

Complexity of the Mw 6.3 2009 L'Aquila (central Italy) earthquake:

1. Multiple finite-extent source inversion

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[1] Strong ground motion recordings of the Mw 6.3 2009 L'Aquila earthquake are analyzed by a newly proposed slip inversion technique. The source model consists of Multiple Finite-Extent (MuFEx) subsources. The slip amplitude, rupture velocity, rake and risetime are assumed constant within each subsurface. The size and location of the MuFEx subsources have to be inferred independently from other methods, preferably those free of strong constraints (such as constant rupture velocity over the whole fault, etc); here we use two published approaches satisfying such requirement: the truncated singular value decomposition and the iterative multiple-point source deconvolution. Each MuFEx subsurface is characterized by an individual set of trial nucleation points, rupture velocities and nucleation times, which are grid-searched. For each combination of these parameters, the subsources' slip is determined by the least squares approach. This procedure thus provides not only the best fitting model, but also a whole range of acceptable models, allowing for the uncertainty analysis. The method is demonstrated on three synthetic tests. When applied to the L'Aquila data, both the best fitting model and the uncertainty analysis suggest that the event consisted of two major episodes, one with the rupture propagating immediately after the nucleation in the updip direction, the other being delayed by 3–4 s with dominant propagation toward the SE along the deeper part of the fault. The retrieved complexity of the rupture propagation warns against attempts to stabilize inversions by the use of a constant rupture velocity over the whole fault.

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1. Introduction

[2] On 2009 April 6th at 01:32 UTC the town of L'Aquila in the Central Apennines (Italy) was hit by a Mw 6.3 earthquake (Figure 1). The earthquake occurred on a normal fault striking 140° along the Apennines dipping at 50°. The event caused nearly 300 casualties and heavy damage in L'Aquila town and several other villages *Ameri et al.* [2009]. The earthquake source process was a subject of many studies utilizing various data and approaches [*D'Amico et al.*, 2010; *Maercklin et al.*, 2011; *Walters et al.*, 2009; *Herrmann et al.*, 2011].

[3] In particular, to invert for the earthquake slip model *Cirella et al.* [2009] used the two-stage nonlinear technique by *Piatanesi et al.* [2007], utilizing both strong motion records and geodetic data. They observed anisotropic rupture propagation (faster in the updip direction and slower along the strike) and two major slip patches. Similarly, *D'Amico et al.* [2010], using back-projection, identified two

slip patches, the one in the SE being delayed and of smaller amplitude than the one close to the hypocenter. In the inversion by *Scognamiglio et al.* [2010] a constant rupture velocity was assumed and two distinct best fitting models were found: for the faster velocity a few slip patches were found at shallow depths, while for the slower velocity the main slip patch was located further SE along the strike and at greater depths.

[4] These results suggest that the earthquake rupture propagation was complex. However, slip inversions are highly non-unique inverse problems, which depend strongly on the imposed constraints (such as constant rupture velocity and/or smoothing) [*Lay et al.*, 2010; *Zahradník and Gallovič*, 2010]. Different slip inversions of even the same event provide different models [*Clévéde et al.*, 2004], some of them being characterized by rupture evolution complexities, and some not. Therefore, there is a need to develop inversion techniques that provide not only the best fitting model, but also some uncertainty estimate. The uncertainty analysis of the slip inversion result is a challenging task, still being often neglected.

[5] Nevertheless, several methods of estimating the slip inversion uncertainties have been proposed [*Hartzell et al.*, 2007; *Piatanesi et al.*, 2007; *Emolo and Zollo*, 2005; *Cirella et al.*, 2008; *Monelli and Mai*, 2008]; for a brief

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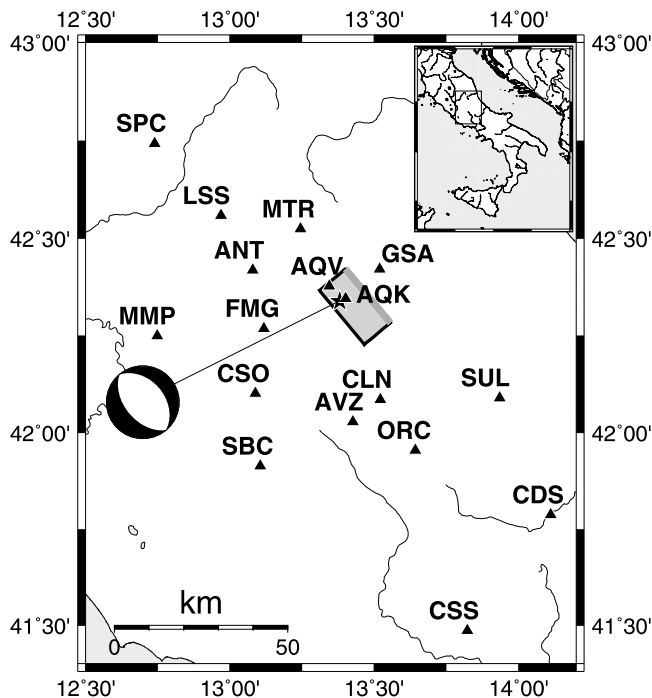


Figure 1. The fault geometry of the L'Aquila earthquake (gray box) with a dark gray line corresponding to the top edge of the fault. Selected strong motion stations operated by INGV and the Italian Civil Protection are shown as triangles. The asterisk indicates the epicenter. The inset shows the map of Italy with the region of interest (box).

review and criticism of the approaches, see the latter reference. In particular, *Monelli et al.* [2009], performed a full Bayesian analysis of the 2000 Western Tottori (Japan) earthquake, showing poor resolution power of the strong motion and GPS data, including strong spatial trade-offs among slip parameters. Although such an approach is perhaps the most complete, it is numerically very demanding (the authors report ~ 40 days of computational time). Also, the inferred trade-offs among parameters make it clear that the problem is rather over-parameterized when applied to real data. This is also in agreement with the finding by *Gallovič and Zahradník* [2011], who analyzed the slip inversion by means of singular value decomposition. Indeed, they showed that only a small fraction of the singular vectors can be utilized in a real data application, which leads to strong trade-off not only among spatial, but also temporal parameters. Thus decreasing the number of model parameters in a reasonable way is advisable.

[6] To have a smaller number of model parameters, it is necessary to parameterize the rupture evolution in a simpler way, while still being able to capture the major potential complexities of the earthquake ruptures. For example, *Vallée and Bouchon* [2004] introduced a patch model consisting of two adjacent ellipsoidal slip regions over which the rupture propagates at two generally different constant rupture velocities. The authors used a neighborhood algorithm to invert for the position and size of the ellipses and the respective rupture velocity values. The algorithm then provided not only the best fitting source model, but also some estimate of

the model uncertainty. However, their parameterization prohibited such features as the rupture delay, rupture jumps, etc.

[7] To allow a more general rupture behavior, while still keeping the number of parameters low, we introduce a new inversion technique called the Multiple Finite-Extent (MuFEx) source model. The MuFEx model describes the earthquake rupture as a composition of slip on a few subsources (asperities/regions of slip). The slip amplitude, rupture velocity, rake and risetime are assumed constant within each subsurface. The size and location of the subsources are a priori estimated (i.e., they are inferred independently by other methods). In particular, here we use the recently introduced approach based on the Truncated Singular Value Decomposition (TSVD) technique by *Gallovič and Zahradník* [2011] and the iterative deconvolution of multiple point sources (ISOLA package) by *Sokos and Zahradník* [2008]. Prescribing the dimensions and locations of the MuFEx subsources, the source parameters that the MuFEx inverts for are four at each subsurface: the slip amplitude, nucleation point, rupture velocity, and nucleation time. Assuming an individual set of trial nucleation positions, rupture velocities and nucleation times for each subsurface, we apply a grid-search procedure over all combinations of these parameters, while simultaneously solving a linear L2 inversion for the slip value. In this way, we obtain not only the best fitting model, but the whole family of plausible models that can be used for uncertainty analysis. Figure 2 demonstrates the approach by a flowchart.

