Optimized passive seismic survey design with simultaneous borehole and surface measurements

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Summary

This project attempts to develop a new integrated framework for optimized multi array passive seismic monitoring programs based on specific requirements set forth at the initiation of the project. We have defined a new framework based on existing microseismic array optimization workflows and deployed this framework into a working implementation within Matlab environment for potential use. While the algorithm as tested shows a lot of promise for actual deployments in the field, tests with real data can provide the necessary confidence to use it for future programs. This project has been funded by a GTI grant and is aimed at understanding the elements which influence the design of multi array passive seismic monitoring programs and to develop a framework for optimization of such arrays for improved Hypocentral locations and source mechanisms while optimizing deployment costs. This report provides an extensive background on the optimization framework used in tour work as well as results with necessary observations and recommendations for future multi array receiver deployments. (Refer Appendix A for the original proposal and work plan).

Introduction

With the increasing potential for use of multiple microseismic arrays in hydraulic fracturing and waste water injection programs, there is a need to look into a standardized scheme for optimizing the design and layout of the different arrays so as to improve upon the observations, processing and interpretations which can be made through each of the individual or the combined arrays. The aim is to maximize the information that can be gleaned from the data collected through these arrays in order to obtain the best possible results during the actual stimulation through improved (high resolution) event mapping, source mechanisms, velocity, stress, other property estimates, etc. This is essential as each monitoring program will have its own unique dynamics which need to be taken into account while designing the arrays. We propose to look at this problem at multiple levels to identify and develop elements of the workflow to design an optimized multi-array survey which works to improve the applicability of the sensor arrays themselves as well as reduce the final deployment costs by taking into account the relevant limits to be placed on the design including for redundancy if the cost benefit analysis requires us to do so. Such a workflow will provide relevant deployment schemes for any future multi-array monitoring programs and provide us with a valuable tool to get the best value for money.

Theoretical Aspects

Most hydraulic-fracturing experiments can benefit tremendously with properly designed micro-seismic arrays and their optimum deployment in ways which cover all potential waveform propagation pathways in the subsurface. Moreover, the limitations and advantages associated with different deployment schemes (such as high noise artifacts and deployment costs for surface data, etc) are now well documented. This places a very high premium on the final deployment costs if we were to design arrays which are exhaustive and designed to cover for all possibilities without checking for possible redundancy. Moreover, in order to save costs, most situations demand the placement of arrays in existing wells and surface locations which are more conducive from an "operational" point of view. While there are existing procedures to optimize micro-seismic array design for either surface phones or borehole measurements, simultaneous optimization for both measurements continues to be underexplored. The challenge becomes even more daunting if additional design constraints (such as tooling design, legal restrictions, etc) come into the picture. Figure 1 shows a generalized listing of some of the design elements which place constraints on any microseismic survey. Which elements within this matrix gets higher importance often depends on the location and the operator and the service provider has to come up with an optimal solution within these restrictions. Figure 2 shows typical deployment possibilities with different seismic & microseismic monitoring programs implemented in the field and indicates the potential complexities which such deployments may face when we try to optimize them.

