# HYBRID BROADBAND SEISMOGRAMS FOR SEISMIC SCENARIOS OF THE PO PLAIN SEDIMENTARY BASIN (NORTHERN ITALY)

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**Abstract**

The sedimentary basin of the Po Plain, northern Italy, is a region of low to intermediate seismicity that has gained attention in the recent years because of the May 2012 seismic sequence reaching magnitudes Mw~6. Its repercussions in Emilia-Romagna, Lombardia and Veneto, regions of a high density of population and industries, lead to an overall damaging cost of about 13 billion euro.
Because of scarce recent seismicity — hence relatively little knowledge based on instrumentally recorded data — but high exposure and hence substantial seismic risk, there is an obvious need to generate detailed seismic shakemaps, based on an accurate physical description of seismic wave propagation. Recent improvements in the knowledge of the three-dimensional structure of the earth's crust and developments of computational seismology allow now pursuing this objective. Nowadays, standard approaches for synthetic waveform simulation are able to reproduce accurately only different portions of the frequency spectrum separately: low frequencies with deterministic methods or high frequencies with stochastic methods. We can hardly find a single method that reproduces the entire spectrum.
We apply and evaluate a hybrid deterministic-stochastic method[1] developed in the recent years at the San Diego State University and implemented in the Broadband Platform[2] at the Southern California Earthquake Center, for the definition of seismic shakemaps in northern Italy. The method consists of integrating deterministic low frequency signals together with stochastic high frequency signals, enabling to obtain the whole gamut of seismic shaking.
More specifically, high frequency seismogram computation follows the S-S backscattering method whereas low-frequency signals are generated externally through the open-source software SPECFEM3D[3] that reproduce accurately the seismic response up to 1sec in a fine grid of 3 million spectral elements based on a regional 3D model, with high resolution description of the Po Plain sedimentary basin[4], and following a finite-source representation.

**Key Words**: Waveform modelling, Seismic scenario, Hybrid Broadband, Po Plain

## 1. INTRODUCTION

Seismic shakemaps and scenarios are two important tools in the field of seismic risk prevention that can help decision makers in the context of emergency procedures. These two kinds of ground motion maps can gain in accuracy and utility through the use of realistic full-waveform simulations. Nowadays this goal is achievable thanks to the combination of an increasing knowledge of rupture mechanism and physics of the seismic waves together with the improvement of computational potential.

Main standard methods for the generation of synthetic seismic waveforms are unable to reproduce the whole frequency spectrum, usually they solve for the low frequency part (LF) or the high frequency one (HF), but rarely for both. Today LF simulations in 1D or 3D are accurate up to ~1Hz with deterministic methods such as finite-difference or spectral elements. In the higher frequencies, deterministic ground motion estimates cannot be reliable unless a huge amount of computational resources is involved and a detailed model of the earth structure is used. Otherwise, empirical-stochastic approaches, based on simplified earth and seismic source models, allow reproducing the high frequency part (>1Hz) of the seismic signal but are unable to give a good representation of the LF part (<1Hz).

Thus, hybrid methods have been developed with the aim to take advantage of each approach and generate broadband seismic signals in the whole spectrum between 0 and 10Hz. Each part of the frequency signal is computed separately with the respective deterministic and stochastic method and are then combined to form the hybrid waveform[5][6][7][8].

In early 2015, the Southern California Earthquake Center (SCEC) has promoted, through numerous papers in Seismological Research Letters, the validation of its Broadband Platform[2] for the generation of hybrid broadband seismograms. This platform proposes to create hybrid signals by choosing among five different approaches developed by several collaborators[1][9][10][11]. In this study, we apply and evaluate the San Diego State University (SDSU) method[1] for the simulation of hybrid broadband seismograms and the definition of seismic shakemaps in the Po Plain, northern Italy, one of the most inhabited and industrialized region of Italy. The SDSU method is quite flexible, enabling the importation of LF seismic signals computed externally and their combination with HF signals computed with the S-S multiple scattering method of Zeng et al.[12][13].

## 2. PO PLAIN SEISMICITY

The Po Plain, northern Italy, is covered by a wide and thick Plio-Quaternary sedimentary basin, bounded at North and South by the Alpine tectonic structures and the Apennines arcs. It is the place of an Northeast–Southwest continental collision between the subducting Adria plate to the North and the northern Apennine block to the South[14]. The area is characterized by complicated variations in crustal thickness and strong intracrustal inhomogeneities[4] that are reflected in the anomalous propagation of seismic waves[15]. These tectonic activities make the region rather active seismically. In particular, from historical and instrumental catalogues[16][17] the seismicity concentrates in the Northern Apennines and Southern Alps (FIG.1). Only about forty large earthquakes with Mw>5.3 are known among which the 1117 Veronese event -the largest one- with inferred Mw=6.5, the 1365 Bolognese event (Mw=5.4), the 1501 Modenese event (Mw=6.0) or the 1570 Ferrarese event (Mw=5.5)[16][17][18]. More recently, in May 2012, the region has been struck by a long and strong seismic sequence in an area of unknown historical seismic activity. The May 20th and 29th earthquakes (Mw=6.1 and 6.0 respectively) are the largest seismic events ever recorded instrumentally in this region. During the aftershock sequence about 2500 events including seven earthquakes with M>5 (the last one on June 3rd) have been recorded and located along a 50km line with a hypocentral depth between 1 and 12km.

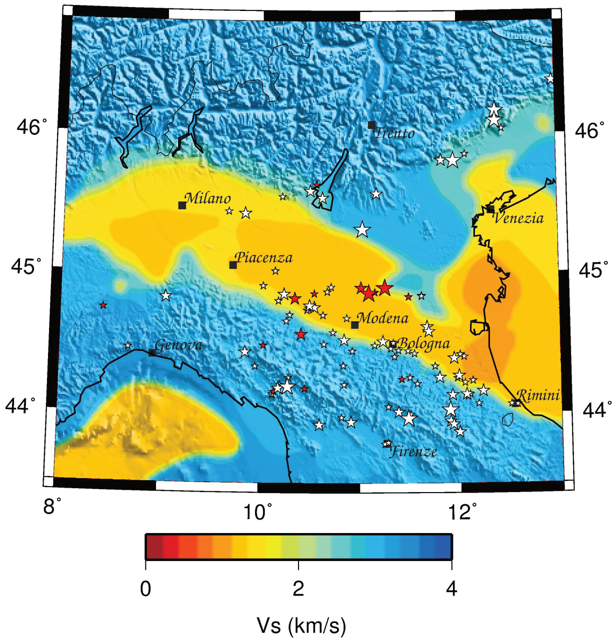


*FIG. 1. Po Plain seismicity plotted above the Vs distribution at 2km depth from MAMBo model[4]: historical (prior to 1970) and instrumental seismicity (white and red stars respectively) for earthquakes with Mw>5.0 (from RCMT[17] and ICTI11 catalogues[18]). Three groups of seismic events are represented: 5.0<Mw<5.5 (small stars); 5.5<Mw<6 (intermediate stars); Mw>6 (big stars). The 2012 seismic sequence, from which the two Mw>6 events (big red stars above Modena), has struck an area of undocumented seismicity.*

## 3. METHOD

### 3.1. Computing broad-band seismograms

Integrating the three-dimensional knowledge of the underground together with a method for the synthesis of the whole seismic response would improve dramatically ground motion estimate and consequently seismic hazard evaluations. Assuming an adequate knowledge of the Earth model, epistemic uncertainty linked to ground motion estimates could be reduced combining stochastic simulation with deterministic ones. The Southern California Earthquake Center (SCEC) has investigated this approach through the ten years project Cybershake[19]. The main goal of Cybershake was the improvement of the Californian Ground Motion Prediction Equations (GMPEs) using the combination of observed ground motion records together with high-resolution physic based numerical simulations for the regions characterized by spare seismic station coverage as well as for seismic scenarios. In this context, the SCEC has created a *Broadband Platform* for the generation of hybrid broadband seismograms with the implementation of five methods developed by different collaborators[1][2][9][10][11].

