.Mai began by presenting new statistical tools for rupture model comparisons. One test, the spatial prediction comparison test (SPTC), tests the models against the null hypothesis that they have equal predictive ability. This test requires knowing the true model, as with the SIV blind tests, or assuming a common reference model (for instance a mean/average model). For the Tohuku earthquake source models, they used a mean-model as reference, for example. The statistical test then examine how models are statistically different from each other. Results of these tests were discussed for the SIV benchmarks and seemed to agree with what one might determine by visual examination. The "winning" models were inversions that allowed a lot of freedom in parameterization; these models didn't fix the hypocenter and allowed subfaults to rupture at any time.

Questions to this talk were:

- *C. Ji commented that these methods may not be stable when there is more noise in the data due to the tradeoff between stability and power.*

Next several modelers gave short presentations about their methodologies and experiences with the SIV benchmarks.

- Cedric Twardzik presented a modeling method using a small number of elliptical subfaults to approximate the sources. JP Ampuero said it was not fair to judge this model with the given SIV tests because it has so few parameters compared to other models.
- Wenyean Fan discussed his experience with the dynamic benchmark. Part of his findings related to an earlier question brought up by W. Ellsworth – whether inversions can really constrain the slip-rate function and help to answer research questions in earthquake dynamics. W. Fan found in his modeling that resolution of the slip-rate function was poor. Higher-frequency data would be needed to better constrain it. W.Fan did find that he had resolution of fault dip – when he assumed the wrong fault dip, the slip model looked "noisy" and the data fit was poor.
- Chen Ji also gave a presentation discussing the error introduced in the model by the parameterization, and the data fit in different frequency bands. He suggested that building a better objective function could allow the inversion to make better use of information at different frequencies.

Peter Shearer commented that it is hard for modelers to answer why their model may look different than previously published models. Science should rely on reproducibility of results, but this currently doesn't occur with inversions (part of the problem is that papers don't have enough information to reproduce the results). From a journal perspective, is it useful to publish so many models? Do we believe the spread in models is a true sampling of the uncertainty space (probably not, it could be only part of it, or some models could simply be wrong).

In response, W. Ellsworth suggested that SIV could provide a standard format that authors could submit – this format would completely describe the slip-time history of the model and give detailed information on the inversion data and methodology. The idea of a "seed standard" for reproducibility was much discussed. It could be published in SRL or EOS, and then it would be up to individual journals to decide if they would require submissions to give this information, in standard format, in an e-supplement.

JP Ampuero brought up the recurring idea to have a real earthquake benchmark at some point in the future, with everyone assuming the same velocity structure and geometry.

M.Mai said that an SIV team could compute synthetics for submitted models to determine the effects of the source-modeling engine. We currently don't know if the models are different because those differences are in the null space, or if something else in the modeling is driving the differences. JP Ampuero then suggested that we could project the models out of the null space, and then compare. This is a very interesting idea, but we would have to make sure everyone is using the same Green's functions to really to it right.

W. Ellsworth remarked that it is very important to get a larger group working on the teleseismic benchmark. This is also extendable (for example, arrays can be added), so it should be interesting to many researchers. R. Archuleta said that $150K in funding (not from SCEC) to support ~10 groups work on this benchmark would be a good way to increase participation. Or, to secure more SCEC

funding, we could bring the teleseismic benchmark to the strong-motion scale and collaborate with other groups in SCEC.

SIV has funding for another workshop from SCEC. It was decided that it would be good to have this workshop in conjunction with the 2015 SSA meeting in Pasadena, CA. The workshop could focus on teleseismic benchmark results and be held at CalTech.

Building of the discussions at the workshop, small breakout teams were set up to further discuss the next SIV workshop, the next SIV benchmark, and a uniform format for inversion model reproducibility. The teams are composed as follows:

SIV workshop 2015 in conjunction with the SSA-meeting in Pasadena (April 21-23):

- to be held on Friday, April 24 (perhaps extending into Saturday)
- arrange also for special session at SSA on 'State-of-the-art of Earthquake Source Inversion'
- planning committee: JP Ampuero, M. Page, M. Mai, S. Minson

Uniform format for kinematic rupture models, to ensure reproducibility

- led by P. Shearer, includes Th. Lay, JP Ampuero, M. Mai
- produce a first set of recommendations on what the format should be able to achieve
- provide suggestions on how the format could look like
- starting points for this format could be the .fsp-format used in the SRCMOD database (http://equake-rc.info/SRCMOD/fileformats/) as well as the .srf-format proposed by Rob Graves and which is used internally in SCEC for ground-motion simulations

→ the team has compiled a document that will be circulated among SIV-participants for further feedback and comments, and then a decision will be taken where and how to best disseminate this proposed format to the global seismological community

The next SIV benchmark (inv4)

- team comprises M. Mai, JP Ampuero, F. Gallovic, C. Ji
- should include near-field and teleseismic synthetics, as well as GPS
- moderate-to-large (M 7 -7.4) rupture, located in Southern California
- the team will ask for SCEC-funding through the SCEC-proposal channels to receive support for the group to actually develop the model and compute the synthetics