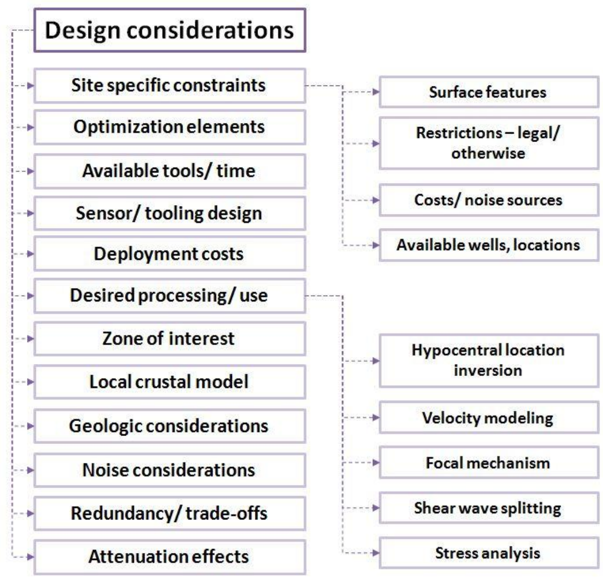

Figure 1: Global design framework

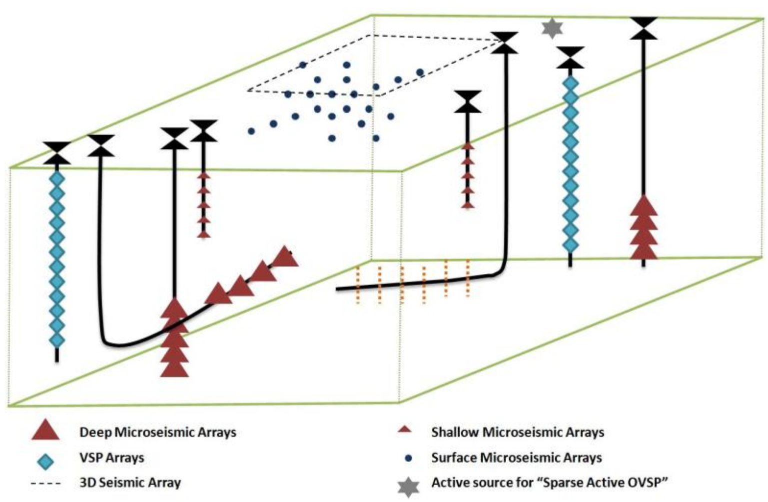

Figure 2: Schematic view of complex survey designs with deep, shallow and surface arrays for passive seismic as well as active arrays for improved reservoir characterization.

The aim therefore is to design and implement a monitoring program which makes the best possible use of the available assets (such as available wells, etc) and to design the program in such a way so as to optimize the design parameters for all of the planned arrays to get the best possible results from the data during processing (for locations, focal mechanisms, etc). This can be achieved through modeling of the arrays and potential ray paths and identifying the specific inversion schemes to used during processing and can be very exhaustive depending on the level of complexity involved. A large number of variables generally define these design parameters. These include the crustal or the local velocity structure, major faults and discontinuities, operational factors (such as operational drilling programs, pumping schemes, etc and their proximity), cost/ time/ resource limitations and finally the "desired degree of precision" in the final results. There are many potential monitoring arrays and their combinations which can be examined. Under this project, we have developed algorithms which provide the ability to add complex array designs in 3D and optimize over the entire search volume. Down-hole (both vertical and horizontal), shallow verticals, surface, etc can all be combined based on existing conditions but the method does require some prior knowledge on the actual zone of interest.

Selected Optimization framework elements

Based on the requirements identified by GTI and our own analysis at ISC, specific elements from within the design framework (Figure 1) were selected for implementation within the optimization algorithm. Elements of the defined work plan (Appendix A) were incorporated and followed as necessary. Based on the potential location of the monitoring arrays and receiver patch design, the receiver locations were modeled in 3D. Similarly, based on the identified zones of interest, artificial sources were placed at depth of interest to mimic actual events that may occur during the monitoring phase of the project. The first component for optimization was the actual ray traces based on all source receiver pairs. The separation of the ray traces and the actual ray lengths have a direct bearing on the final results obtained during inversion runs. The second component that was looked into was the actual moment tensor inversion algorithm (least square inversion for focal mechanism) to be used. Here the stability of the inversion matrix (in the presence of noise and attenuation effects) plays the most important role as far as design considerations go. Figure 3 shows a schematic view of both these elements and how their optimization relates to their evaluation methodology.

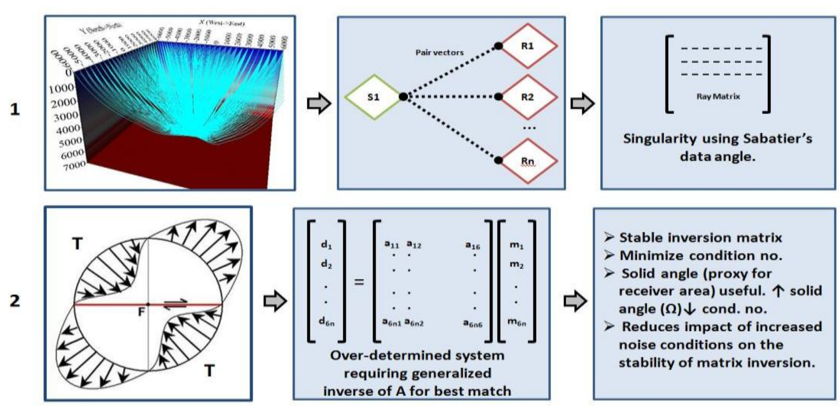

Figure 3: Background on selected design elements.

