Desiging a network of seismic antennas for high resolution source imaging

Lingsen Meng (lsmeng@gps.caltech.edu), Jean-Paul Ampuero

Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125

1. Promblem

Critical information needed to discriminate different physical models of the earthquake source is contained in the smaller scales higher frequencies. The time scales we would like to resolve are: rise time (few seconds or shorter), process zone (less than a second) and source complexity (multi-scale). Poor knowledge of small scale heterogeneities of the crust hampers our ability to generate deterministic Green's functions at frequencies higher than 1 Hz. This limits the resolution of current source imaging techniques to length scales of several km. To resolve these shorter scales we need seismological observations and analysis techniques that are less sensitive to unknown crustal heterogeneities.

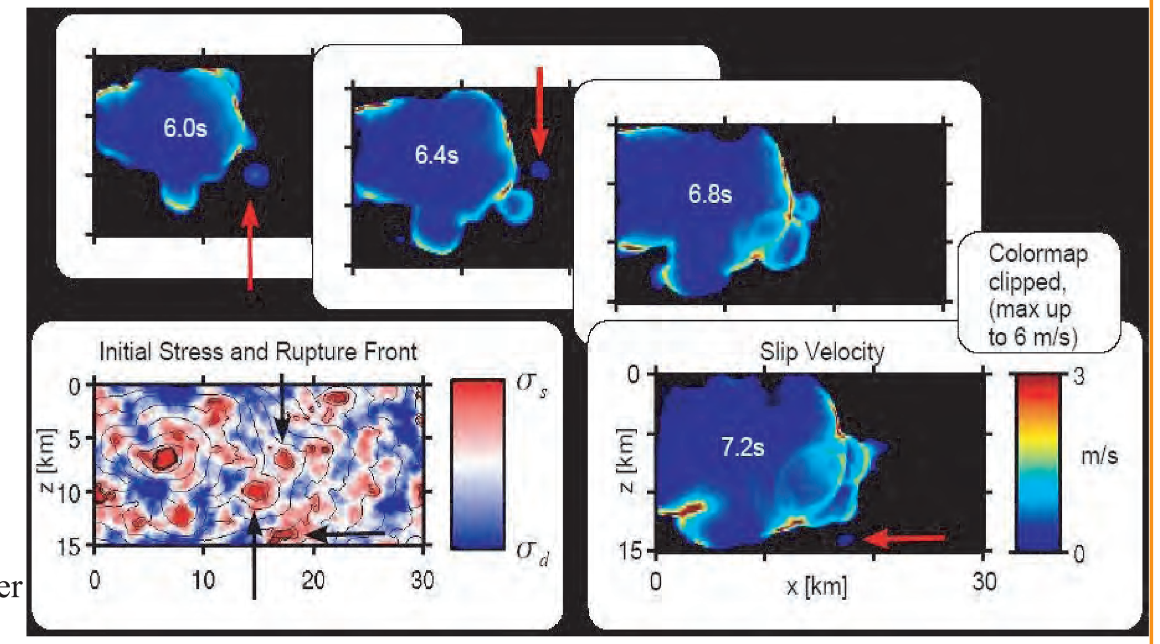


Fig1. *rupture complexity in a typical dynamic rupture*

2.Catching large aftershocks with multiple seismic antennas

Recordings from small scale arrays of seismometers (seismic antennas)can be processed to determine the direction of arrival of high-frequency wave packets (see sections 5 and 6) and then infer the location of the high-frequency emissions on the fault plane. This allows to track the progression of the rupture front and its complexity. Previous realizations of the array source imaging technique have been limited to a single array (e.g. Fletcher and Spudich, 2006) We are investigating how a seismic network consisting of several small clusters of strong motion seismometers can contribute to break the high-frequency barrier in earthquake source imaging. To make this type of array effective , the optimal design of multi-array networks for source imaging, in particular the effect of array aperture and geometrical configuration, and the trade-offs between number and quality of instruments and synthetic modeling of dynamic rupture and wave propagation in heterogeneous media needs to be investigated.