In this study, we tested the San Diego State University (SDSU) method[1]. This approach computes hybrid broadband signals from LF signals (<1Hz), computed internally on the *Platform* with the finite-differences theory or externally, together with HF scatterograms (>1Hz) computed on the *Platform* with the S-S multiple scattering method of Zeng et al.[12][13]. These scatterograms are generated from the convolution of a site-specific scattering Green function together with a source-time function that defines the temporal evolution of the seismic rupture process. Both seismograms are then combined at a defined cut-off frequency (FIG. 2) following the methodology of Mai et al.[8] where a spectral optimization both in amplitude and phase is applied.

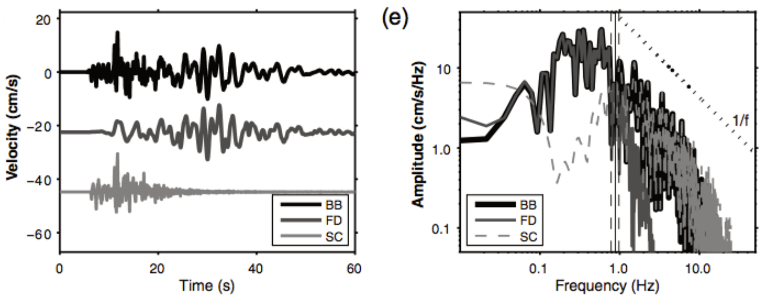


*FIG. 2. Hybrid broadband simulation: left) seismograms: hybrid (BB), LF computed with finite-differences (FD) and HF computed with scattering method (SC); right) Frequency spectra. LF and HF signals have been combined at the cut-off frequency of 1Hz. From Mai et al.[8].*

In our case, we created LF signal externally, using the SPECFEM3D[3] software. This open-source software enables to solve the full numerical equation of the seismic waves in a spectral elements grid using a 3D tomographic model and possibly a finite-fault source model. For the Po Plain representation, we designed a 650x300x60km$^3$ computational grid made of about 3 million spectral elements, whose dimension is nearly of 2km at the surface. This mesh includes a 400x280x8km$^3$ sedimentary basin and a 3D layered tomographic model. The LF frequency seismograms computed in SPECFEM3D are filtered between 1 and 20 seconds before being combined to the respective scatterograms at the cut-off frequency of 1Hz.

### 3.2. Data

The 2012 Emilia seismic sequence generated a rich seismographic database inside the sedimentary basin of high relevance for the validation of the proposed method. In a first step, our validation is thus based on one of the main events of this seismic sequence: the May 29$^{th}$ earthquake with Mw=6.1. We also tested the method with an event occurring outside the basin, in the North Apennines: the January 25$^{th}$ 2013 earthquakes, with Mw=5. For both events, the observed seismograms have been accessed from the ISIDe (Italian Seismological Instrumental and parametric Data-basE) platform and the source parameters from the RCMT catalogue[17].

To obtain realistic LF ground motion evaluations, we need a detailed geophysical model able to reproduce the main characteristics of the observed signal. In particular, crustal models allow considering possible amplification effects in the shallow layers. As reference model for our application, we thus take the recent Po Plain 3D model MAMBo[4] built from a geological and geophysical database. The model is composed with seven sedimentary layers characterized by variable lateral thicknesses and different gradients of velocity and density. It is able to reproduce accurately the main characteristics of the seismic signals as the shaking duration or the waveform. Instead, HF scatterogams, based on stochastic method, can rely on simplified models. The reference model for these simulations is thus the 1D PADANIA Crustal model [20]. For both simulations, source files (TABLE 1) are derived from the RCMT parameterization[17].

TABLE. 1. SOURCE FILES FOR THE 29TH MAY 2012 AND 25TH JANUARY 2013 EARTHQUAKES USED IN THE BROADBAND PLATFORM AND SPECFEM3D.

| **2012_05_29 Mw 6.1** | | | |
|---|---|---|---|
| ***Broadband Platform source file*** | | ***SPECFEM source file*** | |
| *Length* | 9.59km | PDE 2012 05 29 07 00 03.00 11.09 44.85 6.0 5.8 5.8 | |
| *Dlen* | 0.2km | *event name* | 201205290700 |
| *Weigth* | 7.01km | *time shift* | 0 |
| *Dw* | 0.2km | *half duration* | 0 |
| *Depth to top* | 7.43km | *latitude* | 44.85 |
| *strike* | 275 | *longitude* | 11.09 |
| *rake* | 90 | *depth* | 6km |
| *dip* | 52 | *Mrr* | 0.0021033e+23 |
| *lat top center* | 44.84 | *Mtt* | -0.020867e+23 |
| *lon top center* | 11.15 | *Mpp* | -0.0000167e+23 |
| *hypo along strike* | 0 | *Mrt* | -0.0005233e+23 |
| *hypo down dip* | 3.5 | *Mrp* | 0.0000467e+23 |
| *corner freq* | 0.1 | *Mtp* | 0.0001833e+23 |

| **2013_01_25 Mw 5.0** | | | |
|---|---|---|---|
| ***Broadband Platform source file*** | | ***SPECFEM source file*** | |
| *Length* | 2.46km | PDE 2013 01 25 14 48 18.0 10.454 44.168 18.00 4.8 4.8 | |
| *Dlen* | 0.2km | *event name* | C201301251448A |
| *Weigth* | 3.35km | *time shift* | 0 |
| *Dw* | 0.2km | *half duration* | 0 |
| *Depth to top* | 16.38km | *latitude* | 44.168 |
| *strike* | 145 | *longitude* | 10.454 |
| *rake* | -8 | *depth* | 18km |
| *dip* | 75 | *Mrr* | -0.014e+24 |
| *lat top center* | 44.18 | *Mtt* | 0.176e+24 |
| *lon top center* | 10.44 | *Mpp* | -0.162e+24 |
| *hypo along strike* | 0 | *Mrt* | 0.026e+24 |
| *hypo down dip* | 1.68 | *Mrp* | 0.047e+24 |
| *corner freq* | 0.1 | *Mtp* | -0.068e+24 |

## 4. RESULTS

We evaluate our implementation of the hybrid broadband method for the Po Plain looking at different parameters such as GMPEs, waveforms, Fourier spectra and model bias for the two recent seismic events of different magnitudes occurring inside and outside the Po Plain basin.

As reference GMPEs for this region we adopt the ITA10 equations of Bindi et al.[21] that were deduced from 99 Italian earthquakes from the ITalian ACcelerometric Archive database with magnitudes between $4.1 \leq Mw \leq 6.9$, depths up to 35km and epicentral distances up to 200km.

### 4.1. The May 29th 2012 event, Mw 6.1

In FIG. 3 we compare the observed horizontal Peak Ground Acceleration (PGA, left) and Peak Ground Velocity (PGV, right) values with respect to the ITA10 GMPEs values. There is a relatively good agreement between GMPEs and observations: main part of the observed measurements stay inside the standard deviation range. However, we note that the hybrid broadband ground motion parameters tend to be over estimated with respect to the adopted GMPEs, with a major bias for the velocity estimations.