It is important to note that there are many other design criteria which may be implemented and the method proposed here is just one among the many techniques available in theory. There is considerable body of literature available which can be referenced in order to look at some of these methods. To cite a few examples, Genetic Algorithms (GA) based optimization techniques have been used in the past and can be looked into for improved results (Raymer et al., 2004). We did run implementations of GA based optimization but switched to the more exhaustive search method as we also had moment tensor inversion optimization criteria which led to certain implementation issues. Another technique involves the analysis or error ellipsoids observed during hypocentral location inversions. This involves generating synthetic data (based on array design) and running location algorithms with good error quantification and optimizing the array by removing elements showing highest errors (Chen, 2006). Figure 4 shows some examples of such error evaluations for different depths from cited work.

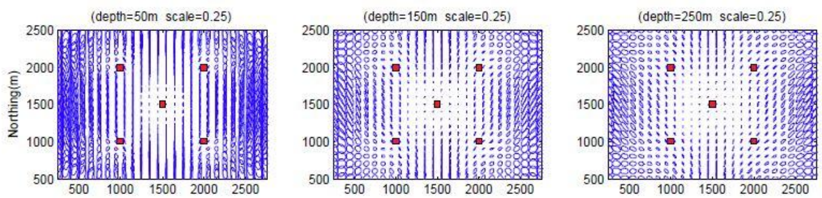

Figure 4: Error ellipses at different depths for 5 receivers (Chen, 2006).

Methods based on analysis of noise levels for different configurations also provide interesting guidelines on array design (Eisner et al., 2010). Other techniques from electrical engineering (which make use of signal processing concepts) are also available and provide unique insights for some diverse perspective. However, we will look at the specific elements within the framework that were utilized in this study.

In case of ray trace focusing, the starting point is to understand any standard inversion method which may be used in hypocentral location algorithms. A generalized solution for arrival time based on model slowness can be represented as $d = A_sM$. Here the ij^{th} element of the A_s matrix denotes the ray-length within the corresponding element. Based on the inverse solution obtainable, the $A_s^TA_s$ matrix can be decomposed numerically and the Eigen values provide an indication of how relevant the information is that can be obtained for the corresponding source-receiver pair (ray trace). While the eigenvalues based quality measure and optimization is a possible pathway to follow (Linear statistical experimental designs by Curtis, 2004), another alternative technique is to use the concept of singularity where zero or near zero eigenvalues for the identified matrix occur if rows in A_s are a linear combination of other rows which in turn indicates redundancy in the data. This approach has been used (Curtis et al., 2004) to design passive surveys in the past and modified implementations are available for use in the open source (experimental design applet for a seismic network: http://alomax.free.fr/projects/expdesign/). The generalized equation for quality measure used is as follows:

$$Quality_{target\ Rec.} = \sum_{other\ Rec.} \{ \sum_{sources} [(1 - \frac{|a_{target\ Rec.} \cdot a_{other\ Rec.}|}{\|a_{target\ Rec.}\| \|a_{other\ Rec.}\|}) \frac{w_{target\ Rec.} w_{other\ Rec.}}{w_{max}^2}]\}$$

Where a gives the partial derivative of the source/ receiver pair and w gives the relative weights assigned to each datum based on ray-length function used as proxy for attenuation. Since each row of A_s

corresponds to a single datum, hence singularity of A_s would indicate that there must be redundancy in the dataset (as per discussion on "data angle" by Sabatier, 1977). The method involves starting with a design which involves all the potential source/ receiver pairs. The dot product of each row with every other row is summed and the same is done for each receiver in turn (they may be weighted by expected data uncertainties, i.e., noise and attenuation affects as well as weights to focus on model subspace). The resulting measure shows the weighted angle between each row and the space spanned by all other rows in the matrix. For a row with angle close to zero, it would indicate that row lies completely within the space associated with all other rows in question indicating data redundancy. On the other hand, if data is adding new information, the angle should be non zero and hence the magnitude of Sabatier's angle measure can be used as a proxy quality measure for receivers. At the end of each iteration, receivers whose pairs show the smallest measure are pruned and the process in continued with the shortened array till adequate number of receivers have been removed. The final quality measure for the component associated with the iteration is calculated as follows:

$$QF_1 = W_1 \times Quality_{target\ \ Rec.}$$

The second component looked into in this work is the moment tensor inversion component. Generalized lease square inversion of 3C amplitudes of P and S wave direct arrivals can be used to retrieve the moment tensor for any event. The relation between observed first arrival data and moment tensor elements can be written in matrix form as:

$$d = Am + noise$$

$$d = \left(a_1^P, a_2^P, a_3^P, a_1^S, a_2^S, a_3^S\right)^T \text{ which give the observed amplitudes of the direct arrivals}$$

$$m = (M_{11}, M_{22}, M_{33}, M_{12}, M_{13}, M_{23})^T \text{ defines the components of moment tensor}$$

