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" International training course in full waveform inversion for moment tensors and multiple source models (ISOLA code) "

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General discussion

At the end of the course, a general discussion took place, the main points of which are briefly summarized below.

Insufficient data. One of the most important conclusions is that users must be aware of the fact that in some cases the available data do not allow successful calculation of the focal mechanism. Typical cases include: (i) availability of only very few stations, (ii) enough stations, but all in a relatively large distance, while the existing velocity model does not allow satisfactory waveform modeling. For example, if working with weak events, their signal-to-noise ratio is good only at frequencies above the microseismic noise peak (~ 0.2 Hz) and, at the same time, waveforms can be modeled only up to ~1-2 Hz at relatively near stations (epicentral distance of a few kilometers). It is important to know this limitation and, if necessary, be able to conclude that 'With the available data we are unable to provide a reliable result'.

Data quality. Quality check is essential. Any ISOLA application should start from a check of all records for possible instrumental disturbances ('mice') and careful selection of suitable frequency range. Also orientation of sensor is important. If metadata are correct, the related information can be obtained from header of SAC files, accessible for example by SeisGram 2K code of A. Lomax (S2K) – the parameters CMPAZ and CMPINC. Reliable poles and zeros are very important, but, unfortunately, it is not easy to check them; often it happens that problem appears only after unsuccessful attempt to match the waveforms (e.g., one station behaves differently than the others). Correct absolute time of records is necessary. Problems with absolute time (temporary failure of the GPS synchronization) should be however revealed before application of ISOLA, during location, in which a station with wrong clock yields very large residuals. Then knowing the theoretical arrival time the record with incorrect time can be shifted properly and thus becomes usable in ISOLA. A possible source of difficulties may result also from contamination of the record by another event, e.g. a large distant earthquake preceding the studied event.

Epicenter and polarity. Weak events recorded at near stations provide a possibility to check their epicenter position (i.e. to check correctness of the location) by means of the particle motion. A simpler procedure is at least to check polarity on all three components. For example, if the event is located NW from a station, and the station has positive Z onset (Z+), then we must have NS- and EW+.

Start time – a practical requirement. In ISOLA all records are adjusted in such a way that they begin in origin time. Removal of data before origin time may yield numerical problems exactly at origin time (time formally denoted t=50 s on the ISOLA waveform plots). Records from short epicentral distances have their signal appearing soon after origin time and therefore may have artifact close to origin time. To avoid the problem, users should apply artificial decrease of origin time by, for example, 20s, which is equivalent to shifting signal 20s to the right. Then the temporal search is not performed around 0, but around 20s. General recommendation is that all records should have their start time at least 30s before origin time in order to allow the above mentioned operation.

Instrument types. ISOLA can be applied using records from broad-band (BB), short-period (SP) as well as strong-motion (SM) instruments. They have complementary pros and cons. For example, BB records can be easily saturated, but they have better (lower) low-frequency instrumental noise. Strong motion records are often not aligned to N,E and have higher low-frequency instrumental noise. Moreover, older types of SM instruments have their frequency response flat only down to 0.1Hz, or similar value (while modern SM's are flat down to DC, i.e., down to 0 Hz). Some older SM's have even no absolute time; the latter can be partly solved as mentioned already above by introducing a shift of P onset to the theoretical arrival time. The SP instruments cannot be easily instrumentally corrected for frequencies below their corner frequency; it means that in practice the 1-sec SP instrument can be often used only at f>1Hz.

Polarities, source depth and velocity model. The first-motion polarities are equally important as waveforms. The moment-tensor (MT) solution by ISOLA should be checked for consistency with the polarities. Such a check also validates the source depth and velocity model (Moho depth), because the projection of stations on the focal sphere depends on these two factors. The polarity check is a must in applications where the correlation diagram (correlation as a function of source depth and time) features a typical ‘strip pattern’, characterized by polarity ambiguity for times which differ of each other roughly by half-period of the studied waves. Formal maximum of the correlation may provide strike/dip/rake which disagrees with the observed polarity. However, the neighboring (slightly lower) maximum of the correlation may agree. As a rule, these two solutions have similar strike and dip, but rake differs by 180°. Better speaking having solution with the values S, D, R, the solution corresponding to the fully reverted waveform sign has rake R-180°.

Polarities –more details. ISOLA has a tool to check polarity, but the tool will need some upgrade in future. At present, if user wants to ‘play’ with the source depth and crustal model, he has to manually edit files *source.dat* and *crustal.dat* in *polarity* folder. A new ISOLA feature allows easy inclusion of polarities from additional stations, not only those used in the waveform inversion. For that purpose, a file *extrapol.pol* should be manually created in *polarity* folder. Columns 1-4 of the file contain: Station code, Lat (°), Lon (°), polarity. The polarity symbols are arbitrary, e.g. U/D, +/-, ?, etc. After application the *extrapol.pol* file is automatically re-named into *extrapol.done* and added extra polarities are used in all subsequent polarity checks.