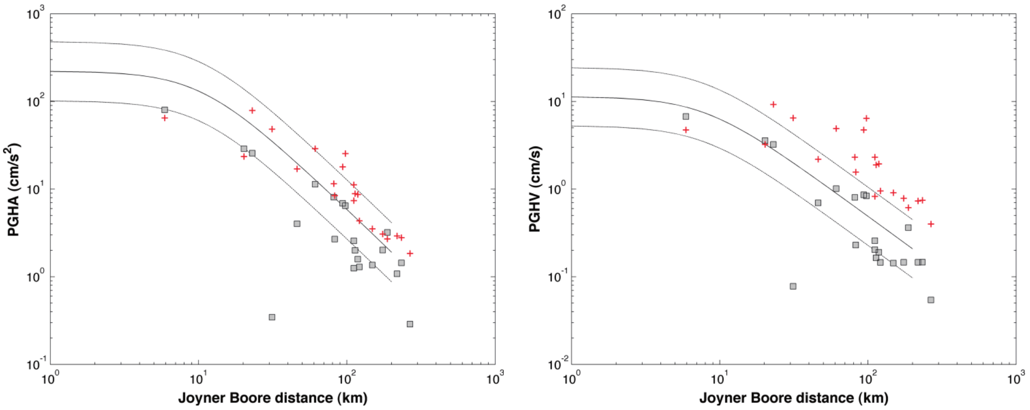


*FIG. 3. Horizontal PGA and PGV comparisons for observed (grey squares) and synthetic hybrid data (red crosses) with respect to ITA10 GMPEs.*

This overestimation of the synthetic simulation is clearly indicated looking at the respective ground motion parameter residuals for each station (FIG. 4). A zero residual indicates a perfect agreement between observation and simulations, whereas a negative residual indicate an overprediction of the ground motion parameter. Here, most of the residuals are higher than -1.

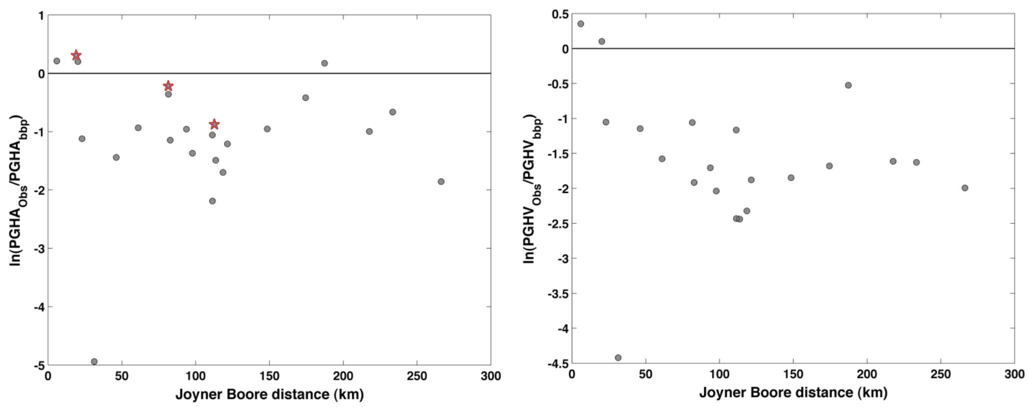


*FIG. 4. Horizontal PGA and PGV residuals between observed and hybrid broadband data in function of the Joyner-Boore distance.*

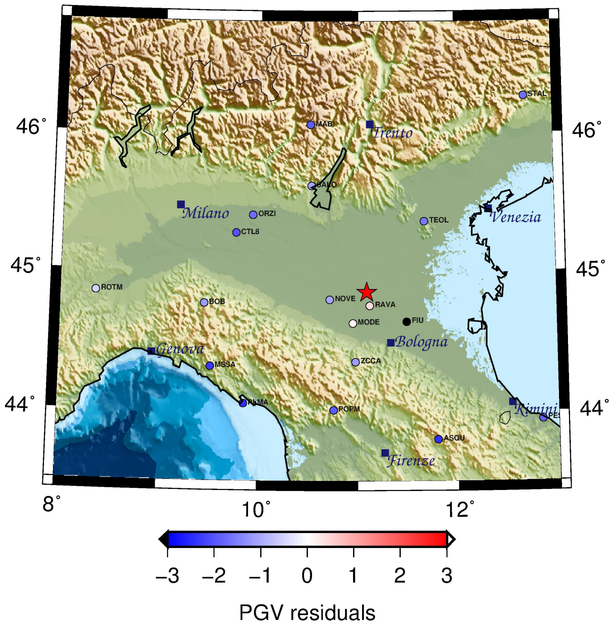


*FIG. 5. Distribution of the PGHV residuals at each station plotted on a topographic map of the region. The red star indicates the event epicenter, in the middle of the sedimentary basin.*

We look in particular at three stations, marked by a red star in FIG. 4: RAVA, SALO and BOB. While RAVA is very close to the epicentre, in the middle of the Po Plain basin, SALO is situated nearly 80km north, below the Alps chain, and BOB, 110km west far from the epicentre, is located in the Apennines chain (FIG. 5). The pseudo spectral acceleration at each horizontal component depicts an increasing overestimation of the synthetic with respect to epicentral distance (FIG. 6). We suggest that this can be due to the sedimentary character of the Po Plain basin or particular strong site effects that might not be totally reproduced through our velocity model.

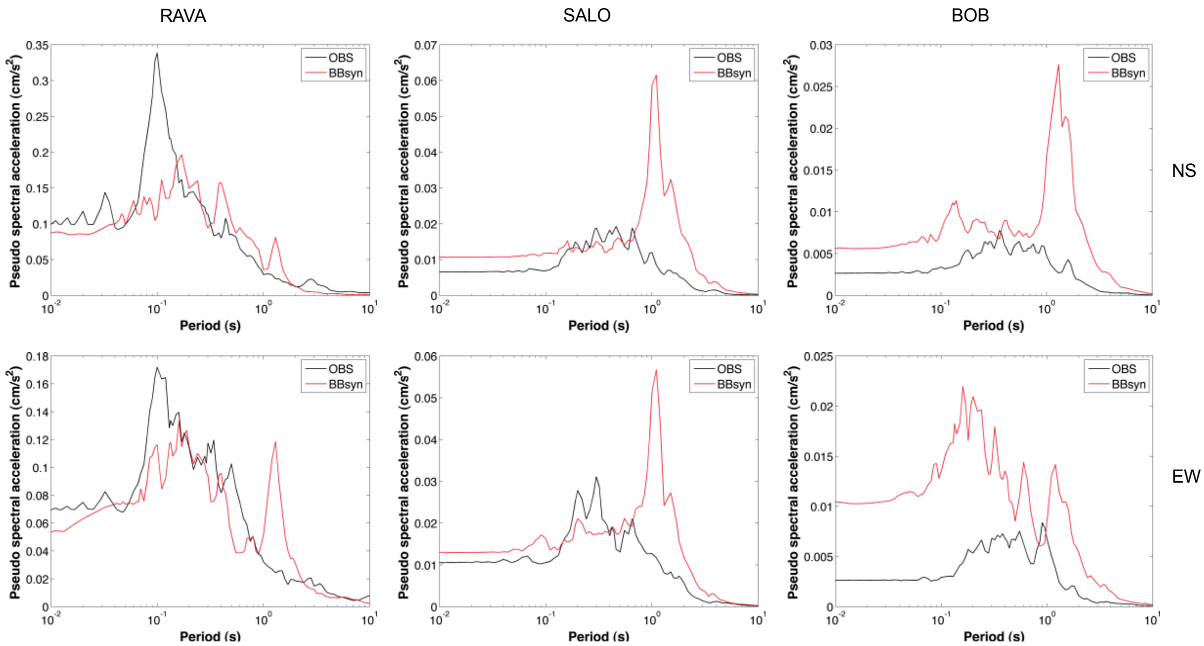


*FIG. 6. Horizontal pseudo spectral acceleration spectra for stations RAVA, SALO and BOB situated inside, north and west of the sedimentary basin. Observed data are indicated in black and hybrid broadband in red.*

We examine the velocity time series and the Fourier spectra on the horizontal components for RAVA and SALO (FIG. 7 and 8). For the RAVA station, situated at an epicentral distance of about 10km, there is a relatively good agreement of the synthetic (red line) with respect to the observation (black line) in terms of seismic waveform and shaking duration. Instead, the SALO station, placed on the north edge of the sedimentary basin at about 100km from the epicentre, shows a clear overprediction of the amplitudes on both components. The Fourier spectra help to understand the origin of such overestimation. The 1Hz merging frequency at which our LF SPECFEM synthetics are combined with the HF stochastic signals is indicated by the dashed line. Whereas in the RAVA case, both the LF and the HF part of the signal are in good agreement with the observation, in the SALO case we note an overestimation in the LF part.