A matrix can be evaluated using P and S wave particle motion equations which makes use of direction cosines(γ), travel times(τ), density(ρ), phase velocities(α & β) and displacement - time function at the source (w) to solve for moment tensor (Aki et al., 2002):

$$u_i^P(x,t) = (4\pi r\rho\alpha^3)^{-1}\{\gamma_i\gamma_j\gamma_k M_{jk}\}w(t - \tau_P)$$

$$u_i^S(x,t) = (4\pi r\rho\beta^3)^{-1}\{(\delta_{ij} - \gamma_i\gamma_j)\gamma_k M_{jk}\}w(t - \tau_s)$$

Due to large number of source - receiver pairs, a least square solution has to be obtained for the resulting over determined system.

$$m = (A^T A)^{-1} A^T d$$

The influence of array design on the computation of generalized inverse has been extensively studied by Eaton (2011) where the stability of the inversion for matrix B = A^TA (condition number of B) is tested. The condition number indicates the stability of the matrix and can be obtained from the eigenvalues as per the following relation:

$$k(B) = \frac{|\lambda_{max}|}{|\lambda_{min}|}$$

We use 'k' as a proxy for the degree of instability of the generalized inverse. Eaton has shown that for the purpose of stable inversion for seismic moment tensors, receivers located at the perimeter of the array are the most important. Since numerical tests indicate that the area of receiver patch may in itself not be a sufficient indicator (it will also depend on the distance of the patch from the source), solid angle is used as a good proxy for parameterization of the optimization problem. Both the observations (high solid angle and peripheral sensors) are based on numerical tests and summarized for a sample case in Figure 5. The final quality measure for the moment tensor inversion component is given by:

$$QF_2 = W_2 \times k(B)$$

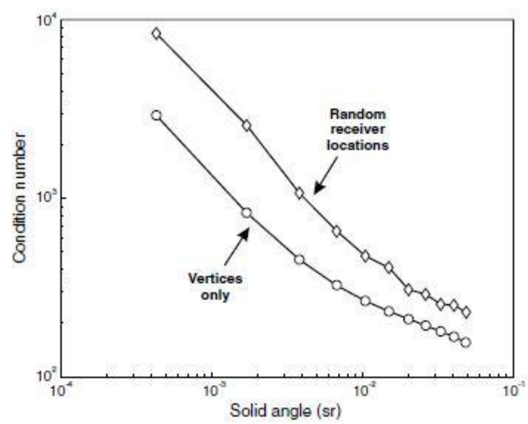

Figure 5: Condition no. vs. solid angle subtended by receiver array validating the major contribution of sensors at the vertices on stability of the inversion (Eaton, 2011).

Experimental setup

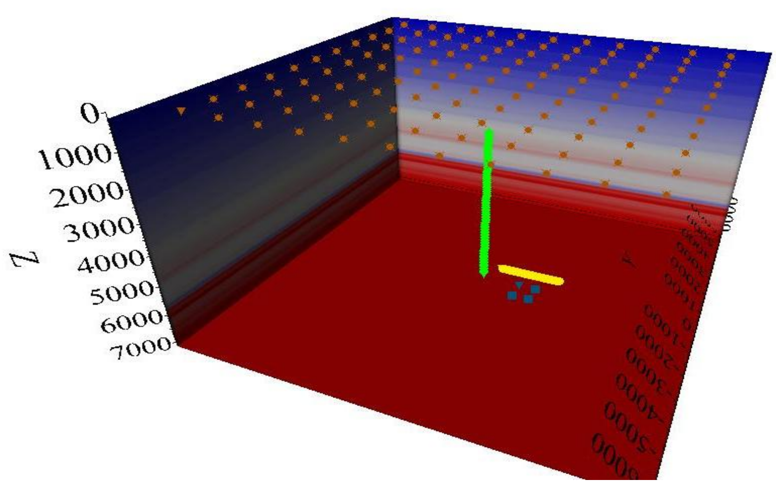

Figure 6: Setup with surface, subsurface vertical & horizontal arrays with pseudo sources.

