Source Properties of the January 2010 M7 Haiti Earthquake Estimated by Back Projection of Waves Recorded by the National Seismic Network of Venezuela and the USarray

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Abstract

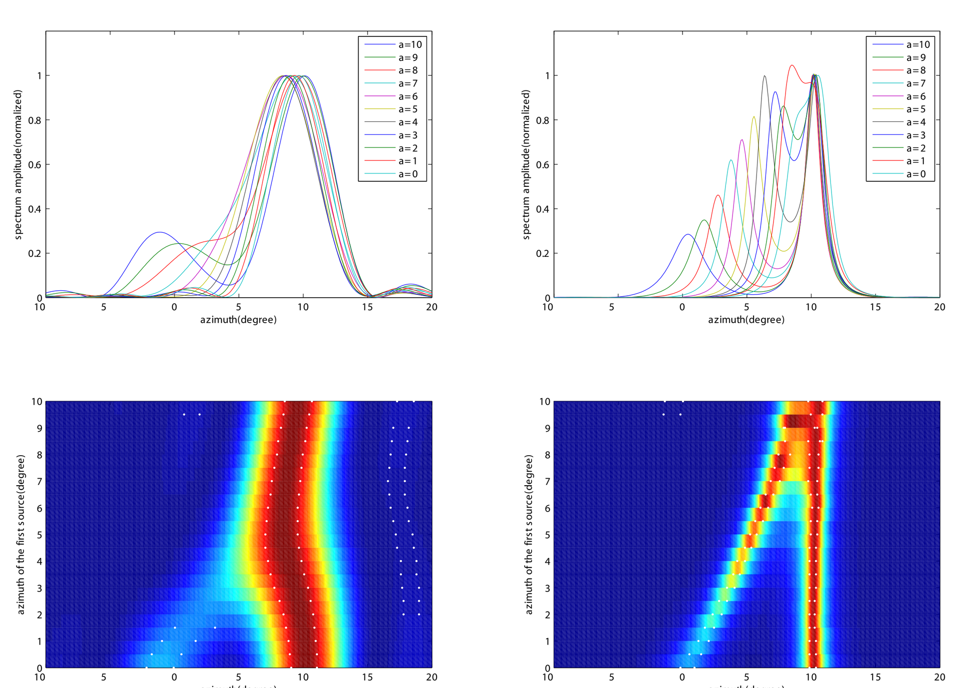
Back projection of teleseismic waves based on array processing has become a popular technique for earthquake source inversion. By tracking the moving source of high frequency waves, areas of the rupture front radiating the strongest energies can be imaged. The technique has been previously applied to track the rupture process of the Sumatra earthquake and the supershear rupture of the Kunlun earthquakes. The challenge with the 2010 M7.0 Haiti earthquake is its very compact source region, possibly shorter than 30km. Preliminary results from back projection using US-Array or the European network reveal little detail about the rupture process. In this study, we made an effort towards imaging the Haiti earthquake using multiple seismic array networks, including the USArray and the National Seismic Network of Venezuela run by FUNVISIS. The FUNVISIS network is composed of 22 broad-band stations with an East-West oriented geometry, and is located approximately 12 degrees away from Haiti in the perpendicular direction to the Enriquillo fault strike. This is the first opportunity to exploit the privileged position of the FUNVISIS network to study large earthquake ruptures in the Caribbean. We applied back projection methods based on traditional stacking and signal subspace techniques, and we incorporated Green's function deconvolution in the array processing. The preliminary result is encouraging: we observe an east to west rupture propagation along the fault, consistent with a compact source and rupture propagation at subshear speed. These efforts could lead the FUNVISIS seismic network data to play a prominent role in the timely characterization of the rupture process of large earthquakes in the Caribbean, including the future ruptures along the yet unbroken segments