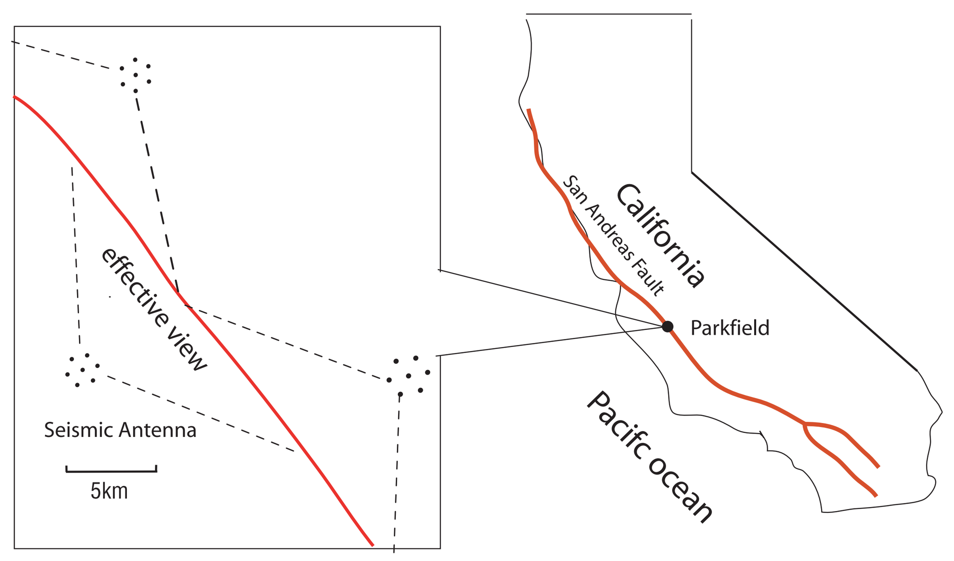


Fig.2 *mulitiple seismic antennas*

Exhaustive deployment of the arrays all along major faults would be unrealistic. An alternative approach is to deploy the antennas immediately after a large (M>7.5) earthquake, near the causative fault, to record large aftershocks (M>6) with unprecedentedly high resolution. A target aftershock fault area can be defined based on earthquake information available early on (aftershock locations, slip distribution along strike). A subset of pre-planned sites are occupied for several months. In the next two sessions, we present our study on general site selection and the chance of the micro arrays to catch large aftershocks.

3. Chance to catch a large aftershock

We estimated empirically the chance of catching a M>6 after shock as a function of deployment date after a M>7.5 mainshock. The statistics is evaluated from the global CMT catalog from 1978-2005, considering aftershocks within 200km and 2 months from their mainshock. The chance of success is over 35% if deployment is done 12 hours after the main shock and decreases to 20% percent after 10 days.

Fig.3 chance of finding at least one large aftershock

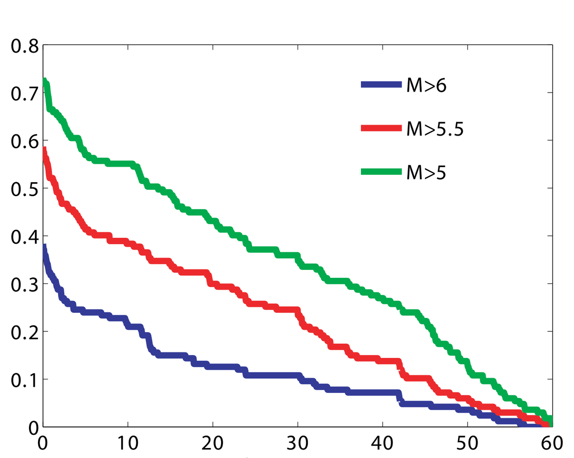
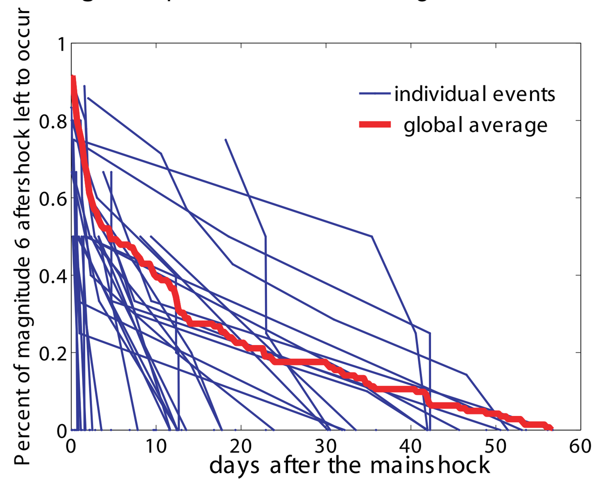