In order to understand the effect of different arrays on the two selected design criteria, the first step was to create an experimental setup including the necessary observation wells, production well, potential source locations, receiver spread and adequately representative velocity models. Based on regional velocity models available in open source and 1D model provided by GTI, a 3D velocity model was generated with adequate "perturbations" through the introduction of multiple dipping layers. However, since exact data on the specifics of the setup were not available, a more generalized setup with rectangular surface array and down-hole vertical/ horizontal arrays was created and tested for optimization possibilities. Figure 6 shows the 3D model slice as well as the surface/ subsurface well setup and some pseudo sources as per the actual deployment in the field. Once the setup was finalized, based on the velocity model, an adequately effective ray-tracing algorithm was used to generate ray-paths for source - receiver pairs as per the setup. Figure 7 shows sample ray-traces for a single source and surface receivers for reference.

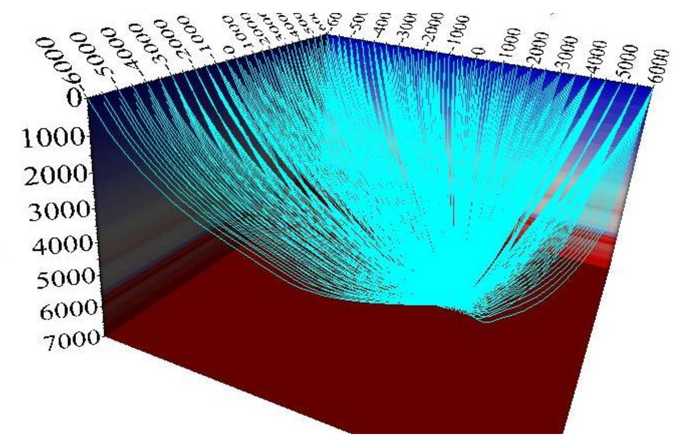

Figure 7: Results from a typical ray-tracing algorithm for partial setup of source - receiver pairs.

Results

Initial tests were run with a constant velocity model and a single source located on the central vertical axis. This was done in order to validate the final algorithm implementation and to make generalized observations on the behavior of the optimization workflow for the two separate optimization criteria described in the earlier sections. Figure 8 (a, b & c) shows three examples of sample runs with different weights assigned to the two different quality measures as obtained from the two separate optimization elements (ray-trace focusing & Moment tensor inversion). The quality measures are referred to as QF_1 & QF_2 which are used to generate the optimization parameter ($w_1QF_1 + w_2QF_2$). We observe that optimization with a higher stress on ray focusing tends to prune receivers from the periphery before moving towards the central section of the receiver patch. On the other hand, for moment tensor inversion optimization, the receivers at the periphery hold more importance and the receivers closer to the subsurface source tend to get pruned first. Solid angle based analysis shared in subsequent discussions does tend to reinforce this observation. We observe that with equal weight given to both quality measures, the selected sensors seem to be closer to the actual source and the sensors from the periphery get pruned. However, sensors at the corner zones (showing highest possible solid angle) remain important. Moreover, the radial pattern (as is seen being deployed by many service companies) also tends to indicate that it is an optimal design under given conditions.