[8] After explaining the MuFEx source model inversion, we apply the procedures to the real L'Aquila data following the MuFEx flowchart (Figure 2). We show that, although the earthquake was recorded with an excellent station distribution, the non-uniqueness of the inversion is expressed by relatively large uncertainties of the MuFEx source parameters. Nevertheless, some model features are shown to be robust, best demonstrated by comparison of the MuFEx results obtained for two alternative setups suggested by the preceding TSVD and ISOLA analysis. In the companion paper [*Ameri et al.*, 2012] we use the robust (major) characteristics of the retrieved model to constrain the modeling of strong ground motions in a broad frequency range (0.1–10 Hz), showing that these source characteristics are one of the most important pieces of information needed for strong ground motion modeling. The performance of the MuFEx source inversion is also demonstrated on three synthetic tests (assuming the fault and station geometry of the real L'Aquila earthquake), one of them being presented in Appendix A, the other two in the auxiliary material.¹

2. Data and Green's Functions

[9] The L'Aquila earthquake provided the largest high-quality near-fault strong motion data set ever recorded in Italy for such a major event. Accelerograms recorded at 17 stations (Figure 1) are band-pass filtered between 0.06 and 0.3 Hz and double integrated to obtain ground displacement time histories. The high-pass filtering at 0.06 Hz is applied due to the long-period noise. Green's functions are

¹Auxiliary materials are available in the HTML. doi:10.1029/2011JB008709.

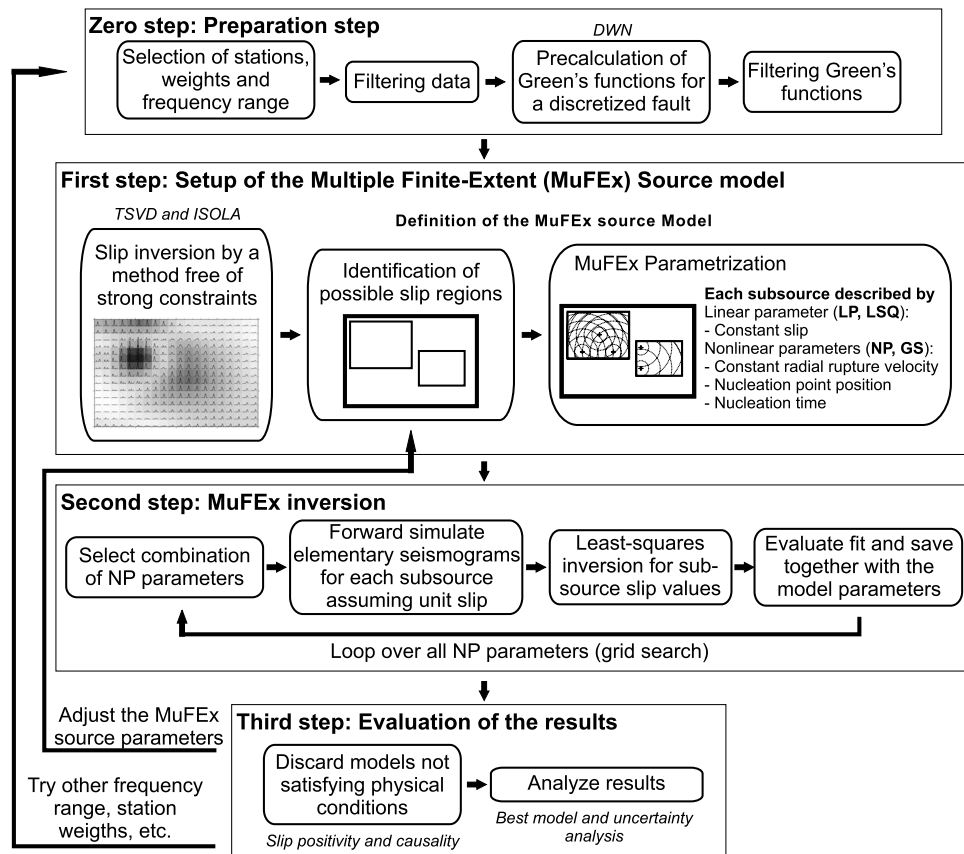


Figure 2. Flowchart of the proposed slip inversion approach. Notes in italics represent our particular choices. DWN denotes the Discrete Wave number approach. LSQ and GS denote whether the respective parameters are inverted by means of least squares approach or grid search, respectively.

calculated using the discrete wave number technique [Bouchon, 1981] in a 1D layered model (see the companion paper *Ameri et al.* [2012]). This technique provides full wavefield Green's functions including the near-field terms. They are also band-pass filtered between 0.06 and 0.3 Hz. The low-pass filtering at 0.3 Hz is applied due to the incompleteness of the crustal model leading to inability to correctly model Green's functions at higher frequencies. Moreover, in the frequency range considered, Green's functions are not very sensitive to the crustal model. No station weights according to epicentral distances and/or amplitudes were applied. For each waveform, we invert the complete wavefield of 100 s duration. Note that the same processing was applied in the synthetic tests.

3. Method

[10] The characterization of an earthquake rupture as a sequence of finite-extent subsources is not new. The Multiple Finite-Extent (MuFEx) source model results from the following reasoning. Generally, effects of the earthquake source finiteness are present in the wavefield at all distances and frequencies. However, under some conditions, these effects become negligible, allowing for simplification of the earthquake source description. At very low frequencies and distances much larger than the fault size, a finite-extent earthquake source can be approximated by a point source

(centroid). Increasing the frequency range (and/or decreasing the source distance), finite-extent characteristics start to be apparent in the wavefield; thus, e.g., second-order seismic moments might be retrieved [Backus, 1977; Adamová and Šílený, 2010]. This means that the source can be approximated by a finite fault with constant slip and simple (radial) rupture propagation. Increasing the frequency range and decreasing the source distance even more (as in our case), we suppose that the earthquake can be further described by a few slip patches (finite-extent subsources). To capture possible complexities of the rupture propagation, we assume that these subsources can have their own independent nucleation points, rupture velocities and time delays. In this way, the number of estimated parameters can be held small enough so that the grid-search procedure (being best suitable for uniform exploration of a relatively small model space) can be used.

[11] The MuFEx source model has to be set up by a preliminary analysis (see the flowchart in Figure 2). In particular, the MuFEx inversion requires reasonable estimates of the number of subsources together with a reasonable estimate of their locations and dimensions. This part has to be attained by methods with no strong constraints (such as constant rupture velocity over the whole fault, etc). Here we use the Truncated Singular Value Decomposition (TSVD) and ISOLA techniques; alternatively other methods can be

used to setup the MuFEx model, e.g., based on imaging techniques [Gallovič *et al.*, 2009, and references therein].

4. Preliminary Setup of the MuFEx Subsources

[12] The Multiple Finite-Extent (MuFEx) source model requires a preliminary setup of the subsources, i.e., their number, position and dimensions. Here we show two (out of many) possible ways based on the Truncated Singular Value Decomposition (TSVD) approach and the multiple-point

source deconvolution approach (ISOLA). Note that the two methods (when applied to the real L'Aquila records) result in somewhat different subsurface setups. However, when using the two setups, the results remain similar, which indicates that the MuFEx inversions yield robust results (see further).

[13] ISOLA (from 'ISOLated Asperities') is a program package based on a multiple point-source iterative deconvolution of complete low-frequency waveforms. The moment tensor is solved by the least squares method, while the position and origin time of the point sources is grid searched [Sokos and Zahradník, 2008]. Besides routine application in the seismic service of the University of Patras, Greece, the method proved useful in a number of earthquake studies [e.g., Zahradník *et al.*, 2008, and references therein]. Finite-extent source applications of ISOLA work with no constraints on the rupture velocity and the nucleation point [Zahradník and Gallovič, 2010; Gallovič *et al.*, 2009]. In the application of this paper the multiple point-sources have a pure double-couple mechanism prescribed by the strike, dip and rake angles.

[14] The TSVD method needs a more detailed explanation here as it has been introduced very recently. Gallovič and Zahradník [2011] used this approach to study the performance of slip inversions, mostly to explain the non-uniqueness of the slip inversion and the nature of possible artifacts [see also Zahradník and Gallovič, 2010]. Equivalently, instead of "artifact" we use term "bias of the solution" against the true one. The approach was demonstrated for a line fault; however, its formal generalization to rectangular faults is straightforward.

[15] The TSVD inversion is based on a linear formulation utilizing the discretized version of the representation theorem [Aki and Richards, 2002]. We assume the slip velocity time history without any constraints, only that it has a finite duration (namely 10 s in the present applications). Thus, only the fault geometry and source duration are prescribed; the rupture propagation and shape of the slip velocity functions are not constrained. The slip can occur anywhere on the fault and anytime during the given source duration.