Classic back projection

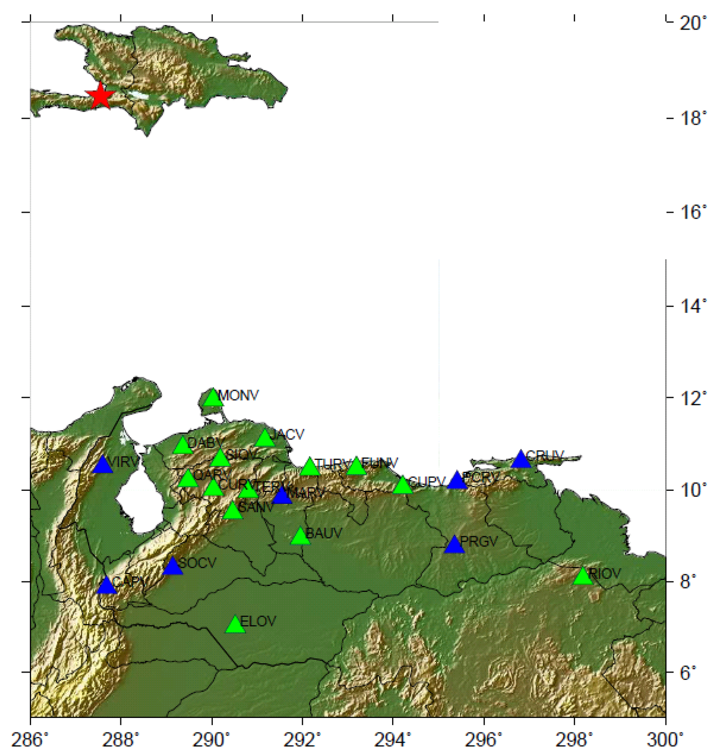
Classic back projection is closely related to the standard array beamforming technique, which uses a set of time-delays corresponding to the direction of plane wave arrivals to shift and stack the signals from sensors to obtain the spectrum of energy radiation of all directions. In classic back projection, the time shifts are arrivals of hypothetical sources calculated from a velocity model. The seismograms are then shifted back and stacked to located the asperity in the source region much like the principle of seismic migration in exploration seismology. The seismograms are first aligned by the initial P arrivals to account for perturbations of the arrival times due to 3D structural

Multiple signal classification(MUSIC)

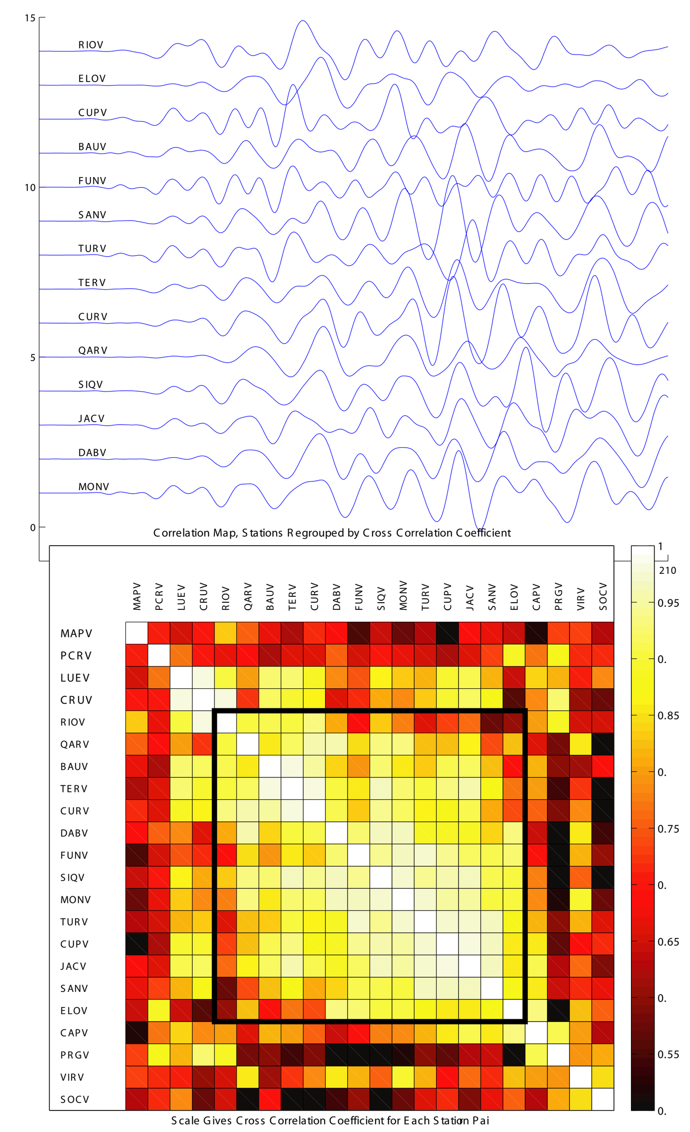
As an effort to improve the resolution of beamforming, the Multiple signal classification (MUSIC) has been developed to estimate the source location based on the data covariance matrix using an eigenspace projection method. The method assumes the signals are composed of multiple waves arriving from different direction plus Gaussian white noise. The direction of arrivals can be resolved through eigenvalue decomposition of the data covariance: the eigenvectors corresponding to the largest eigenvalues span the signal subspace, while the rest of the small eigenvectors span the noise space. A steering vector, which is a set of complex phase shifts as a function of frequency, sensor locations and signal direction, should be orthogonal to all the noise eigenvectors. The direction of arrival is then