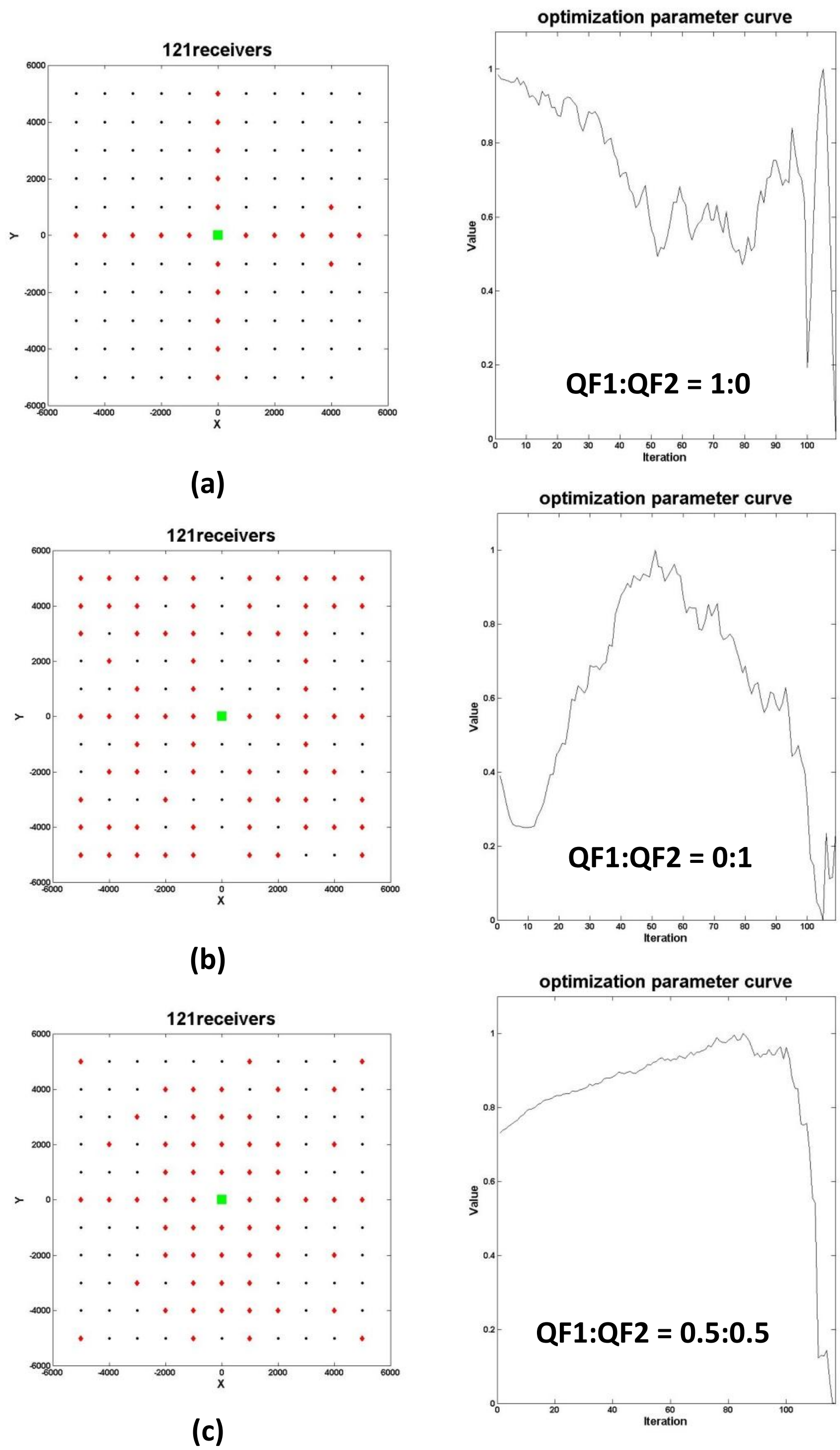

Figure 8: Sample runs with non-variant velocity model, surface receiver array and source at central vertical. (a) shows results with full weight for ray-trace focusing, (b) shows results for full weight on moment tensor inversion and (c) shows results with equal weight assigned to the two components. Red dotted locations are those finally selected based on parameter.