[16] The samples of the slip velocity time history (in time and space over the discretized fault) compose the model parameters vector $\mathbf{m}$. This vector is linearly related

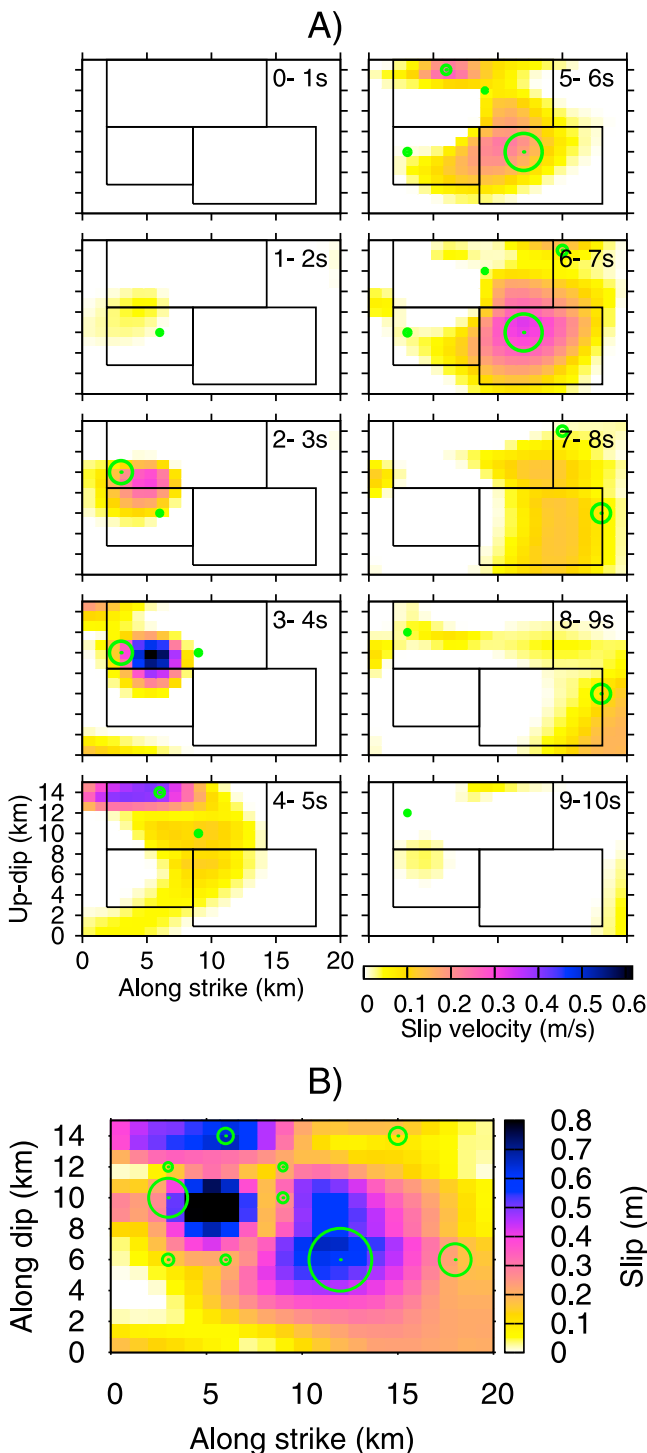


Figure 3. Setting up the MuFEx source model for the L'Aquila earthquake. (a) Rupture evolution snapshots obtained by the TSVD technique with truncation at 1/10 of the largest singular value. The fit with seismograms (variance reduction $VR = 0.77$) is shown in Figure 4. The areas with large slip velocities (see the color scale of the snapshots) are used for the preliminary setup of the MuFEx subsources (Figure 5a). Their final positions (rectangles) are constrained by trial-and-error to obtain reasonable fit with the observed data. The multiple point source (ISOLA) inversion is marked by green circles proportional to the moment (the largest circle corresponding to 6.6×10^{17} Nm, $VR = 0.62$). (b) Final slip model obtained by the TSVD inversion of the observed records of the L'Aquila earthquake. Note that the final slip is presumably highly biased (due to the TSVD truncation and the limited frequency range) as suggested by synthetic tests. Thus, the model has to be re-analyzed in terms of the MuFEx model.



Figure 4. Comparison between observed (black) and synthetic displacements for the L'Aquila event (green for the TSVD approach, red for the best fitting MuFEx model shown in Figure 5a). The records are band-pass filtered in the range of 0.06–0.30 Hz and have a duration of 100 s. The maximum amplitudes of the observed records in mm are shown as numbers.

with the vector of seismogram samples $\mathbf{d}$ via matrix $\mathbf{G}$ containing the appropriate Green's functions [Gallovič and Zahradník, 2011]. Note that this formulation is equivalent to that of the commonly used multitime window method [Sekiguchi et al., 2000] if the latter is used under relatively nonstandard conditions: number of time windows equal to one, duration of the time window equal to the entire duration of the event, and the time window at any point on the fault opens at the origin time of the earthquake. A similar approach, formulated in the frequency domain, was used for synthetic slip inversion tests by Olson and Anderson [1988]. In the present application of the TSVD method, the 20×15 km rectangular fault is discretized by 21×16 points. As data we use seismograms 102.4 s long, sampled at 0.4 s. The same sampling rate applies also to the slip velocity time windows (i.e., 10 s consists of 25 samples).

[17] The positivity constraint on the slip velocity is applied using the NNLS approach [Lawson and Hanson, 1974]. To regularize the solution, only the leading singular vectors are used which leads to the so-called truncated SVD

solution. To be able to truncate while using NNLS, the augmented matrix approach is used [Olson and Apsel, 1982]. A new set of equations is thus added to the problem, zeroing the contribution from the truncated singular vectors in the solution.

[18] Similarly to Gallovič and Zahradník [2011] in the application to the 2008 Mw 6.3 Movri Mountain, Greece, earthquake, we found that the leading singular vectors (composing the final solution) are smooth functions of time and space, thus no additional smoothing is required. These vectors thus not only yield a stable solution, but they are also not very sensitive to the uncertainties in Green's functions in the investigated frequency range. Generally speaking, the success of the inversions depends on how well the true (unknown) slip model can be decomposed into the leading singular vectors. Thus it is important to have the singular vectors with a 'rich' space-time pattern; this happens, e.g., with a good station azimuthal coverage. Gallovič and Zahradník [2011] also showed that, if relatively strong truncation is applied (as in our case), the inversion result is close to the so-called dark spot introduced in the paper by

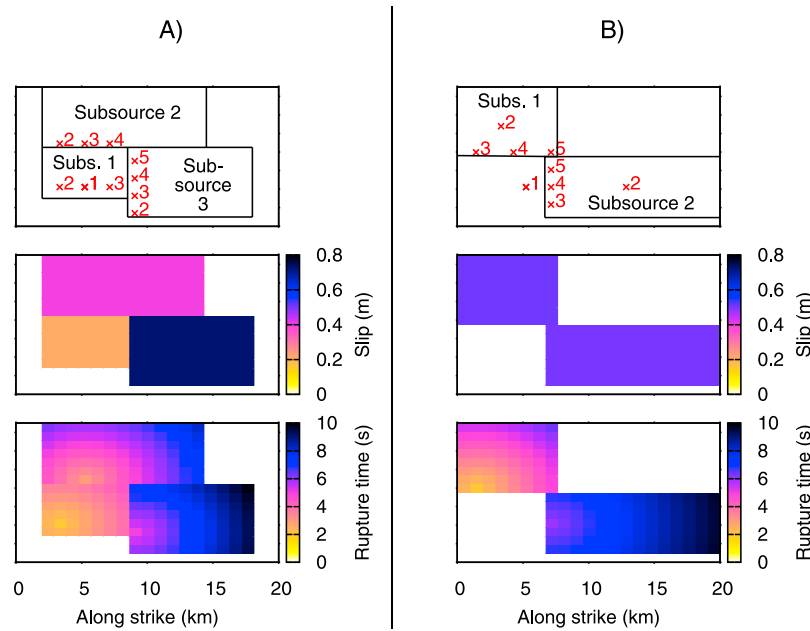


Figure 5. (a) Best fitting MuFEx model of the L'Aquila earthquake ($VR = 0.72$, see Figure 4). The top panel shows the subsources of the MuFEx model as obtained from the TSVD preliminary inversion (see Figure 3) and subsequent tuning by trial-and-error to obtain the best fit with the data. The numbered crosses represent trial nucleation points of the subsources. These are different for the different subsources, except for trial nucleation point #1 (corresponding to the published hypocenter location) common to all the subsources. The middle and bottom panels show the best fitting (grid-searched) MuFEx source model in terms of the final slip (assumed to be constant on the subsources) and rupture times (assuming a constant rupture velocity on each subsource), respectively. (b) Same as Figure 5a, but for an alternative setup of the MuFEx model ($VR = 0.63$), based on the ISOLA inversion (see green circles in Figure 3). Note the time delay of the bottom right subsource obtained independently of different MuFEx source setups. Furthermore, for both setups the seismic moment of the bottom asperity is close to $2e18\text{Nm}$.