Fig.4 temporal distribution of large aftershocks



4. General site selection

On one hand locating the antenna close to the fault reduces the uncertainty in the source location. On the other hand a distant array will give a larger field of view. We illustrate this trade off assuming a typical velocity model (Fig.5a) and ray-theoretical considerations (Fig.5b). Errors on source depth are caused by uncertainties on the incidence angles (or slowness), which depend on the velocity model, the source-receiver distance (Figs 6, 7) and the source radiation patterns (Fig.8).
We find 5kms is the optimal distance and the S-wave has a larger resolvable range than the P-wave. A network of multiple antennas with complementary coverage (field of view) would require a spacing of 20 km between antennas.

Fig.5 determination of errors using ray theory

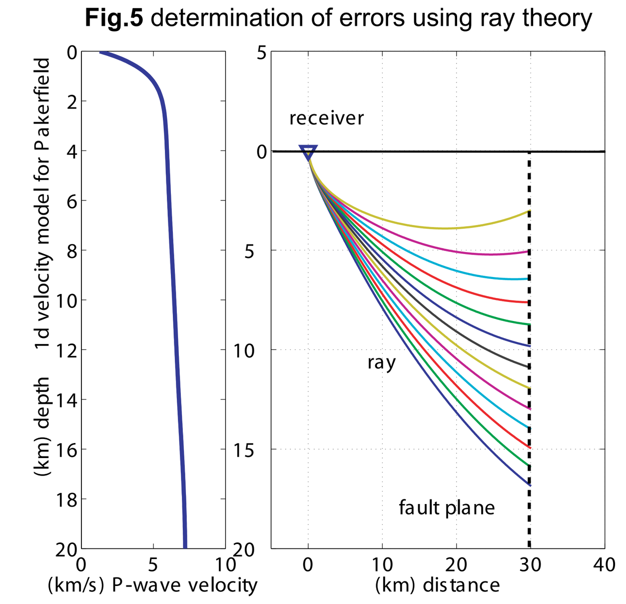


Fig.6 dz/ds depth uncertainty in km^2/sec

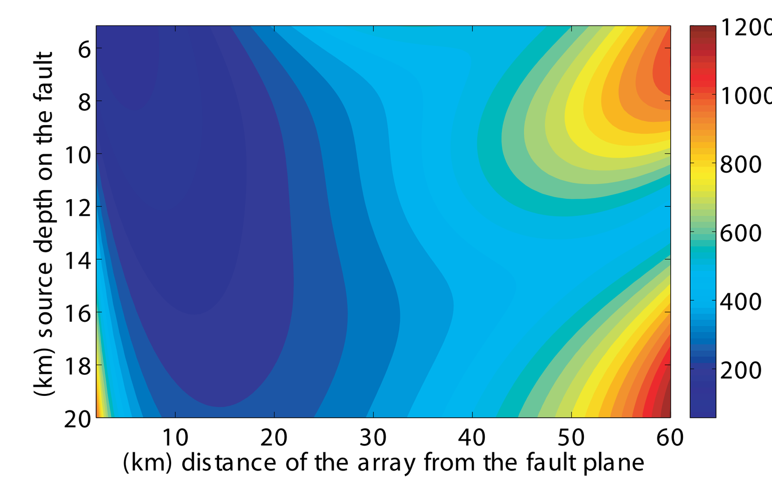


Fig.7 dz/ds depth uncertainty in km^2/sec

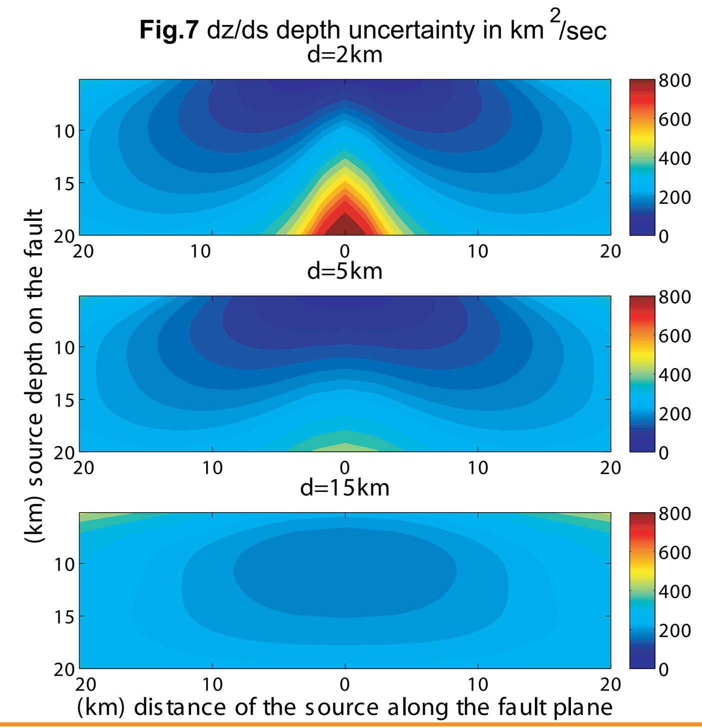
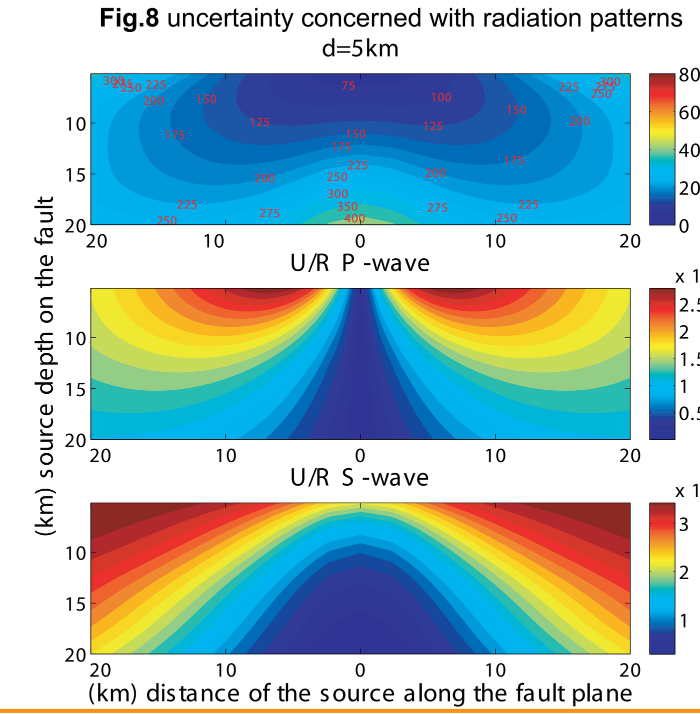


Fig.8 uncertainty concerned with radiation patterns



5.Array processing based on seismic antennas

The data recorded on each array can be processed in two analysis modes:
* identify and locate hot spots of the source as a function of time by high resolution direction of arrival (DOA) estimation on moving time windows
* obtain spatio-temporal source power: scan small areas of the fault by focusing the array beam on narrow direction ranges (array steering and beamforming)

The idea of the second mode is essentially to multiply the outputs of each receiver by complex weights to increase the gain from certain direction and minimize the gain from other directions. To achieve satisfying beamforming performance, the array aperture has to be several wavelengths large. However, the array aperture is limited by the coherence decay as a function of receiver distance. Currently we focus on the first mode.