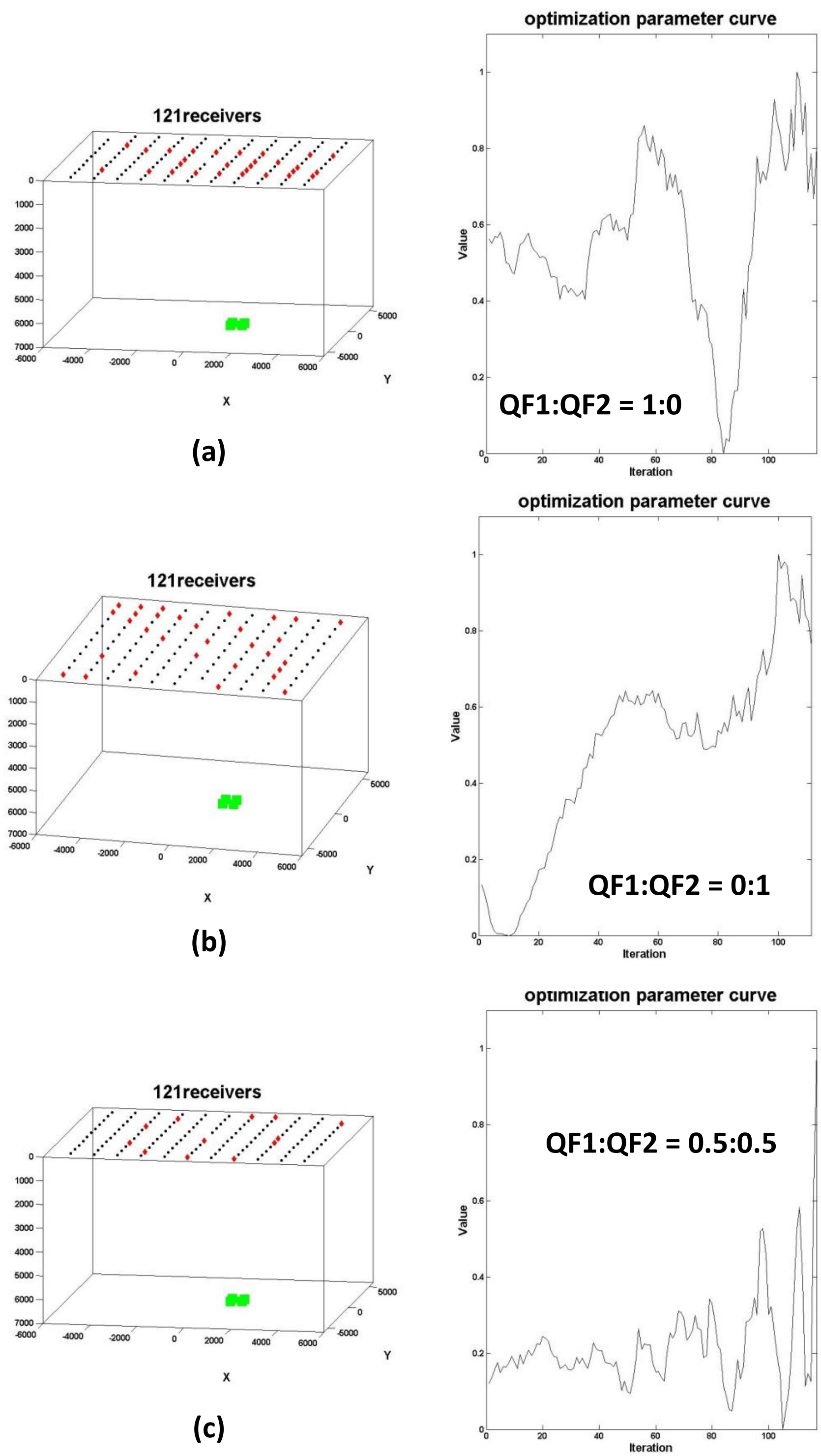

Figure 9: Sample runs with complex velocity model, surface receiver array and source at lateral offset. (a) shows results with full weight for ray-trace focusing, (b) shows results for full weight on moment tensor inversion and (c) shows results with equal weight assigned to the two components. Red dotted locations are those finally selected based on parameter.

Once the algorithm was validated, tests were conducted with sources located at lateral offsets (from origin) and various receiver configurations as per the baseline configurations introduced in the earlier section. For a simple equally spaced rectangular array (Figure 9), again the ray trace focusing based optimization leads to denser receiver spread close to the actual event cloud and the pruning moves from outer periphery towards the zone of interest. For moment tensor inversion optimization, receivers at the corners and the periphery seem to hold importance. The optimization curves also show that the results are relatively poorly conditioned for all the test cases which seem to be a problem with most surface deployments. We hypothesize this as an artifact of source - receiver separation which is the highest for the surface array. Moreover slight variations in velocity profiles (dipping layers incorporated in our tests) lead to substantial perturbations in the ray trace matrix (compared with scenario with no velocity variations). It is important to remember that through solid angles can be used as a good proxy for identifying the best receivers from among all receivers within the patch; receivers beyond critical separation must be pruned as attenuation effects can lead to significant degradation in SNR.

The next case (Figure 10) involved a single vertical array at a lateral offset from the source locations (zone of interest). We again observe that in case of ray trace focusing based optimization, the sensors closest to the zone of interest remain important. In case of moment tensor inversion optimization, the final array tends to be segmented with maximum possible separation angle between the two arrays. However, in this particular case, the shape of optimization parameter curve indicates the failure of the moment tensor based inversion scheme to work for a vertical array (figure 10b). This could be due to the inherent limitations of a vertical array to provide good moment tensor inversion results. Such arrays also show zero solid angle further validating the observation. However, a segmented array seems to provide the most optimum solution in case only a single vertical array is deployed. However, an improved solution could be the presence of a few receivers at the surface and the main vertical array within the wellbore close to the zone of interest. This becomes necessary considering cost/ design issues associated with geophones for wellbore deployments.

Figure 11 shows sample runs with both the surface and the vertical array deployed at one go. This allowed analysis of the impact of first array on selection of receiver locations on the second array and vice versa. Again maximum weight on ray trace focusing based optimization leads to selection of receivers closets to the zone of interest. For optimized moment tensor inversion problem, the surface array provides the best solution (and the vertical array seems redundant). However, solid angle analysis may provide different results as selecting some receivers of the wellbore array may provide good solid angle projections when considered in conjunction with surface receiver locations (though such deployments cannot provide backup receivers due to design). Such analysis has not been conducted for this study. Again the parameter solutions for the three test cases show highly unconditioned results (considered to be carried over effect of surface arrays). We consider optimization based on selections made from among locally optimal solutions in subsequent discussion. Another important scheme not tested for is the presence of multiple vertical arrays which can provide adequate sensor count for good moment tensor inversion results thereby making surface arrays redundant (specifically within wellbores around the zone of interest).