Zahradnik and Gallovič [2010]. The dark spot shows areas in time and space (over the fault) whose ‘partial’ point source synthetics have a high correlation with the observed data (calculated simply as $\mathbf{G}^T \mathbf{d}$). Thus, the dark spot, on the one hand, contains all the asperities of the true model, while, on the other hand, the intensity of the dark spot may not correspond well to the significance of the asperity. This also results in the artifacts analyzed in those studies.

[19] Figure 3a displays the resulting rupture snapshots from the TSVD inversion. The waveform fit is demonstrated in Figure 4. The truncation in TSVD is done at a singular value equal to $1/10$ of the largest singular value. This provided what we subjectively judge to be the most complex rupture evolution without any major unphysical features such as “random” rupture occurrence on the fault. The truncation is required due to imprecise Green’s functions in the real application. (Note that in the case of synthetic data, if we truncate at the machine double precision accuracy, the inversion result is almost perfect.) The truncation at $1/10$ has a number of drawbacks, some of them being analyzed on three synthetic tests explained in Appendix A and the auxiliary material. A minor problem of the truncation is an analogy of the Gibbs effect, i.e., spurious oscillations (‘ghosts’) appear due to the use of a limited number of singular vectors. A major problem is related to strong artifacts, especially of the final slip model obtained by temporal integration of the slip velocity functions (Figure 3b). Indeed,

Gallovič and Zahradnik [2011] showed that the regularization can cause hardly detectable artifacts common to many inversion approaches. The problem is that the inversion result is not unique in principle, because only a limited number of singular vectors is used. Note that a similar conclusion was drawn by Olson and Anderson [1988]. Therefore, any single inversion result is insignificant. To determine the range of possible models in the TSVD method, one would have to explore all possible combinations of the unused singular vectors, which is obviously practically impossible. This leads us to introduce a more practical approach based on the MuFEx source model to alternatively obtain the uncertainty estimate.

5. MuFEx Source Inversion

[20] As there is no universal ‘recipe’ how to set up the MuFEx subsources, we present two alternatives in Figure 5. First let us concentrate on the setup shown in Figure 5a and Figure 3, dictated by the hypocenter position and the position of the large slip velocity values in the TSVD snapshots. Note that we prefer defining the subsources based on large slip velocity values instead of the final slip because the experience is that the latter is biased much more (see above). In the present setup, subsource 1 lies in the hypocentral area of the earthquake, subsource 2 at shallow depths, and the largest subsource 3 is located in the deeper part, further

along strike. Note that the TSVD final slip model (Figure 3b) suggests a relatively small slip for the subsurface 3.

[21] The 'local' rupture on each of the MuFEx homogeneous subsources is assumed to propagate at constant velocity and radially from a nucleation point (several nucleation points are subject to the grid search). We assume several nucleation points to capture even cases in which the earthquake consisted of more than one event (e.g., a doublet). Another reason for allowing for more than a single nucleation point is that in real applications the major nucleation point (the hypocenter, obtained during kinematic location) is never free of errors. The slip velocity function at each fault point is assumed to have duration shorter than the reciprocal of the maximum frequency considered, 0.3 Hz, i.e., the risetime is arbitrary but smaller than 3.3 s. Thus the slip velocity time function is effectively a delta function in the investigated frequency range. Releasing this assumption might be a point for further studies.

[22] Eventually, each subsurface is described by four parameters. Three of them – nucleation position, nucleation time, and the rupture velocity – are related nonlinearly to the wavefield. Their ranges (trial values) are selected according to the preliminary TSVD and ISOLA analysis and/or to be in reasonable physical limits. The three parameters are grid searched. The fourth parameter – slip of each subsurface – is related linearly to the wavefield. Thus, for each combination ($\sim$ millions) of the subsurface parameters, the slip is obtained by the least squares approach; we have checked that the least squares inversion is well-posed by inspecting the conditional number.

[23] In the present application, we tested rupture velocities between 1.5 and 3.5 km/s; the nucleation times vary between 0 and 7 s. The trial positions of the nucleation points can be seen in Figure 5a. They are different for the different subsources, except for trial nucleation point #1, corresponding to the published hypocenter location that is common to all the subsources.

[24] Grid-searching all the possible combinations of the input parameters ($\sim$ 3 millions) results in an extensive database of models with quantitatively evaluated fit in terms of the variance reduction, $VR = \Sigma(obs-syn)^2 / \Sigma(obs^2)$, where *obs* and *syn* denote the observed and synthetic waveforms, and the summation is over all stations, components and time samples. This database can be used to explore the uncertainty of the inverted model. To take into account only physically plausible models, grid-search results are filtered according to the following additional criteria: (1) all subsources must have positive slip, and (2) subsurface 1 must originate at least 1 s before the other two subsources (if not nucleating from the common nucleation point #1).

[25] After the MuFEx model inversion is performed, the whole procedure can be repeated. Positions and/or dimensions of the subsources can be modified (including changes of the trial parameters) in order to obtain a possibly better fit with the data. Our experience is that modifications within ± 2 km do not change the results significantly in the present application.

[26] The best fitting model out of all ($\sim$ 3 millions) grid-searched models is shown in Figure 5a. The rupture starts at nucleation point #2 in subsurface 1. It is quickly followed by the onset of the shallow subsurface 2. Later (~ 5 s after the earthquake origin) subsurface 3 is activated. In terms of the

slip values, subsurface 3 has the highest slip amplitude, which is in contradiction with the preceding TSVD analysis (see Figure 3b). This can be attributed to the different parameterizations of the TSVD and MuFEx inversions; MuFEx is much more constrained with fixed rectangular subsources, constant slip and radial rupture propagation. The fit of the TSVD and MuFEx synthetics with the observed records is shown in Figure 4. Note that the fit for the best fitting MuFEx source model is only slightly worse than for the TSVD model, although the former is much simpler than the latter. Moreover, for some station components the MuFEx source model provides an even better waveform fit than the TSVD model.

[27] Figure 6a shows the analysis of the plausible models. Each model is represented by a dot, represented by its parameter value and its VR value. This allows for studying uncertainties as a function of a threshold VR (the lowest acceptable VR). Note that only models with VR larger or equal to 95% of the best model (approximately 300 models) are shown for clarity. The plots allow the analysis of the uncertainty of the individual parameters separately. For example, regarding the rupture velocity at subsurface 1, allowing only a small decrease of the fit with respect to the largest VR, almost all the tested velocity values are allowed. The uncertainty is slightly smaller for the rupture velocities at the other two subsources. The preferred values (in terms of VR) are 2 km/s, but for the deep asperity even larger values are allowed (especially for the smallest subsurface 1).

[28] Thus, we can conclude that the inversion is very weakly sensitive to the actual rupture velocity inside the subsources, perhaps due to the relatively low frequency range and the source-station configuration in the present application. Note that the large uncertainty is the consequence of a strong trade-off among parameters; if a different rupture velocity is used, almost the same fit can be obtained when altering other parameters. Note that in alternative inversion approaches, working with a larger number of parameters, it would be much more difficult to investigate such a trade-off. In this sense, a reasonably limited number of the MuFEx parameters is advantageous.