The direction finding problem has been extensively studied for the past three decades. Multiple techniques, ranging from conventional delay-and-sum to super resolution sub-space based methods like MUSIC and computationally intensive Maximum Likelihood methods, have been applied to various signal processing issues in communication and acoustic science.
In the context of localization of earthquake sources with micro arrays, we face a number of complications which are not considered in typical DOA estimation applications:
* Scattering at shallow depth compromises the coherency at high frequencies and cause low signal-to-noise(SNR) ratio.
* Signal nonstationarity prevents the application of DOA estimation based on large sample statistics and also the time-resolution of DOA evolution due to the minimum resolvable length of the time window.
* The DOA of wideband seismic signals can not be estimated with conventional narrowband techniques.
* Multiple simultaneous sources, possibly coherent

To circumvent some of these issues, we explored a new seismic DOA estimator based on the multitaper cross power spectrum and the Incoherent MUSIC method. First we align the signals with the first arrival to allows the covariance matrix to be computed on short time windows. Then the multitaper technique provides several independent estimates of the cross power spectrum from which a robust average of the covariance matrix can be derived. Then we perform the Incoherent MUSIC on the 5 to 20 Hz frequency band: the MUSIC algorithm quantifies the slowness spectrum at each frequency which are then stacked to reduce the noise and aliasing.
Fig.9 and Fig.10 shows a comparison between our proposed method and the conventional delay-and-sum method. Both methods are applied on the first 0.5 sec P-wave arrival of the 2004 parkerfield event main shock. Clearly our method shows much higher resolution.