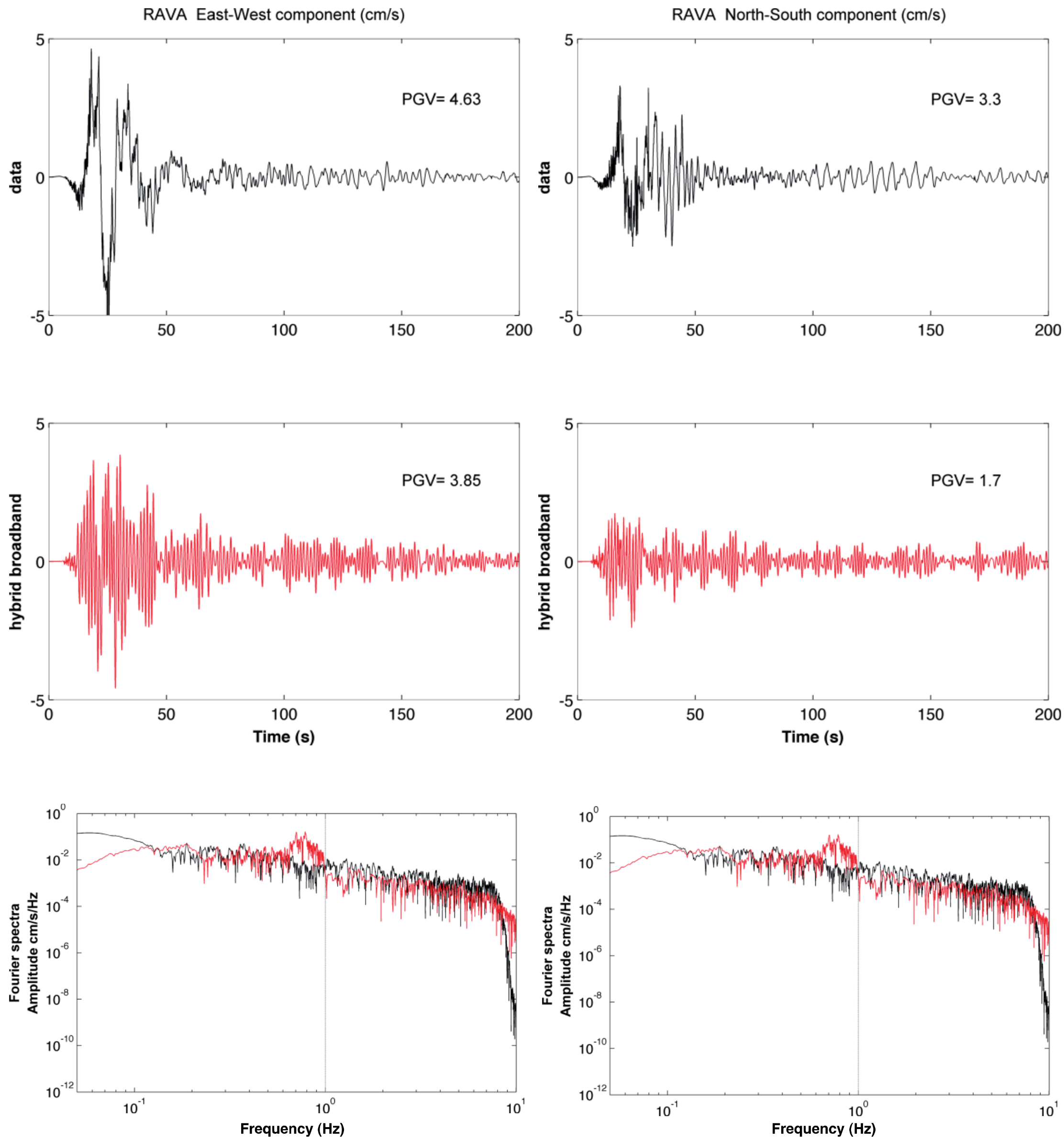


*FIG. 7. RAVA seismic waveforms EW (left) and NS (right) components for observed data (top, black) and Hybrid Broadband (middle red). The third line boxes compare the Fourier spectra for both data (black) and synthetic (red).*

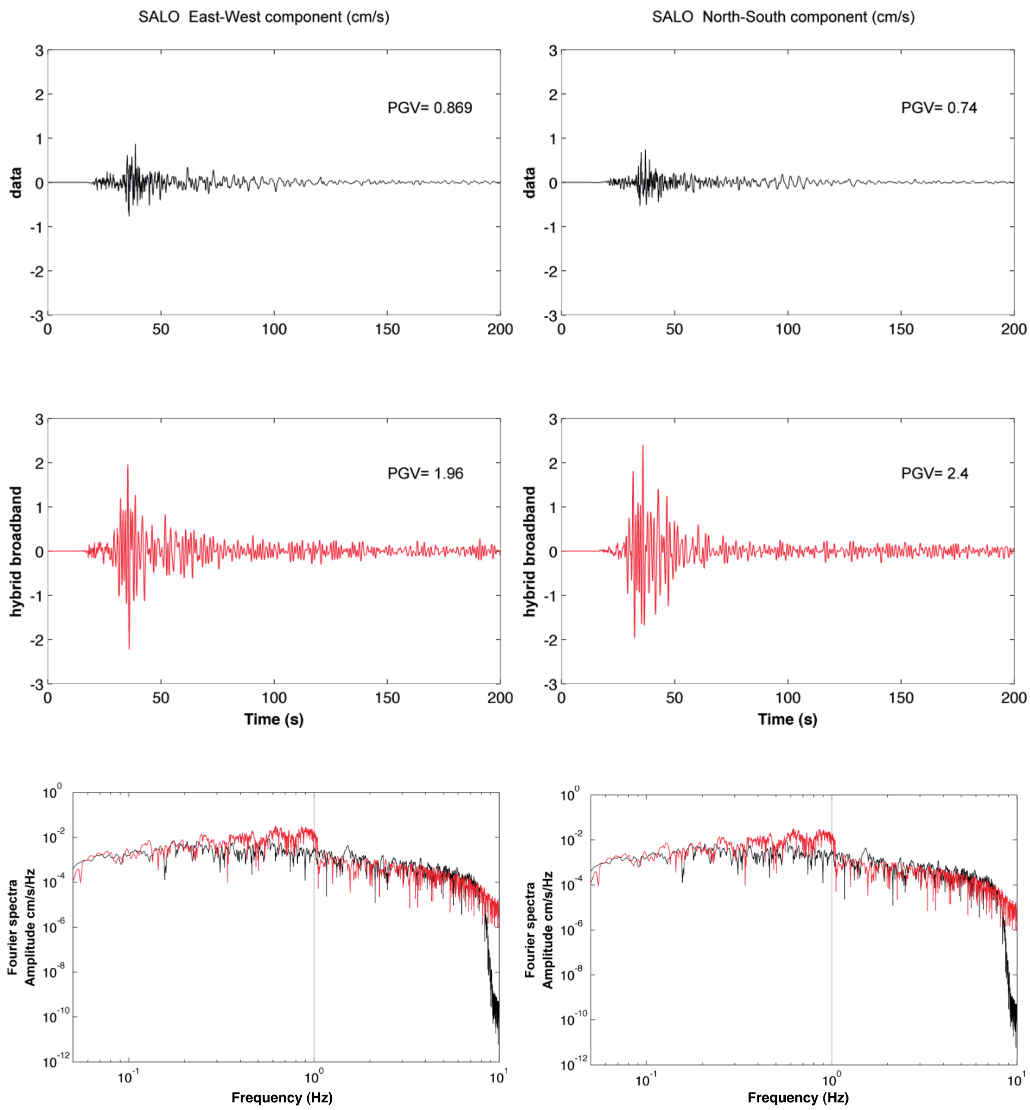


*FIG. 8. SALO seismic waveforms EW (left) and NS (right) components for observed data (top, black) and Hybrid Broadband (middle red). The third line boxes compare the Fourier spectra for both data (black) and synthetic (red).*