[29] Studying the uncertainty plot in Figure 6a regarding the nucleation points, one can again observe the relatively small sensitivity of the data to the tested locations. Common nucleation point #1 is allowed for all subsources when decreasing the acceptable fit slightly ($\sim 3\%$). On the contrary, the data are relatively sensitive to the nucleation times of the subsources. While the shallow subsurface 2 prefers to rupture about 1 s after subsurface 1, the deeper subsurface 3 requires a longer time delay (4–6 s) despite approximately the same distance to the hypocenter on subsurface 1. Although the subevent activation times are relatively well constrained, their interpretation in terms of average rupture velocities can be misleading. For example, the inferred time delay of the deep asperity might be equally well due to either slow-down of the rupture or partial rupture arrest.

[30] Figure 6a also shows the uncertainty of the slip on the individual subsources, as well as the total seismic moment. One can see that subsurface 1 has the least amount of slip; allowing for a misfit as low as 95% of the largest value, the slip of subsurface 1 can be even (close to) zero. Contrarily, subsources 2 and 3 require relatively large slip values ranging from 0.4 to 0.8 m. The retrieved total seismic

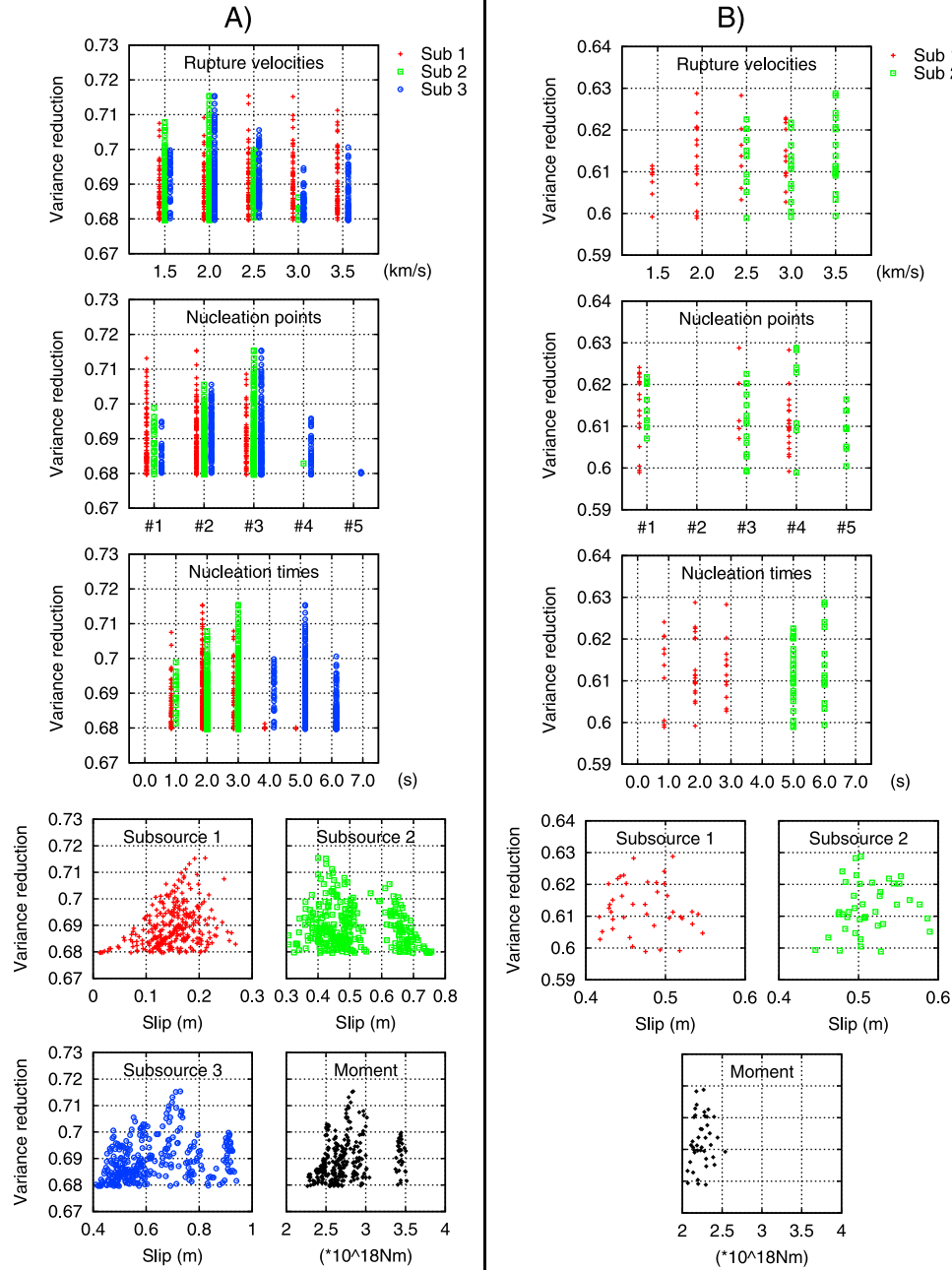


Figure 6. (a) Analysis of the grid-searched MuFEx source models with $VR > 0.68$ for the L'Aquila earthquake based on the TSVD preliminary inversion. The analyzed set consists of approximately 300 models out of 3 million trial ones. The first three plots from the top show the uncertainty of the MuFEx model parameters, namely the rupture velocities, nucleation points and nucleation times. For the location of the tested nucleation points see Figure 5. The remaining four plots analyze the slip distribution of the three subsources individually and the total seismic moment. Let us emphasize that all the analyzed models are characterized by the delayed start of subsource 3 (by 4–6 s), observable also in the best fitting model in Figure 5. (b) Same as Figure 6a, but for the MuFEx source models based on the ISOLA inversion (40 models with $VR > 0.60$ out of 40,000 trials). Note that the delayed bottom asperity is present again, and that the nucleation points located in the centers of the subsources (#2) are rejected by the inversion.

moment 2–3.5 $\times 10^{18}$ Nm covers a variety of results from published moment tensor solutions and other slip inversions.

[31] To verify the robustness of the inversion, we repeat the MuFEx analysis for an alternative setup based on the

ISOLA inversion (see the green circles in Figure 3). We assume only two subsources, the centers of which are set to the locations of the maximum moment release. The dimensions of the subsources were estimated from the seismic

moments using the empirical relations of *Somerville et al.* [1999]. Figures 5b and 6b address this alternative setup. They again show the best fitting model and its uncertainty analysis, respectively. With this setup the fit to data is slightly lower. Nevertheless, the comparison with Figures 5a and 6a demonstrates that some results persist with both setups of the MuFEx source model: (1) a delay of the deep asperity is required, (2) the common nucleation from the earthquake hypocenter (point #1) is not prohibited, and (3) although the slip values for the deep asperity are different for the two setups, in both cases the corresponding seismic moment is close to 2×10^{18} Nm. However, some differences between the two setups can be observed. For example, the total seismic moment is lower for the ISOLA setup, which is related to neglecting a part of the fault with non-negligible slip. Also, higher rupture velocities (2.5–3.5 km/s) inside the deeper asperity are required for the ISOLA setup than for TSVD. In the ISOLA setup we have also tested an additional feature, namely the trial nucleation points located in the centers of the subsources (points #2); Figure 6b demonstrates that local bilateral rupture propagation on the subsources is rejected by the MuFEx uncertainty analysis.

6. Discussion and Conclusions

[32] The present paper deals with the inversion of the very well recorded Mw 6.3 2009 L'Aquila earthquake. This event had a complex rupture, with rapid changes of rupture velocity and/or rupture delay, so it had to be analyzed by a slip inversion technique free of strong constraints (such as constant rupture velocity over the fault). To this end, we used the Multiple Finite-Extent (MuFEx) source model with two or three homogeneous subsources to characterize the earthquake rupture; see the flowchart of the inversion in Figure 2. The preliminary inversions obtained with the Truncated Singular Value Decomposition (TSVD) method and the iterative deconvolution of multiple point sources (ISOLA) were used to initially constrain the positions and dimensions of the subsources. The use of several setups is important to assess the robustness of the MuFEx inversion. Note that in the present application we assume the subsources to be of rectangular shape just because of their simplicity (ellipses could also be used). The constant slip considered on the subsources and, hence, the stress singularities at the edges, do not harm the low-frequency slip inversion. Nevertheless, the MuFEx source model should not be used in 'high-frequency' (e.g., stress) analysis prior to proper tapering.