Comparison of the MUSIC and beamforming techniques on the direction of arrival analysis of the capability of separating closed spaced sources. two synthetics are impinging the a linear array.As their azimuth difference decreases. the two methods shows different ability of separating them. in this example music has resolution to 2 degree while the beamforming can not separate at 8 degree.



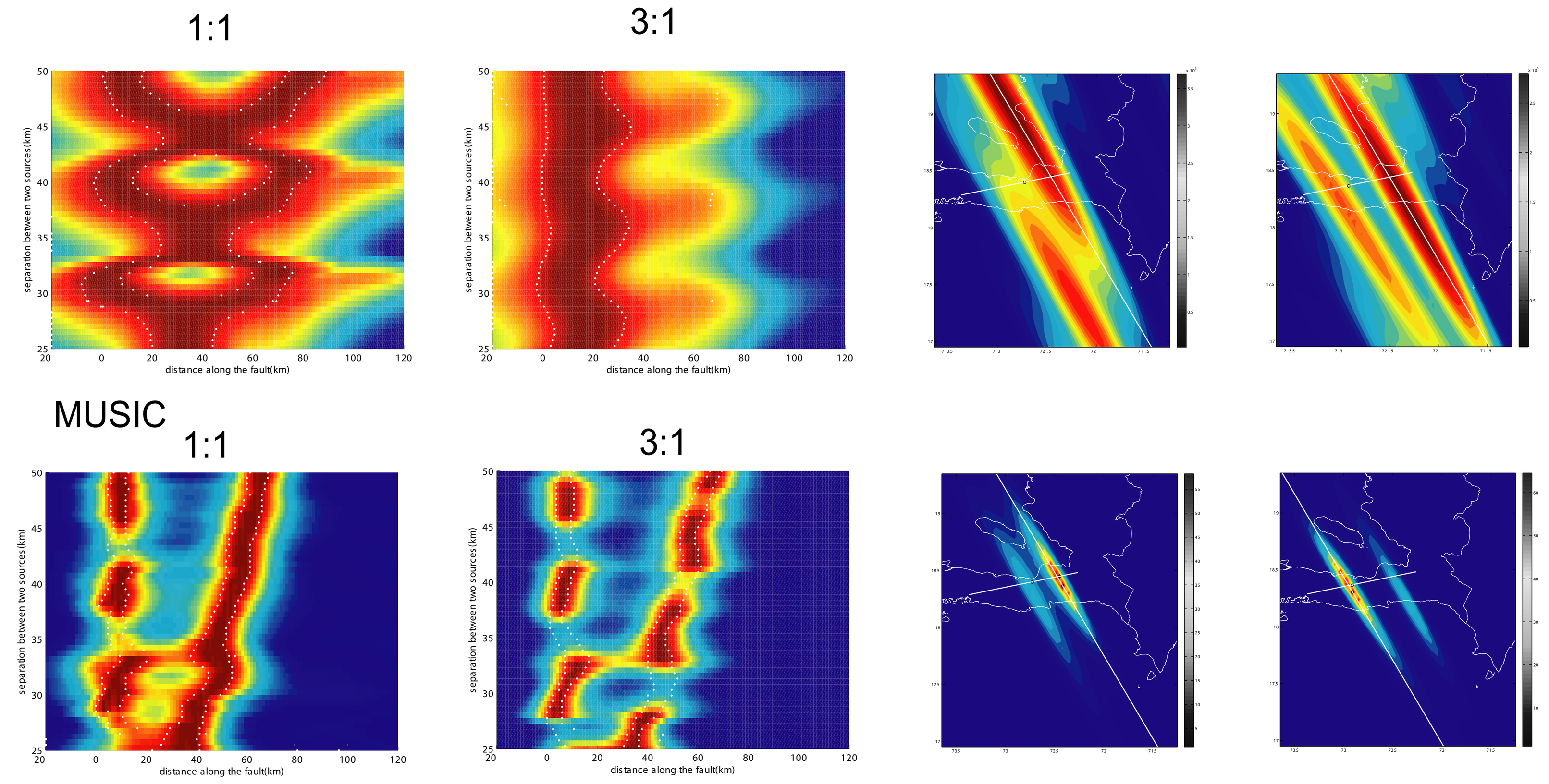
National network of Venezuela
The National Seismic Network of Venezuela is maintained by the Fundaci¨®n Venezolana de Investigaciones Sismol¨®gicas (FUNVISIS) and is composed of 22 broad-band stations with an east-west oriented geometry, located approximately 12 degrees away from Haiti in the perpendicular direction to the Enriquillo fault strike. The Rayligh criterion for array resolution indicates that source location uncertainties for classic beamforming (location error ~ epicentral distance * wavelength / array aperture) are expected to be of order 10 km. This suggests the FUNVISIS network can provide marginal resolution for a 30km source in Haiti if classic beamforming analysis is applied, and warrants exploration of higher-resolution array techniques like MUSIC.