Following the procedure of Mai et al. (2010) we finally look at ensemble statistic for the spectral acceleration, in terms of model bias and standard error. For each horizontal component, as well as for their geometric mean, we compute the model bias based on the residual values at each period. In FIG. 9, the 90% confidence interval is indicated by a grey area and the standard error by a light grey area on both side of the model bias median (black line). A perfect match with the data should be indicated by a zero model bias (horizontal dotted line) and a negative model bias would reflect an overestimation.

We obtain an overall overprediction from 0.05 to 8 seconds period: the zero bias remains above the positive standard error. Only between 0.3 and 0.5 seconds the zero bias remains close to the 90% confidence interval. The model bias deviates negatively more away from the zero bias around 1 second period and come back slightly to its previous position from 2 to 8 seconds period. This 1-second period coincide with the 1Hz merging frequency for our hybrid broadband seismograms. Thus we can see here again, that the LF part of our signal tend to overpredict the observation and has a strong influence on the hybrid broadband characteristics.

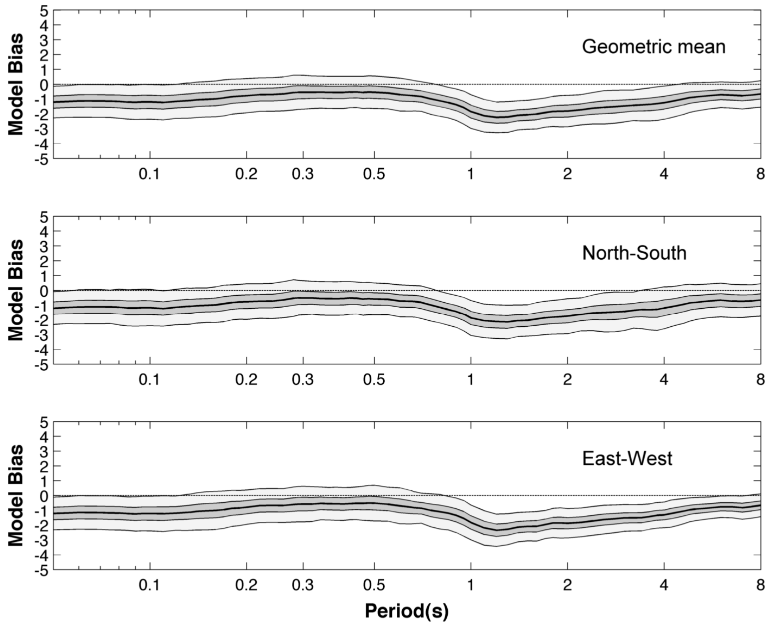


*FIG. 9. 29th May 2012 model bias on horizontal components. The median is indicated by the black line, the 90% confidence interval by the grey area and the standard error by the light grey one. An overall overprediction is delineated here (negative model bias).*

### 4.2. The January 25th 2013 event, Mw 5

The January 25th 2013 earthquake happened outside the Po Plain basin in the North Apennines (FIG. 12). This earthquake of moderate magnitude is interesting as, for the seismic stations situated in the Po Plain, its seismic waves crossed the sedimentary basin and could delineate particular effects of the structure.

In this second case, both observations and hybrid broadband simulations are in agreement with the ITA10 GMPEs for both PGA and PGV parameters (FIG. 10).
Whereas in the first case (FIG. 3) all residuals where concentrated between 0.5 and -2, here they present a larger spreading from 1 to -2 (FIG. 11), still with an overprediction trend.

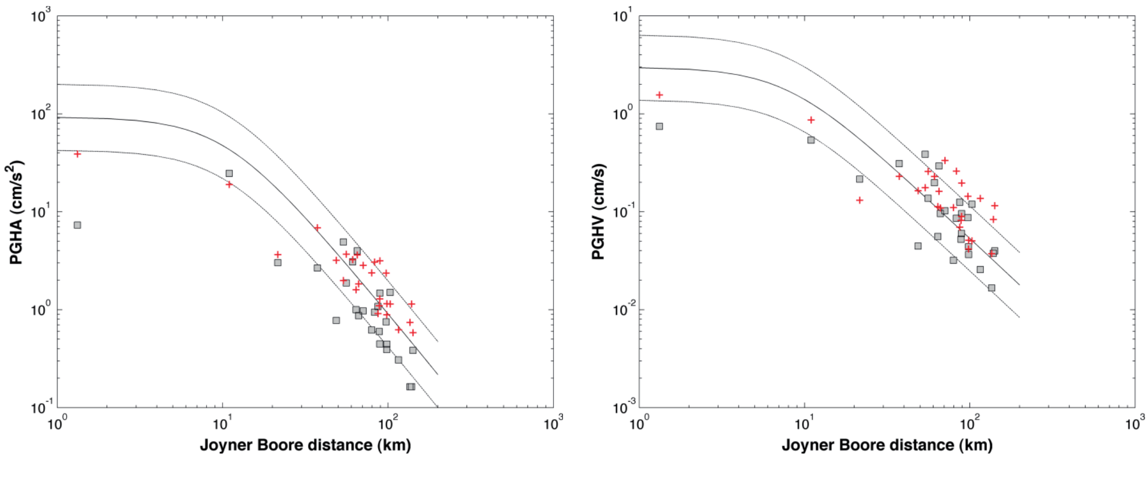


*FIG. 10. PGA and PGV comparisons for observed (grey squares) and synthetic hybrid data (red crosses) with respect to ITA10 GMPEs.*

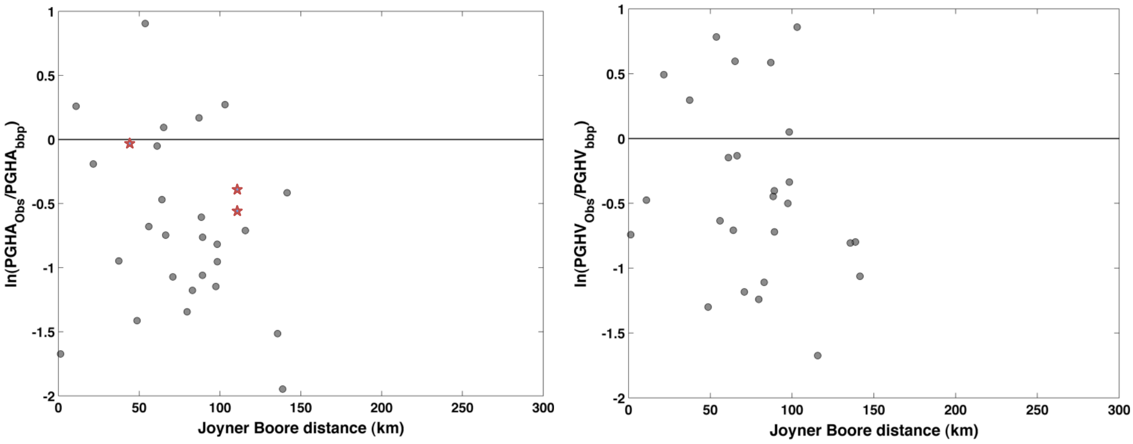


*FIG. 11. PGA and PGV residuals between observed and hybrid broadband data in function of the Joyner-Boore distance*

We focus on three stations: BDI in the Apennines, close to the epicenter, BOB around 90km west far in the Apennines, and SBPO at around the same distance but inside the sedimentary basin (FIG. 12). The horizontal pseudo spectral acceleration spectra for these station present different behaviours (FIG. 13). Whereas the BDI station presents a good estimation of the spectral acceleration on both components, the BOB stations tends to overpredict this parameter and the SBPO station, in the sedimentary basin, even more.