Fig.9 delay-and-sum

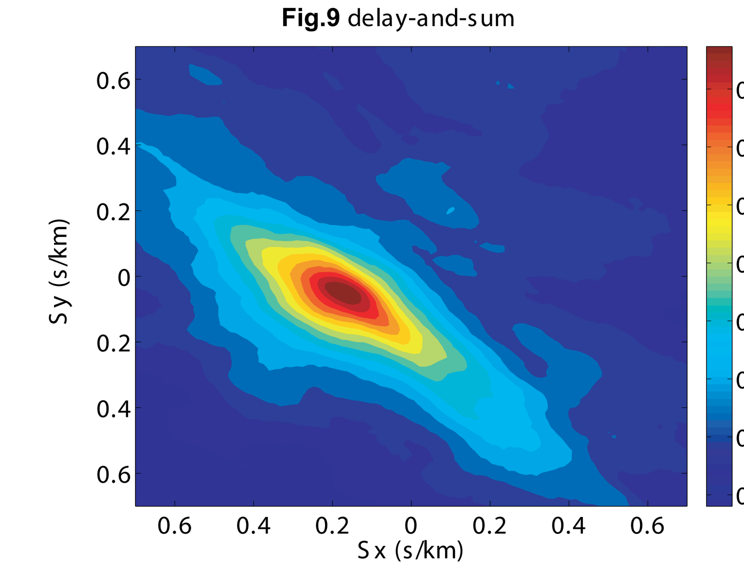
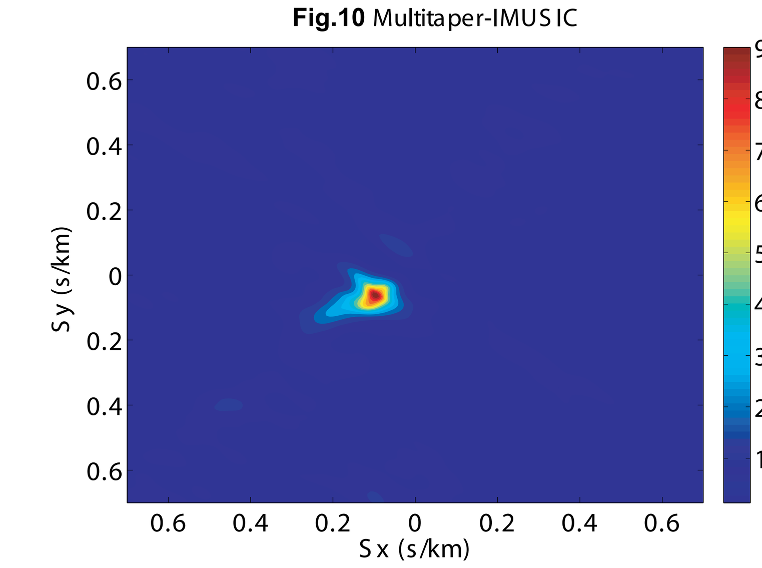


Fig.10 Multitaper-IMUSIC



6.Tracking the rupture propagation of the 2004 parkfield earthquake

We applied our proposed method to track the mainshock rupture propagation of the 2004 Parkfield earthquake recorded by the UPSAR array (Fletcher Spudich ,2006). The multitaper-IMUSIC is applied on the S-wave in 0.5s sliding windows with step of 0.1s. The result shows the earthquake is nucleating around the hypocenter in the first 1.5s. The rupture hot spot moves rapidly towards the north in the next 0.3s, then strong energy radiating from south of the hypocenter indicating a southwards rupture propagation Finally, the source propagates northward to a relatively broad region(pink contours). A second peak is observed in the IMUSIC spectrum. A possible explanation is that two hotspots are generating the seismic waves simultaneously.