Data selection
Since the epicentral distance of the network ranges from 7 to 15 degrees , the initial P arrivals are dominated by the crustal Pnl complications which vary significantly as a function of distance and back-azimuth. To maintain reasonable coherence within the data set we selected a subset of stations (Green) with multi-channel correlation matrix reordering technique in the 0.2 to 0.5 Hz band.

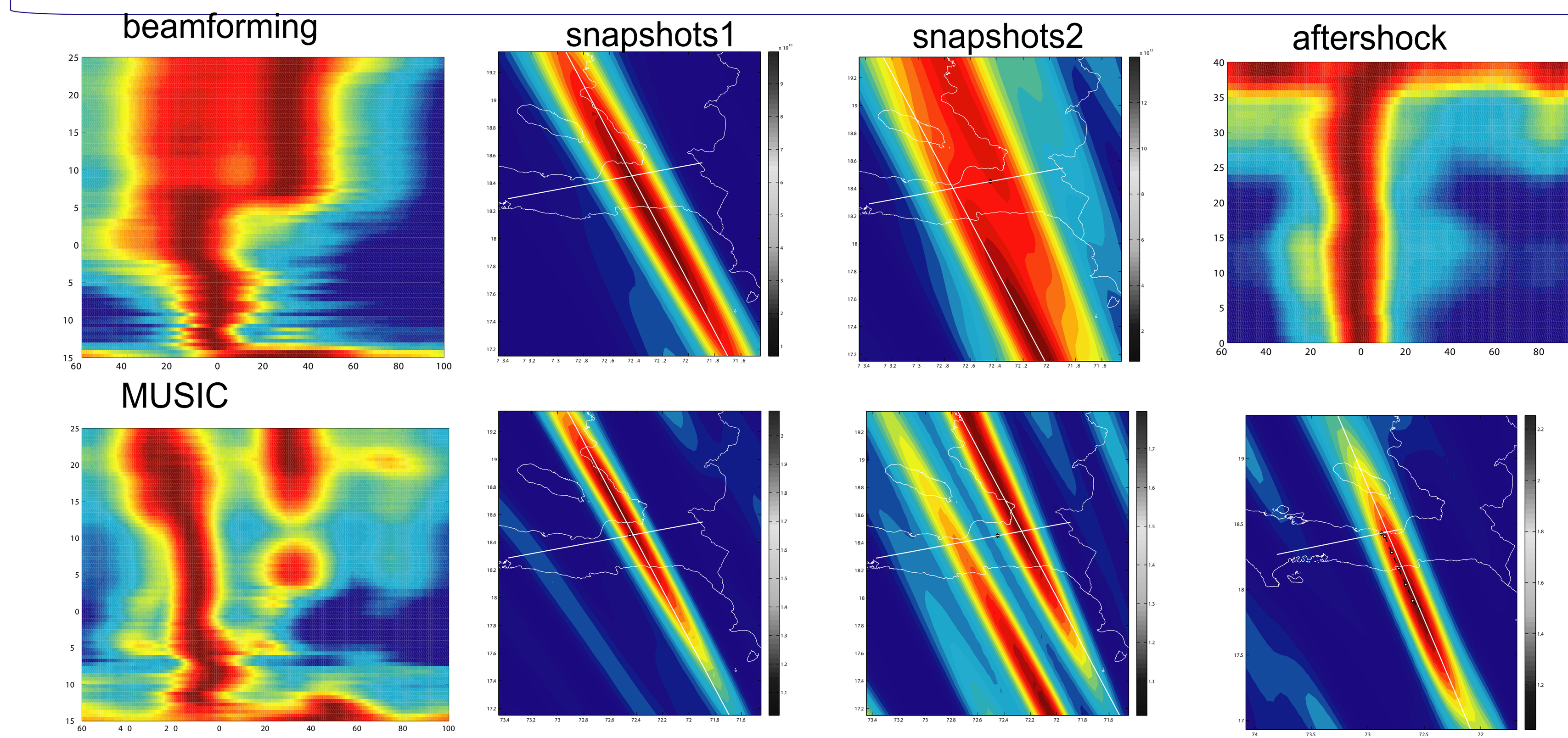
Synthetic test

To understand the performance and potential bias of the back projection using the Venezuela network we test the two algorithms by synthetics. We compute the full wave field synthetics using a Frequency-Wavenumber (FK) method (Zhu 1996). We test scenarios with a fixed source case and a moving source with multiple asperities. The synthetics are first aligned with the initial P arrival. The two proposed back projection techniques are then applied.



We test the performances of the two algorithms by assume two point sources located East from the epicenter along the fault plane with various seperation in distances(25 to 