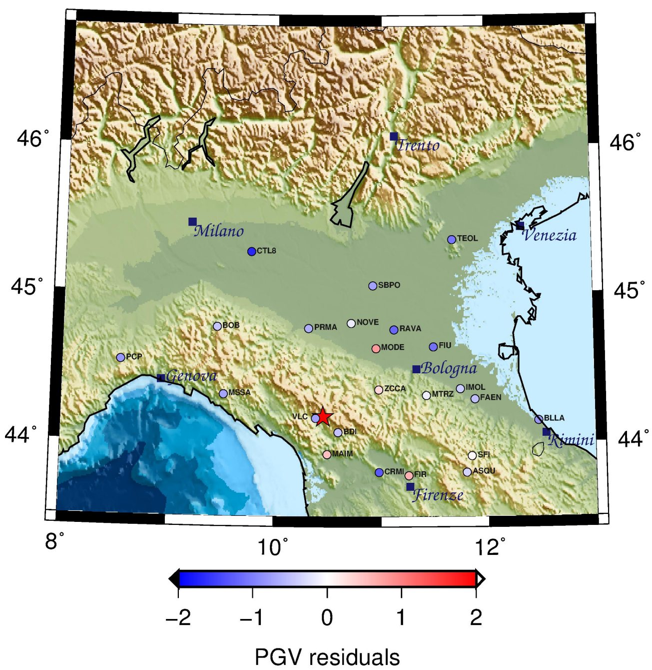


*FIG. 12. Distribution of the PGHV residuals at each station plotted on a topographic map of the region. The red star indicates the event epicenter, outside the sedimentary basin in the North Apennines.*

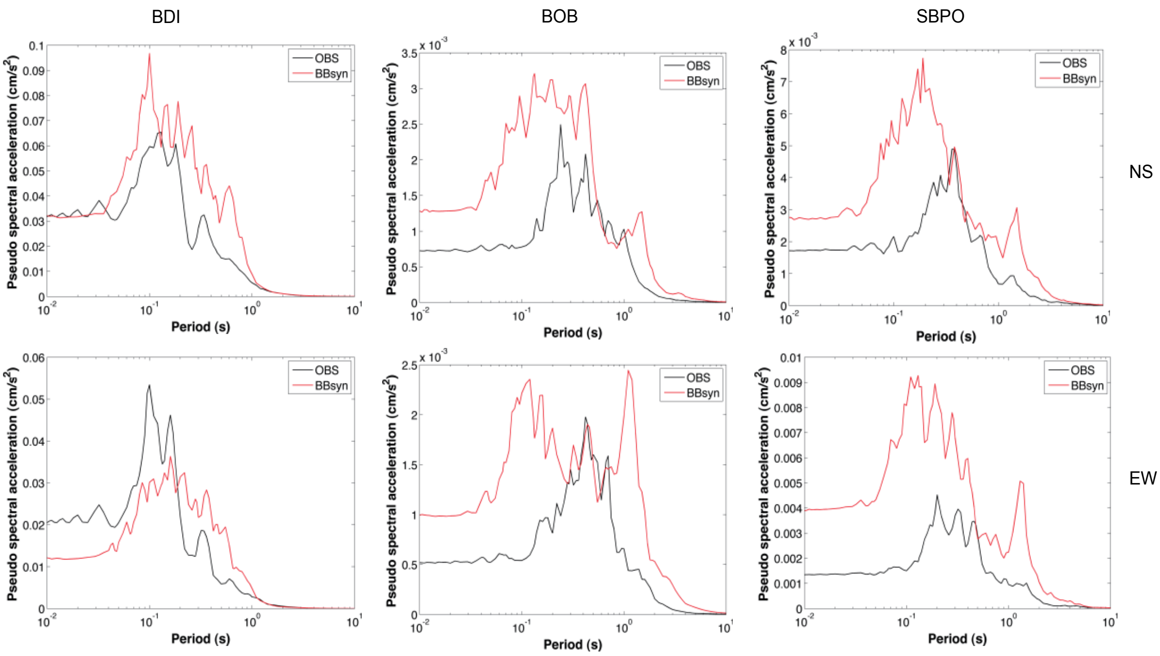


*FIG. 13. Horizontal pseudo spectral acceleration spectra for stations BDI, BOB and SBPO situated in the Apennines (BDI and BOB) and in the sedimentary basin (SBPO). Observed data are indicated in black and hybrid broadband in red.*

We look at the velocity time series and the Fourier spectra on the horizontal components for BOB and SBPO that are nearly at the same epicentral distance but in a different geological context (FIG.14 and 15). We note a relatively good agreement of the synthetic (red line) with respect to the observation (black line) in terms of seismic waveform, shaking duration and Fourier spectra for the BOB station. The tendency to overestimate the amplitude is more pronounced in the LF part, under 1Hz. The SBPO station does not present a good fit in terms of amplitude, with an overestimate of the shaking. Its Fourier spectra shows an overprediction in the LF part that remains also in the HF part, whereas for the BOB station, the stochastic simulation is able to constrain well the HF part of the spectrum.

As previously, we ended our evaluation with a look at ensemble statistic for the spectral acceleration, in terms of model bias and standard error. In this case (FIG. 16), the model bias presents a better behaviour: even if overprediction dominates, the zero bias remains quite close to the standard error interval. Only between 0.3 and 0.5 second the zero bias remains close to the 90% confidence interval.
The model bias deviates negatively more largely from the zero bias from 3 to 1 second period and from 0.3 to 0.05. The best trend is found above 4-second period and between 1 and 0.6 second period.