[33] An exhaustive automatic grid search of the free parameters of the MuFEx source model (namely individual nucleation points, rupture velocities and time delays of the subsources) allows robust identification of gross features of the rupture propagation complexity. Note that the approach is easily parallelizable; the present applications require ~ 20 minutes on a standard 4-core PC.

[34] The inverse problem is characterized by a large uncertainty. Besides the analysis of the real data, the inversion uncertainty is analyzed also on three synthetic experiments (see Appendix A and auxiliary material). The input models for the synthetic tests are not only close to the real-data inversion result, but they also cover a range of different rupture propagation regimes and/or asperity positions.

The tests show that the ISOLA technique and even more the over-parametrized TSVD inversion may provide highly biased results (see the discussion of the cause of the bias by *Zahradník and Gallovič* [2010] and *Gallovič and Zahradník* [2011]). However, they both serve as good indicators for the MuFEx setup source positions. The MuFEx source inversion shows large uncertainties for most of the parameters of the subsources, although we have pointed out above that the source-station geometry is excellent. This merely reflects the non-uniqueness of the inverse problem considering the present accuracy of Green's functions. Note that the retrieved uncertainties of the parameters can be analyzed also in terms of trade-offs among the analyzed parameters of the MuFEx source model. This is left for further studies.

[35] In spite of the considerable uncertainty of the finite-fault model, there is an important stable parameter: The MuFEx source inversion indicates that the L'Aquila event can be considered as a doublet. This is a robust feature, found for the two MuFEx source models obtained by the two preceding analyses by the TSVD and ISOLA approaches. (A similar unique stable feature was demonstrated for another event by *Monelli et al.* [2009]; this was the shallow asperity of the 2000 Western Tottori earthquake.) In the case of the L'Aquila earthquake, the first event, a shallow asperity located updip from the hypocenter, was reached by the rupture front relatively quickly after the earthquake origin. This might suggest a rupture jump ahead, meaning that the shallow asperity was triggered by P waves from the nucleation area. Or, perhaps more likely, the rupture propagated updip from the hypocenter at a relatively high rupture velocity due to the observed high S-wave velocity body in the source area, discovered by means of receiver functions [*Bianchi et al.*, 2010]. In the companion paper [*Ameri et al.*, 2012] it is shown that the shallow asperity is responsible for the low-frequency motion at the near-fault stations due to the updip directivity effect. The second event of the earthquake doublet is the SE slip asperity at larger depths characterized by a larger seismic moment and, most importantly, a considerable rupture delay of ~ 3 –4 s.

[36] *Cirella et al.* [2009] explained the observed L'Aquila data by a model with different rupture propagation velocities in the along-strike and updip directions, say by a smooth model. This is not in contradiction to our interpretation. Indeed, in the MuFEx model the detected delay might be only a manifestation of a fast slow-down of the rupture along a part of the fault SE of the hypocenter. The uncertainty of the MuFEx parameters demonstrates that the data resolution in the given frequency range is not capable of distinguishing whether the observed rupture propagation complexities were due to the highly varying rupture velocity or due to a temporal stopping of the rupture propagation.

[37] Note that the inferred complex rupture behavior is a distinct feature, suggesting that prescribing a constant rupture velocity over the whole fault in the slip inversions is not an adequate stabilizing constraint (as often used in practice). Indeed, in the inversion by *Scognamiglio et al.* [2010] a constant rupture velocity was assumed and two distinct best fitting models were found: for faster velocity few slip patches were observed at shallow depths, while for slower velocity the main slip patch was located further along the strike and at greater depths.

[38] Nevertheless, we found that constant velocities may be a good approximation for the individual subsources (the decrease of the variance reduction due to the simplification of the rupture model in the MuFEx approach was only a few percent compared to the TSVD technique). This suggests that the constant rupture velocities of the subsources are possible only due to the limited resolution of the data used. To increase the inversion resolution, one would need more precise (3D) Green's functions. It would allow the use of higher frequencies, thus involving more subsources in the MuFEx source model and/or allow the source properties to be characterized in even more detail.

[39] Note that a common approach in recent studies is to consider several so-called rupture segments [Kaverina *et al.*, 2002; Sekiguchi *et al.*, 2000]. As a rule, only a few alternative models with varying segments (and their parameters) are tested in such techniques. On the contrary, the MuFEx model is simpler because it has constant slip values over the individual subsources, but one can fully automatically explore all combinations of the rupture velocities, nucleation times and positions, thus assessing the inversion uncertainty. Despite the simplicity of the MuFEx model, it is still characterized by a relatively large uncertainty in most of the parameters. This suggests that the MuFEx parameterization is plausible. Over-parameterization in other methods might lead to incorrect interpretations and misleading conclusions, especially if a thorough uncertainty analysis is not performed.

[40] To conclude, the L'Aquila earthquake was characterized by a complex rupture process. Such complex ruptures have so far been reported mainly for large (mostly strike-slip) earthquakes. Indeed, strike-slip faults with significant surface ruptures are known to be composed of geometrically distinct segments with a complex style of rupture propagation (a partial rupture arrest on fault bends, a varying rupture velocity from sub-shear to super-shear, etc.), [Beroza and Spudich, 1988; Kaverina *et al.*, 2002; Oglesby *et al.*, 2004]. In other examples, such as the 1980 Mw 6.9 Irpinia earthquake, Italy, three distinct segments ruptured, being separated by 20 and 40 s from the first shock [Bernard and Zollo, 1989]. Zahradník *et al.* [2005] and Benetatos *et al.* [2007] reported a doublet character of the 2003 Mw 6.2 Lefkada, Greece, earthquake, where two segments were separated 40 km in space and 14 s in time. Here we inferred such robust behavior on a smaller and shorter scale (3 s time delay). It is important to identify the space-time complexities of earthquake ruptures as they might serve as constraints for dynamic models of earthquake ruptures. Accounting correctly for the rupture propagation complexities is also critical to strong ground motion simulations (see companion paper).

Appendix A

A1. Synthetic Test #1: Rupture Model Similar to the L'Aquila Earthquake

[41] Here we apply the MuFEx source inversion (see the flowchart in Figure 2) to synthetic data to test the performance of the inversion. The general characteristics of the source model (position and dimensions of the fault plane and focal mechanism) are the same as in the application to the real data of the 2009 L'Aquila earthquake.

[42] Figures A1a and A1b show the input slip model in terms of the slip-velocity snapshots and the final slip map, respectively. The model consists of two asperities located in the top left and bottom right portions of the fault. The rupture propagates radially at a constant rupture velocity of 3 km/s from a prescribed nucleation point. This synthetic model resembles the result from the inversion of the observed L'Aquila data (see the main text), excluding the inferred temporal delay. Additional tests with considerably different input models are presented in the auxiliary material.

[43] For the test slip model we calculate the 'observed' time series and then use them in the slip inversion as if they were real data. Green's functions are the same as in the real data application. To simulate the real-data application, the displacement seismograms are band-pass filtered between 0.06 and 0.3 Hz. No station weights according to epicentral distances and/or amplitudes have been applied. For each waveform we invert the complete wavefield of 100 s duration. The same processing is applied to the synthetic data in the inversion.

A2. Setup of the MuFEx Source Model

[44] Figure A1c shows the result of the TSVD and ISOLA inversions by means of snapshots of the rupture evolution. The fit of the TSVD synthetics with the 'observed' data is shown in Figure A2. The truncation in TSVD is done at a singular value equal to 1/10 of the largest singular value, i.e., at the same value as in the real data application. Note that the result again contains spurious oscillations ('ghosts') due to the use of a limited number of singular vectors. As the slip can occur anywhere at anytime along the fault within the prescribed 10s time windows, only gross features of the truncated SVD result have to be considered, e.g., the large slip velocity values and their positions in space and time. The fit with the observed data is almost perfect (Figure A2, green seismograms; VR > 0.99).

[45] The final slip model obtained by the TSVD method is displayed in Figure A1d. As can be seen by comparing Figures A1b and A1d, the resulting slip model is highly biased against the true solution. The reason is not imperfect Green's functions, because we use "perfect data" in the synthetic test. The bias is solely caused by the effect of the truncation (regularization). If we truncate at the machine's double precision accuracy, the inversion result is almost perfect. Additional tests indicate that, in the regularized solution, the NW top asperity is enhanced and the SE bottom asperity is weakened due to the proximity of the AQV and AQK stations. Note that the slip velocity snapshots as well as the final slip suggest a split of the shallow asperity. It is noteworthy that the independent analysis by ISOLA (see the green circles in Figures A1c and A1d, VR = 0.95) also splits the compact top-left asperity of the input model into two patches. This confirms that the observed artifacts may be common to different methods, even those not explicitly using any regularization. On the other hand, contrarily to the result of TSVD, ISOLA retrieved the bottom right asperity better in this case.