50 km) and in time(assuming a 3km/s constant rupture speed). The focal mechanism is 259/64/26 (strike/dip/rake) with a depth of 13km. The source time function is a Brune function with a duration of 3 seconds. For the classic back projection the data is filtered to 0.25 to 1 Hz, while in the MUSIC test the data is analyzed at 0.3 Hz. Due to the frequency band averaging In the Mulititaper spectrum estimates, we use a 60sec long window to reduce the bias. the Music tends to have sharper source image and it gives better seperation of closed spaced sources(15km). The source location along the source-array direction is poorly constrained due to the limitation of the array geometry, but here we can constrain the source to lie along the known fault trace.The amplitude systematic bias is still existing due to the interference of the sources and this effect is more prominent when the sources are close,but the position which contrained by the white dots are quite well resolved.

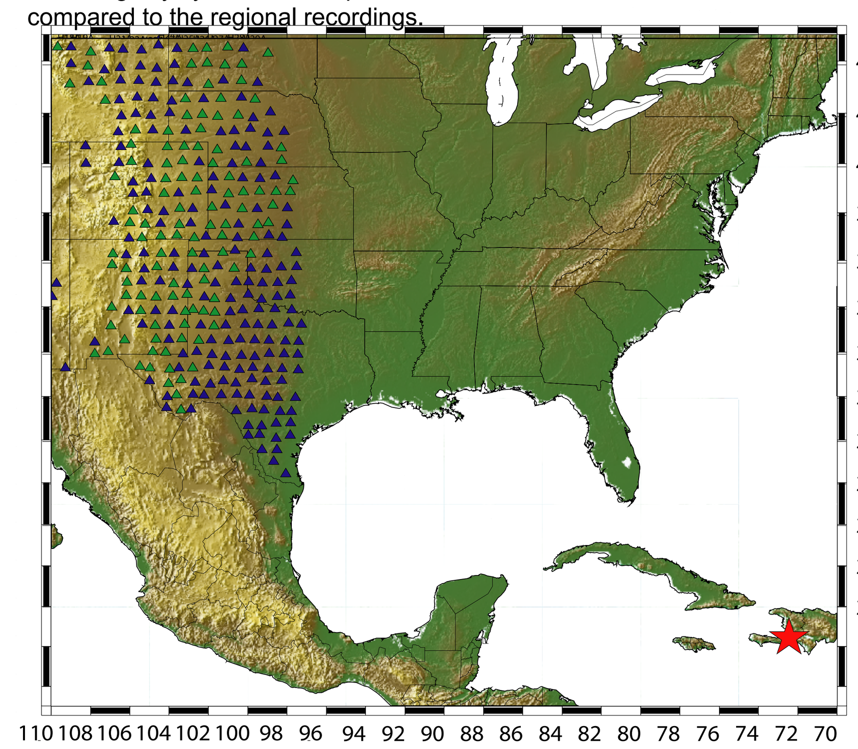
Back projection of the Haiti earthquake by the Venezuela network