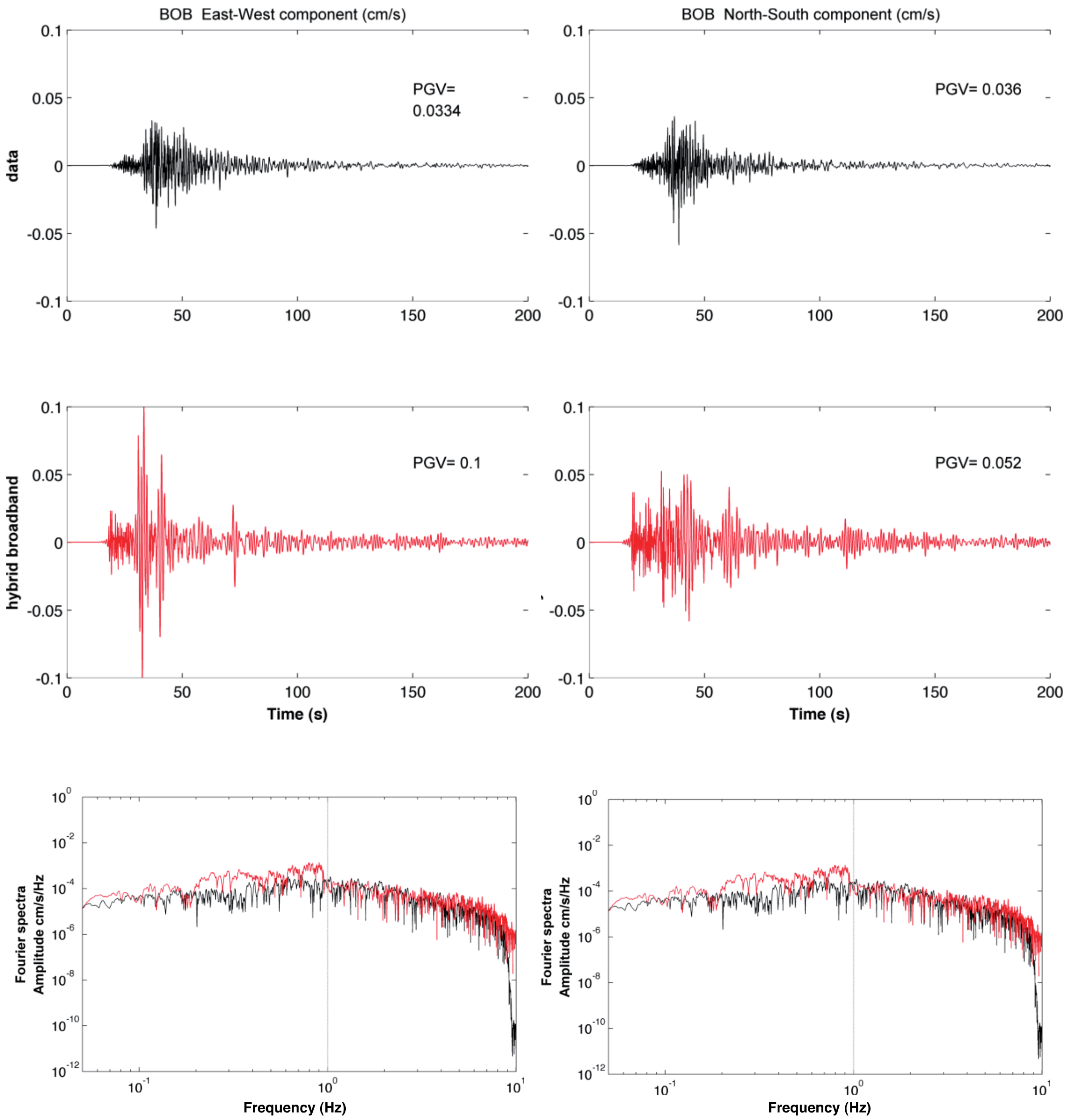


*FIG. 14. BOB seismic waveforms EW (left) and NS (right) components for observed data (top, black) and Hybrid Broadband (middle red). The third line boxes compare the Fourier spectra for both data (black) and synthetic (red).*

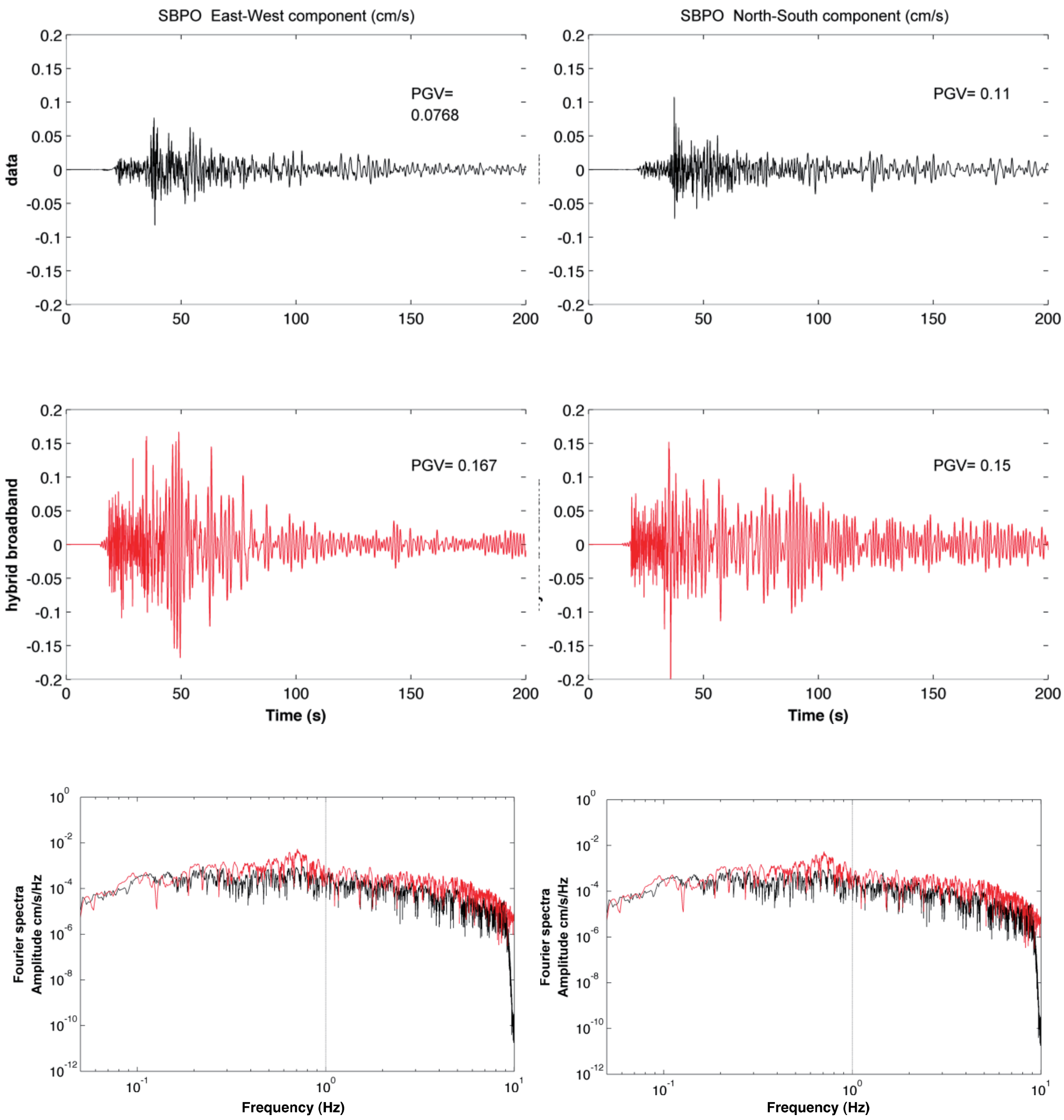


*FIG. 15. SBPO seismic waveforms EW (left) and NS (right) components for observed data (top, black) and Hybrid Broadband (middle red). The third line boxes compare the Fourier spectra for both data (black) and synthetic (red).*

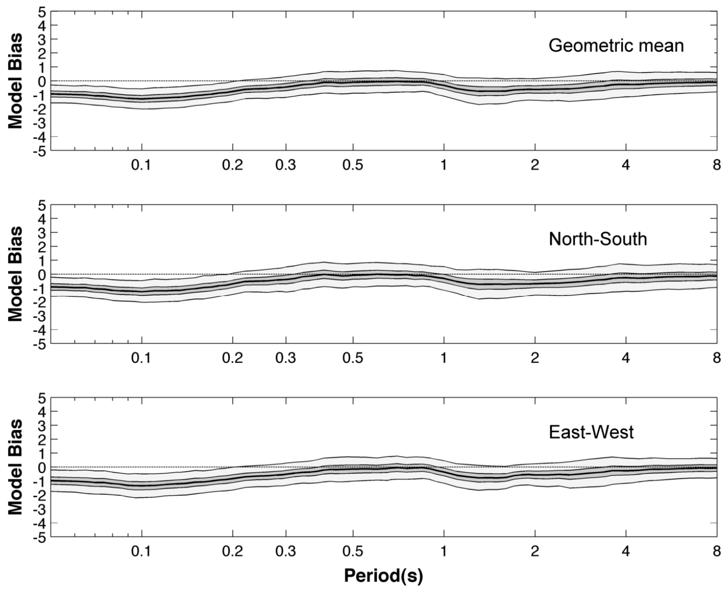


*FIG. 16. 25th January 2013 model bias on horizontal components. The median is indicated by the black line, the 90% confidence interval by the grey area and the standard error by the light grey one. An overall overprediction is delineated here (negative model bias).*

## 5. DISCUSSION AND CONCLUSION

This evaluation of our preliminary application of the hybrid broadband method to the Po Plain basin with two recent seismic events of different location and magnitude demonstrates that we currently tend to overpredict the ground motion parameters. This overprediction dominates particularly in the low frequency part of our broadband frequency spectrum, where signals are computed deterministically using the spectral element method in SPECFEM3D. We have also seen that below 0.2 seconds period we have an overprediction in the stochastic based HF spectrum estimation, especially for the second case of study with the January 25th 2013 event. This might serve as an indicator for the limit of validity of such a stochastic computation.