[46] Despite the bias of the final slip model, the major features of the TSVD snapshots can be used to build a preliminary MuFEx source model. We set the (three) MuFEx subsources to areas where large slip velocity values in the snapshots of Figure A1c occurred. We assumed two subsources covering

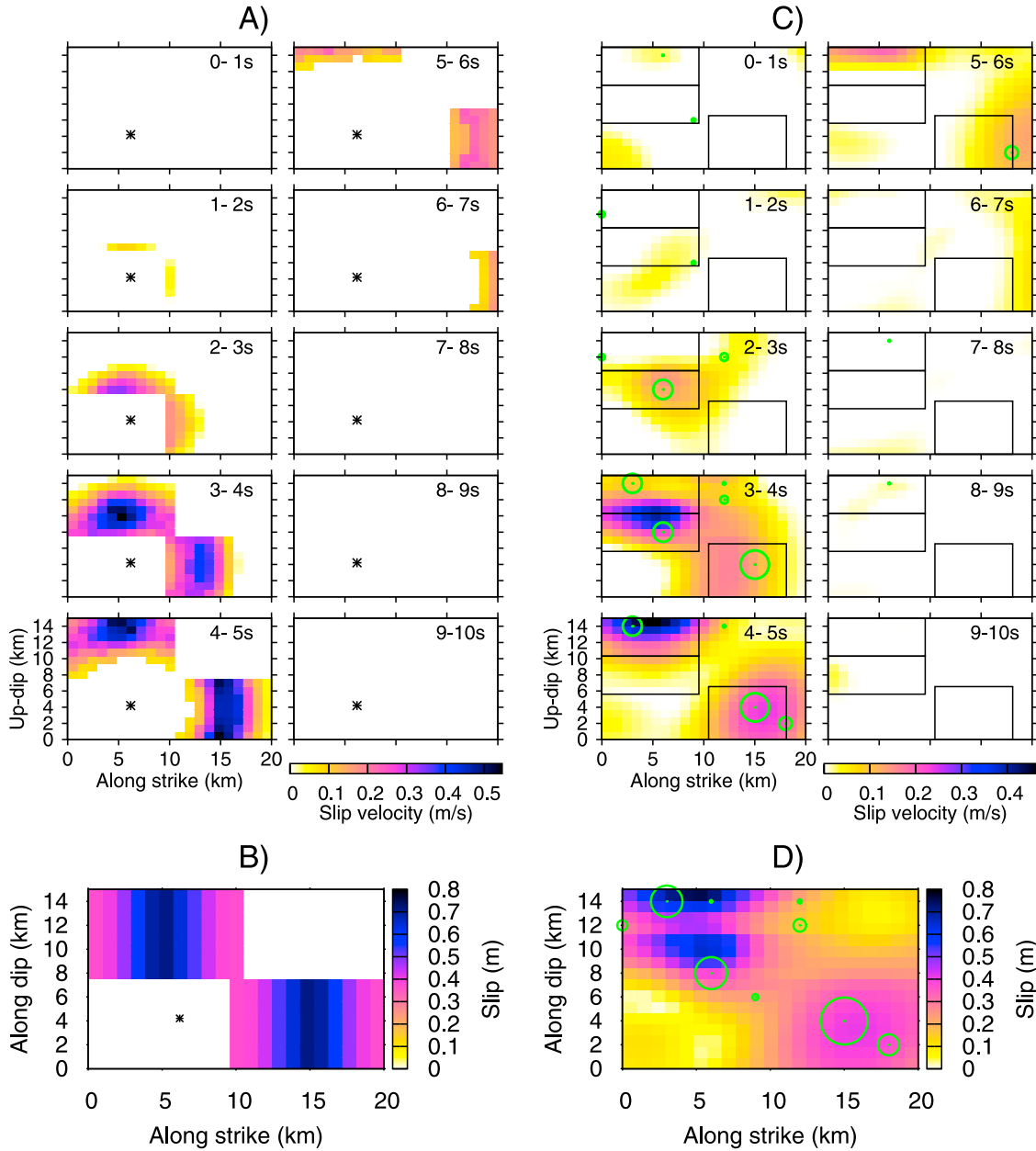


Figure A1. Setting up the MuFEx source model for synthetic test #1. (a) Slip velocity snapshots of the input model with radial rupture propagation at a velocity of 3 km/s from the hypocenter (star). (b) Final slip of the input model. (c) Snapshots of the model inverted by the TSVD approach with truncation at 1/10 of the largest singular value. The truncation level is the same as in the application of TSVD to the real data. The fit of the seismograms ($VR = 0.99$) is shown in Figure A2 (black and green). Green circles ($VR = 0.95$) correspond to the result of the ISOLA inversion; the largest circle corresponds to 6.5×10^{17} Nm. Here the ISOLA result is in good agreement with TSVD. Areas with large slip velocities (or location of the largest ISOLA point sources) are used for the first setup of the MuFEx subsources. The final MuFEx subsources are shown as rectangles. (d) Final slip of the inverted model. Note that the slip map is highly biased due to the effect of the truncation (regularization) during the inversion: compared to Figure A1b, the bottom right asperity is underestimated in TSVD and the top asperity is incorrectly split into two by both TSVD and ISOLA.

the area of the artificial split to simulate the real data application, in which we were not sure whether this was an artifact or a true slip feature. The dimensions of the subsources are given approximately by the spatial extents of the large slip velocity patches in Figure A1c.

A3. MuFEx Source Inversion

[47] The subsurface positions together with the positions of the testing nucleation points are shown in Figures A3c and A3d. The nucleation points are different for the different

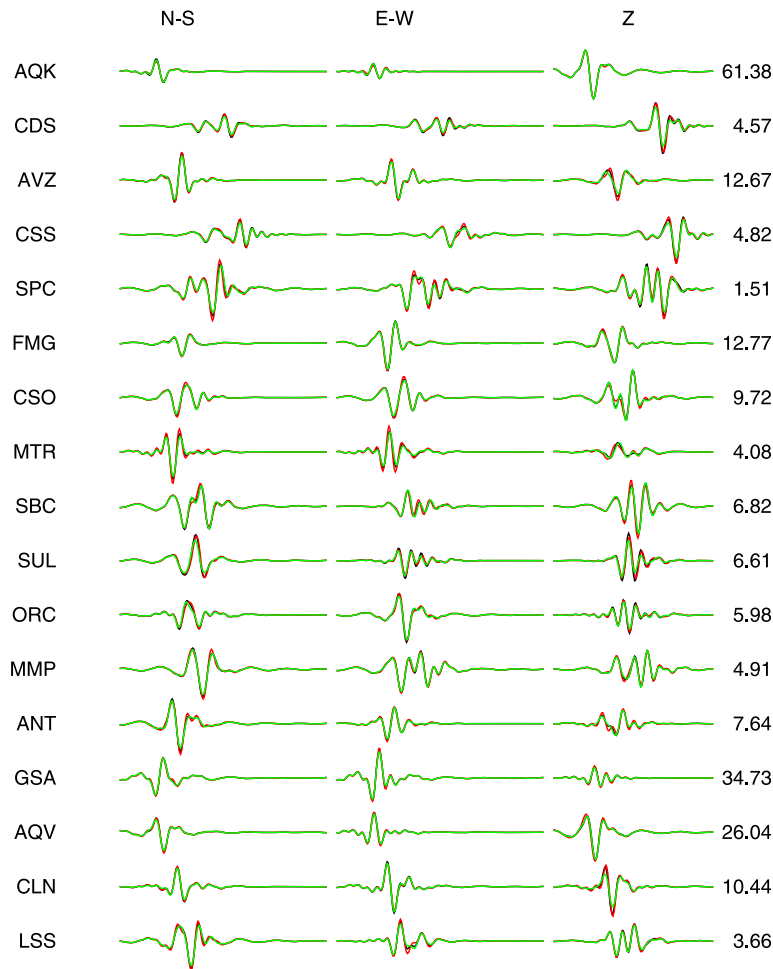


Figure A2. Comparison between ‘observed’ (black) and synthetic displacements for synthetic test #1 (green for the TSVD approach, red for the best fitting MuFEx model). All seismograms are band-pass filtered in the range of 0.06–0.30 Hz and have duration of 100 s as in the real data application. The maximum amplitudes of the observed records in mm are shown as numbers.