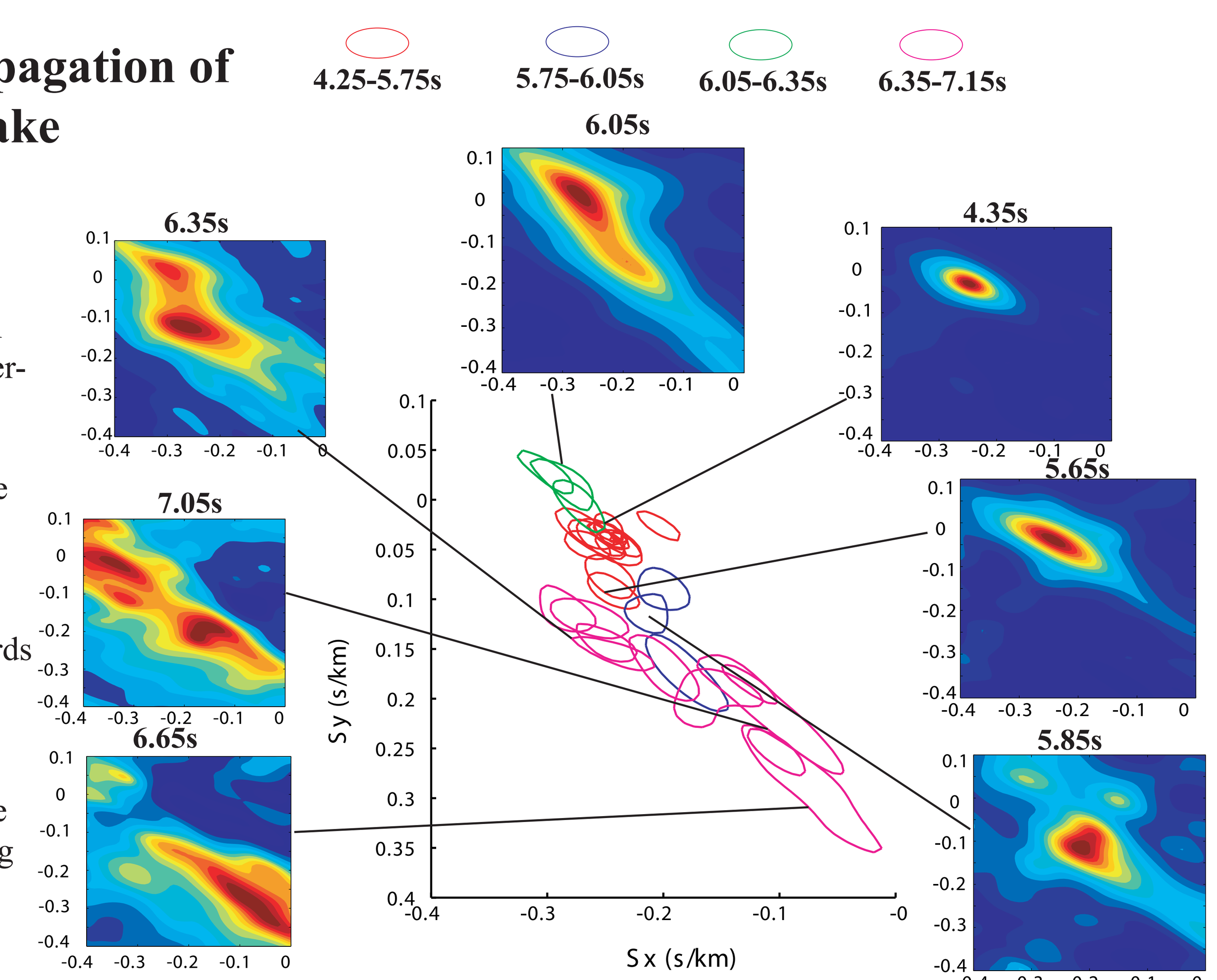


Fig. 11

7.Conclusion

Micro arrays deployed near the major fault can capture small scale features of the earthquake rupture process which can improve our understanding of earthquake physics. In this work, we proposed the concept of large after shock targeting multiple seismic antennas. We quantified the chances of success of such strategy, optimized the general site selection and proposed an improved array processing technique based on the Multitaper and IMUSIC. Finally, we tested our proposed method on the 2004 Parkfield earthquake data set (UPSAR). The results shows the rupture hotspot movement is well tracked and a possible double sources are observed.

8.Perspective

* Array geometry optimization
* Trade off between quality and number of sensors
* Exploring the advantage of multiple arrays
* Site selection based on empirical correlations between waveform coherency and topographic/geomorphologic attributes
* Site coherency assessment based on noise measurements and cross-correlation *Green's functions
* Feasibility of collocated rotational+translational seismometers (possibly in boreholes) for DOA estimation