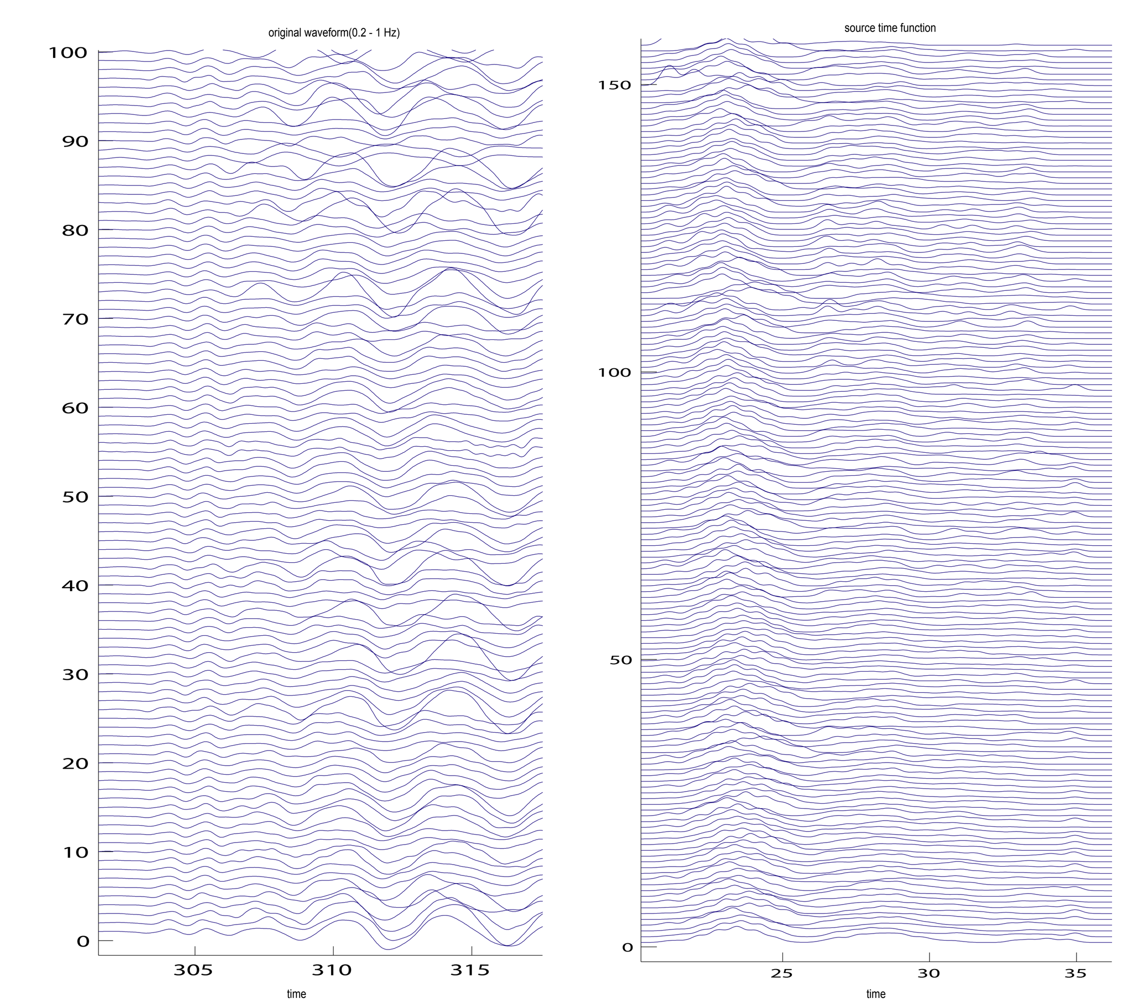


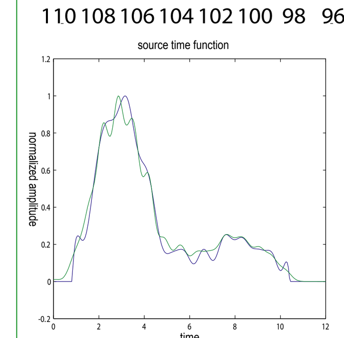
We apply both methods on the actual recordings of Haiti earthquake by the Venezuela network with both long window(60s) and short window(10s). Both algorithms indicate two prominent asperities to the west of the epicenter.In the short window case the two asperities tends to dominent different time windows, while the long windows give more robust location. As expected the music gives more clear separation in the source image.

Source time function back projection of the USarray network

One of the challenges we encountered in the analysis of the Venezuela data is the waveform complexity due to the regional crustal phases. Since seismograms are generated by the convolution of the source time function by the Green's function. Ideally, long time windows are required to include the full waveforms from each asperity. However, such scenario is usually unlikely to be achieved due to the simultaneous arrival of waves from several asperities. One possible solution is to apply back projections to the source time functions derived by deconvolution of array recordings by synthetic or empirical Green's function. To achieve better robustness, we analyze teleseismic recordings from the USArray, which have relative simple and coherent waveforms compared to the regional recordings.

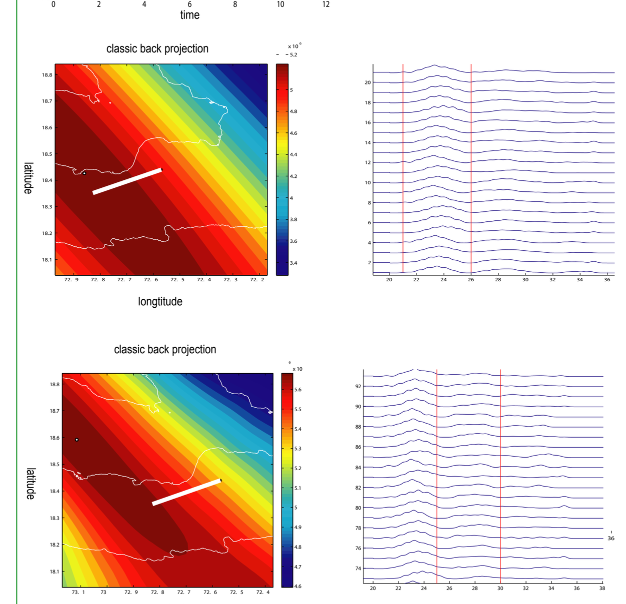






Time domain deconvolution

We caculated synthetic Green's function using generalized ray theory. The source time function is then obtained by the iterative Kikuchi-Kanamori deconvolution technique.(Chu, 2009) or by a non-negative least-squares deconvolution. The two methods show very similar source time function indicating relative robustness.



Back projection of the source time function

TThe source time functions indicate two prominent asperities at about 5 and 8 seconds after the origin time. We apply classic back projection with 5 second windows centered at these two asperities. We find again that the two asperities are located West from the epicenter. The location uncertainty in the source-array direction is smaller than in the Venezuela data. However the location of the first asperity seems to be too far away from the epicenter to obey causality. This technique has to be further explored

Conclusions

Back-projection of regional and teleseismic seismic data from the Venezuela seismic network and the USArray reveals the existence of two asperities in the source process of the Haiti earthquake and the rupture directivity towards the West.

Application of a subspace method (MUSIC) yields a sharper source image than classic beamforming.

We also developed a new technique that incorporates Green's function deconvolution into the back-projection frame. The result is encouraging: the method is able to isolate asperities temporally.

There are still systematic bias in the analysis that should be improved in order to implement these techniques in real time, waiting for the next large earthquake along the Enriquillo and the Septentrional faults. The next position of the USArray will actually be more favorable to reduce the bias in a joint (USArray-Venezuela) array processing approach.