In this two cases, the May 29th 2012 Mw=6.1 and January 25th 2013 Mw=5 events, the best results are found in the HF part, between 0.3 and 0.5 seconds period. This range is elongated until 1 second period in the second case, where the LF part was better represented than in the first case.

As the LF part of the frequency spectrum might have a main imprint on the final hybrid broadband seismograms, we have to find the way to reduce the bias observed. This can be done by refining the velocity model, taking into account the possible site effects more precisely, including attenuation or finite-fault modelling. Considering that these LF simulations seem to be relatively satisfying up to a period of 4 seconds we could also think to shift our merging frequency at 0.25Hz but this poses the problem to consider stochastic evaluation in this part of the spectrum.

***Acknowledgement***

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## REFERENCES


[1] OLSEN, K., TAKEDATSU, R., The SDSU Broadband Ground-Motion Generation Module BBtoolbox Version 1.5, Seismological Research Letters, 86, No. 1, 81-88, doi: 10.1785/0220140102, (2015).

[2] MAECHLING, P. J., SILVA, F., CALLAGHAN, S., JORDAN, T. H., SCEC Broadband Platform: System Architecture and Software Implementation, Seismological Research Letters 86, No. 1, 27-38, (2015).

[3] PETER, D., KOMATITSCH, D., LUO, Y., MARTIN, R., LE GOFF, N., CASAROTTI, E., LE LOHER, P., MAGNONI, F., LIU, Q., BLITZ, C., NISSEN-MEYER, T., BASINI, P., TROMP, J., Forward and adjoint simulations of seismic wave propagation on fully unstructured hexahedral meshes, Geophys. J. Int., 186(2):721–739, 2011. doi: 10.1111/j.1365246X.2011.05044.x.1, 1.1, (2011).

[4] MOLINARI, I., ARGNANI, A., MORELLI, A., BASINI, P., Development and testing of a 3D seismic velocity model of the Po Plain sedimentary basin, Italy. Bulletin of the Seismological Society of America, 105 (2a), doi: 10.1785/0120140204, (2015).

[5] IRIKURA, K., Prediction of strong acceleration motions using empirical Green's function, in Proc. 7th Japan Earthq. Eng. Symp. 151-156, Tokyo, Japan. 10-12 December 1986.

[6] GRAVES R. W., PITARKA A., Broadband time history simulation using a hybrid approach, Proc. 13th World Conf. Earthq. Eng., Vancouver, Canada, paper no. 1098, (2004).

[7] MAI, P. M., IMPERATORI, W., OLSEN, K. B., Hybrid Broadband Ground-Motion Simulations: Combining Long-Period Deterministic Synthetics with High-Frequency Multiple S-to-S Backscattering, Bulletin of the Seismological Society of America, 100, No. 5A, 2124-2142, doi: 10.1785/0120080194, (2010).

[8] LIU, P., ARCHULETA, R., HARTZELL, S. H., Prediction of broadband ground motion time histories: Frequency method with correlation random source parameters, Bulletin of the Seismological Society of America, 96, 2118-2130, (2006).

[9] DOUGLAS, S. D., BEROZA, G. C., DAY, S. M., GOULET, C. A., JORDAN, T. H., SPUDICH, P. A., STEWART, J. P., Validation of the SCEC Broadband Platform V14.3 Simulation Methods Using Pseudospectral Acceleration Data, Seismological Research Letters, 86, No. 1, 39-47, doi: 10.1785/0220140118, (2015).

[10] GRAVES, R., PITARKA, A., Refinements to the Graves and Pitarka (2010) Broadband Ground-Motion Simulation Method, Seismological Research Letters, 86, No. 1, 75-80, doi: 10.1785/0220140101, (2015),

[11] CREMPIEN, J. G. F., ARCHULETA, R.J., UCSB Method for Simulation of Broadband Ground Motion from Kinematic Earthquake Sources, Seismological Research Letters, 86, No. 1, 61-67, doi: 10.1785/0220140103, (2015).

[12] ZENG, Y. H., SU, F., AKI, K., Scattering wave energy propagation in a random isotropic scattering medium 1. Theory, J. Geophys. Res. 96, no. B1, 607-619, (1991).

[13] ZENG, Y. H., AKI, K., TENG, T. L., Mapping of the high- frequency source radiation for the Loma Prieta earthquake, California, J. Geophys. Res. 98, No. B7, 11, 981-993, (1993).

[14] PICOTTI, V., PAZZAGLIA, F.J., A new active tectonic model for the construction of the Northern Apennines mountain front near Bologna (Italy). J. Geophys. Res., 113, B08412, doi:10.1029/2007jb005307, (2008).

[15] MORASCA, P., MASSA, M., LAPROCINA, E., MAYEDA, K., PHILLIPS, S., et al., Improved 2-D attenuation analysis for Northern Italy using a merged dataset from selected regional seismic networks. Journal of Seismology, Springer Verlag (Germany), 14 (4), pp.727-738, (2010).

[16] ROVIDA, A., CAMASSI, R., GASPERINI, P., STUCCHI, M., (eds.), CPTI11, the 2011 version of the Parametric Catalogue of Italian Earthquakes. Istituto Nazionale di Geofisica e Vulcanologia, Milano, Bologna, http://emidius.mi.ingv.it/CPTI,
doi:10.6092/INGV.IT-CPTI11, (2011).

[17] PONDRELLI, S., SALIMBENI, S., EKSTRÖM, G., MORELLI, A., GASPERINI, P., VANNUCCI, G., The Italian CMT dataset from 1977 to the present, Phys. Earth Planet. Int., doi:10.1016/j.pepi.2006.07.008, 159/3-4, pp. 286-303, (2006).

[18] VANNOLI, P., BURRATO, P., VALENSISE, G., The Seismotectonics of the Po Plain (Northern Italy): Tectonic Diversity in a Blind Faulting Domain, Pure and Applied Geophysics, Volume 172, Issue 5, pp. 1105-1142, (2014).

[19] GRAVES, R.W., AAGAARD, B.T., Testing long-period ground-motion simulations of scenario earthquakes using the Mw 7.2 El Mayor-Cucapah main shock: evaluation of finite-fault rupture characterization and 3D seismic velocity models. Bull. seism. Soc. Am.; 101(2): 895-907, (2011).

[20] MALAGNINI, L., HERRMANN, R. B., MUNAFÒ, I., BUTTINELLI, M., ANSELMI, M., AKINCI, A., BOSCHI, E., Studying the Ferrara seismic sequence 1 of 2012: from a 1D crustal structure for moment tensor solutions to strong implications for seismic hazard. Geophys. Res. Lett., Vol. 39, L19302, doi:10.1029/2012GL053214, (2012).

[21] BINDI, D., PACOR, F., LUZI, L., PUGLIA, R., MASSA, M., AMERI, G., PAOLUCCI, R., Ground motion prediction equations derived from the Italian strong motion database, Bull. Earthquake Eng., 9 (6), 1899-1920, doi: 10.1007/s10518-011-9313-z, (2011).