Polarities – still more details. A critical point is that during the polarity check user has to decide which discontinuity of his velocity model most likely generated head waves, forming first arrivals at large epicentral distances. This discontinuity must be the last discontinuity of the velocity model in *polarity* forlder. If model used in ISOLA for waveform inversion is different, i.e. it contains also deeper but less strong discontinuities, not likely generating first-arriving head waves, user has to provide his preferred *crustal.dat* into *polarity* folder, and, correspondingly, un-check the box entitled ‘Disable crustal.dat editing’.

Velocity model. Velocity model plays always an important role, sometimes more and sometimes less critical. For example, in regional applications up to epicentral distance of ~100km and frequencies f<0.1 Hz, as a rule, use of different existing models of the crust does not yield very different results. However, when increasing the maximum used frequency and/or increasing the used epicentral distance, the velocity model is more critical. Extremely critical is the knowledge of the velocity model if only few stations are available and/or the studied event is weak (recall that in the latter case we can work only above microseismic noise, e.g. between 0.4 and 1 Hz). In cases where the effect of the model is critical, user should try as much as possible to make independent study of the crustal model before starting ISOLA calculations. Current possibilities include, for example: (i) codes jointly inverting for location and velocity model (e.g. VELEST),

(ii) codes inverting dispersion curves of surface waves to velocity model, (iii) codes inverting full waveforms for velocity model. Advantage of (ii) compared to (iii) is that (ii) does not need prior knowledge of the focal mechanism.

Constrained inversion modes. In case of poor knowledge of velocity model, any non-double-couple (non-DC) components are dubious. In case like that, the inversion might be stabilized by avoiding full MT mode, using ISOLA in the deviatoric or DC-constrained mode.. Multiple-point source models need almost always a fixed focal mechanism (i.e. ISOLA mode in which user prescribes the strike, dip and rake angles and these are kept constant for all subevents). It is because allowing different mechanism of subevents may often yield un-physical results due to tradeoff between the inversion parameters.

Uncertainty analysis. Linear uncertainty analysis (Zahradnik and Custodio, BSSA 2012) has been implemented in ISOLA. It is a method useful for a relative uncertainty estimate; 'relative' means comparing various source station configurations. For example, working with very few stations, the MT inversion problem is ill-conditioned, the condition number (CN) is 'large'. What is 'large' and 'small' can be illustrated by running ISOLA not only for the real source-station configuration (very few stations), but also with fictitious stations, added with intention to model a denser network. Mapping the MT uncertainty (Zahradnik and Custodio, BSSA 2012) will be implemented soon in a future ISOLA update. It is useful for network design, because it does not need any waveform data. Other uncertainty measures, currently implemented in ISOLA include jackknifing and the FMVAR-STVAR indices (sokos&zahradnik_srl2013.pdf).

Comparison with GCMT and other solutions. After obtaining MT result by ISOLA, it is always recommended to compare with any alternative solution; for example, solution by regional or global agencies for larger events, e.g. Harvard GCMT, and/or with pure polarity solutions for weak events. ISOLA, containing a tool for space grid search of centroid, may provide a better centroid position than GCMT, because the latter is based on linearization. Another case where ISOLA may be useful: If apparent non-DC components of the focal mechanism are similar to those of GCMT, hence seemingly are not only formal artifact of mismodeling, may be explained with ISOLA in terms of 100% DC multiple-point sources. On the other hand, a possible disadvantage of ISOLA is that it sometimes provides lower Mo and Mw values of large events than global agencies, because in regional applications we do not dispose with extremely long wavelengths.

Time function. The assumed duration of elementary moment-rate time function is important. In the majority of cases users work well below corner frequency of their studied events, then delta-function is an applicable choice of the moment-rate function. However, when approaching the corner frequency of the event (e.g. at ~0.1 Hz for M>6) it is useful to use triangular elementary moment-rate function and repeat the calculations with a few different values of its duration T, monitoring behavior of the variance reduction (VR) and moment Mo.

Time function – more details. Current ISOLA version has an important (so far rather overlooked) tool to get a more realistic time function consisting of a linear combination of (closely spaced) elementary triangular functions. The tool is simply applicable also for 2-point models, whose position, time and focal mechanisms were calculated by the iterative deconvolution, or were arbitrarily setup by user. In such a case the code jointly resolves the time functions of both sources of the source pair, and also provides the total time function (summing the two sources). The non-negative least square method is used (NNLS). New updates of ISOLA will include also a tool for searching *position* (and time function) of the source pairs by NNLS method. As shown on example of Van earthquake (Zahradnik and Sokos, GJI 2014), the NNLS joint search of 2 sources might be sometimes preferable over iterative deconvolution (ID), mainly if the station coverage is poor.

ISOLA-related codes. Recently developed codes, potentially useful for ISOLA users include: (i) automatic ISOLA (triantafyllis_etal_2013.pdf), (ii) slip inversion and uncertainty analysis by MUFEX method (gallovic_zahradnik_jgr2012.pdf), (iii) location without picking by the source-scanning algorithm (Zahradnik et al. submitted), (iv) combined use of FOCMEC and ISOLA for weak events in sparse networks (Fojtikova and Zahradnik, submitted).

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