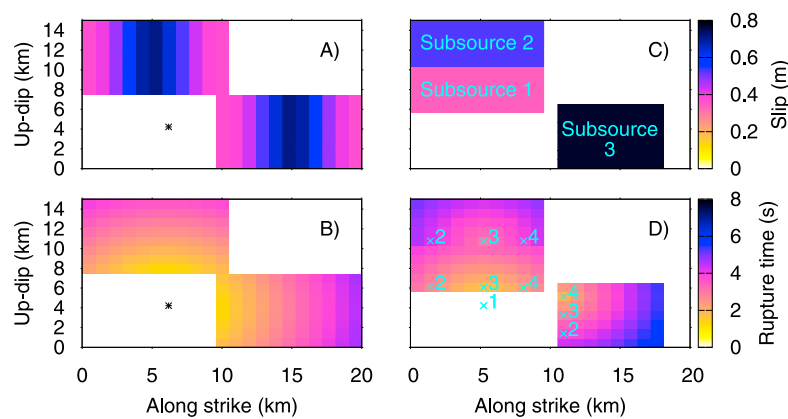
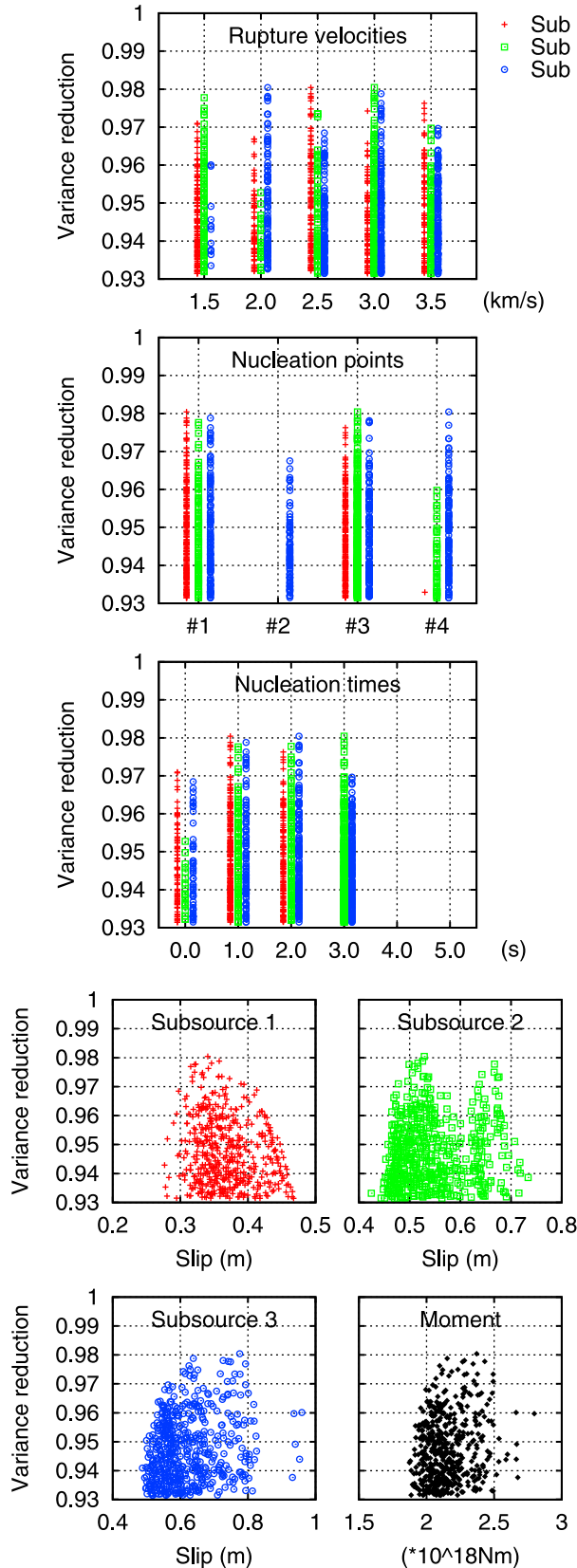


Figure A3. Synthetic test #1 of the inversion by the MuFEx source model. (a) Final slip (same as in Figure A1b), and (b) rupture times of the input test model. Asterisk denotes the hypocenter. (c, d) Best fitting (grid-searched) MuFEx model in terms of the final slip and rupture times, respectively. The numbered points represent trial nucleation points of the subsources; these are different for the different subsources, except for trial nucleation point #1, common to all the subsources. Figures A3c and A3d are to be compared with Figures A3a and A3b, respectively. The fit of the seismograms is shown in Figure A2 (black and red time histories); VR = 0.98. Note that total seismic moments of the two input asperities are well resolved by the MuFEx inversion.

subsources, except for trial nucleation point #1, corresponding to the hypocenter location of the input model, common to all the subsources. The tested rupture velocities and nucleation times cover the ranges of 1.5 to 3.5 km/s and 0 to 5 s, respectively.



[48] Figures A3c and A3d show the best fitting MuFEx source model in terms of slip and rupture times, respectively, to be compared directly with the corresponding values of the input model in Figures A3a and A3b. Let us first emphasize that, in this synthetic test, the fit with the ‘observed’ data for such a simplified source model is almost as good as that for the TSVD inverted model (see Figure A2, red seismograms). At first sight, the agreement between the input and inverted source models is not perfect. However, perfect agreement cannot be anticipated because different parameterizations are used for the two models (namely a constant slip on localized subsources in the MuFEx model, opposed to a ‘smoothly’ varying slip along the fault in the input model). Furthermore, the subsources are not localized perfectly on the asperities of the input model. Therefore, subsource 1 and 2 have different slip values because they cover different parts of the fault area including those with no slip in the input model. Subsource 3 was setup smaller than in the input model and the slip is larger. Interestingly, summary moment of subsources 1 and 2 matches the moment of the top left input asperity ($1e18\text{Nm}$), and the moment of subsource 3 fits the moment of the bottom right asperity ($1.4e18\text{Nm}$). Thus the inversion has a tendency to constrain better the seismic moment of the subsources than their actual slip values. To conclude, considering the modelization errors, the general features of the rupture propagation is relatively well resolved.

[49] The uncertainty analysis of the MuFEx models is performed in the same way as in the main text with the real data. We only use models satisfying physical conditions as in the real data application. In Figure A4 we study the population of all grid-searched models (with VR down to 5% below the best model, for clarity). Regarding the rupture velocities, the plausible MuFEx source models include the true rupture velocity (3 km/s) but also almost all other tested velocity values with only a small drop of VR. One can see that the sensitivity to the rupture velocities is relatively poor (especially for subsource 1). Similarly in terms of the nucleation points, the correct common nucleation point #1 is included among the plausible models, however, more nucleation points are also allowed considering even only a slightly smaller VR. For subsources 1 and 2, the nucleation from the left part of the fault (point #2) is not allowed by the data. Regarding the nucleation times, the plausible values range from 0 to 3 s for all subsources, depending on the other parameters of the MuFEx source model. This suggests that, in agreement with the input model, no significant time delay is suggested (in contrast to what we found for the real data in the main text). Regarding the uncertainties of the subsources’ slip and total seismic moment, the correct values (0.5 m for the slip values and $2.4e18\text{Nm}$ for the scalar

Figure A4. The uncertainty analysis of the whole population (500 models with $\text{VR} > 0.93$ out of ~ 2 million trial ones) of the grid-searched MuFEx source models for synthetic test #1. The description of the panels is the same as in Figure 6. For the location of the tested nucleation points see Figure A3. Note that the seismic moment of the input model ($2.4e18\text{Nm}$) corresponds to the best fitting model. The rupture velocity of 3 km/s of the input model is not well constrained.

moment) are covered. Moreover, the best fitting model has assigned the correct scalar moment. Note that the latter is not the case in all the synthetic tests we have performed, see the auxiliary material.

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