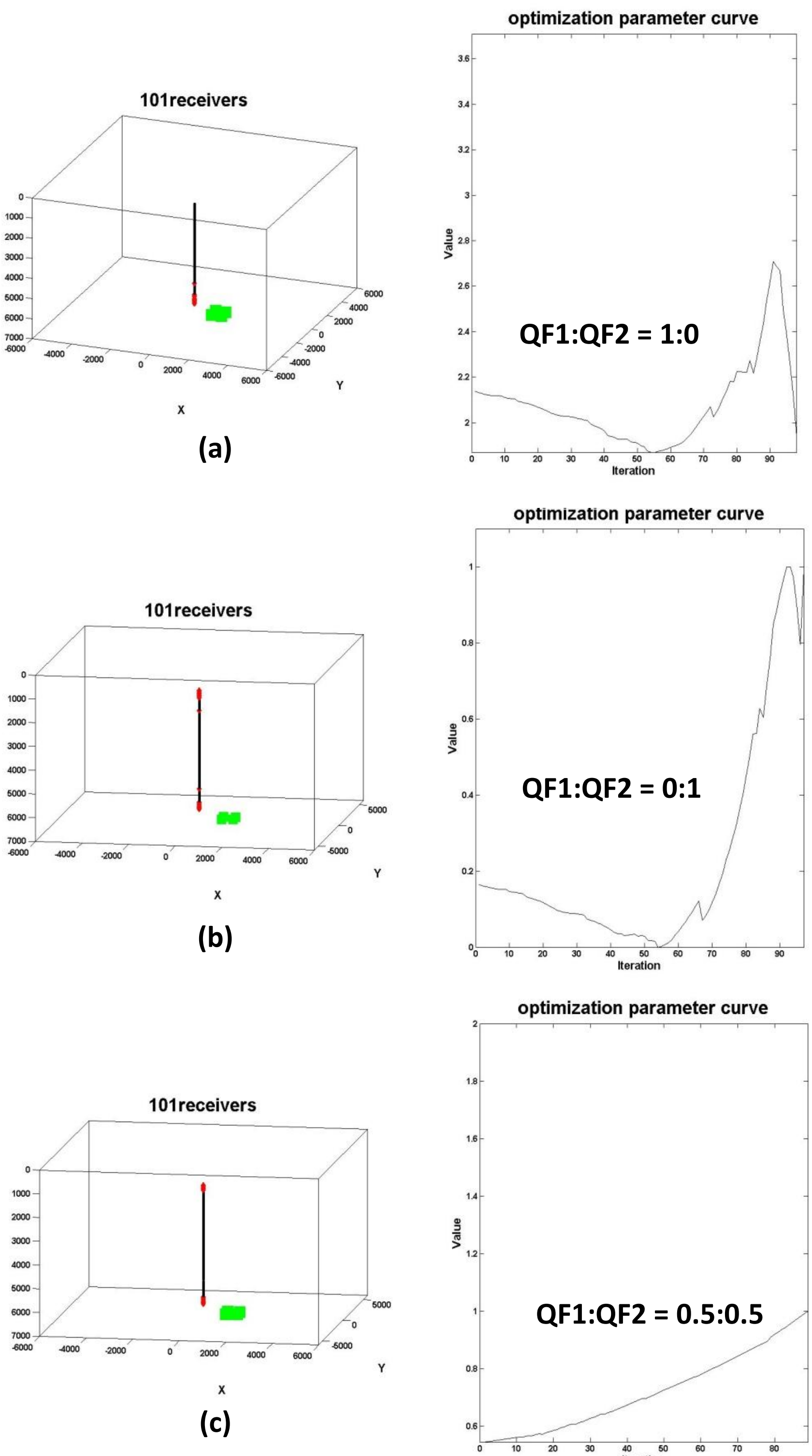

Figure 10: Sample runs with complex velocity model, vertical receiver array and source at lateral offset. (a) shows results with full weight for ray-trace focusing, (b) shows results for full weight on moment tensor inversion and (c) shows results with equal weight assigned to the two components. Red dotted locations are those finally selected based on parameter.

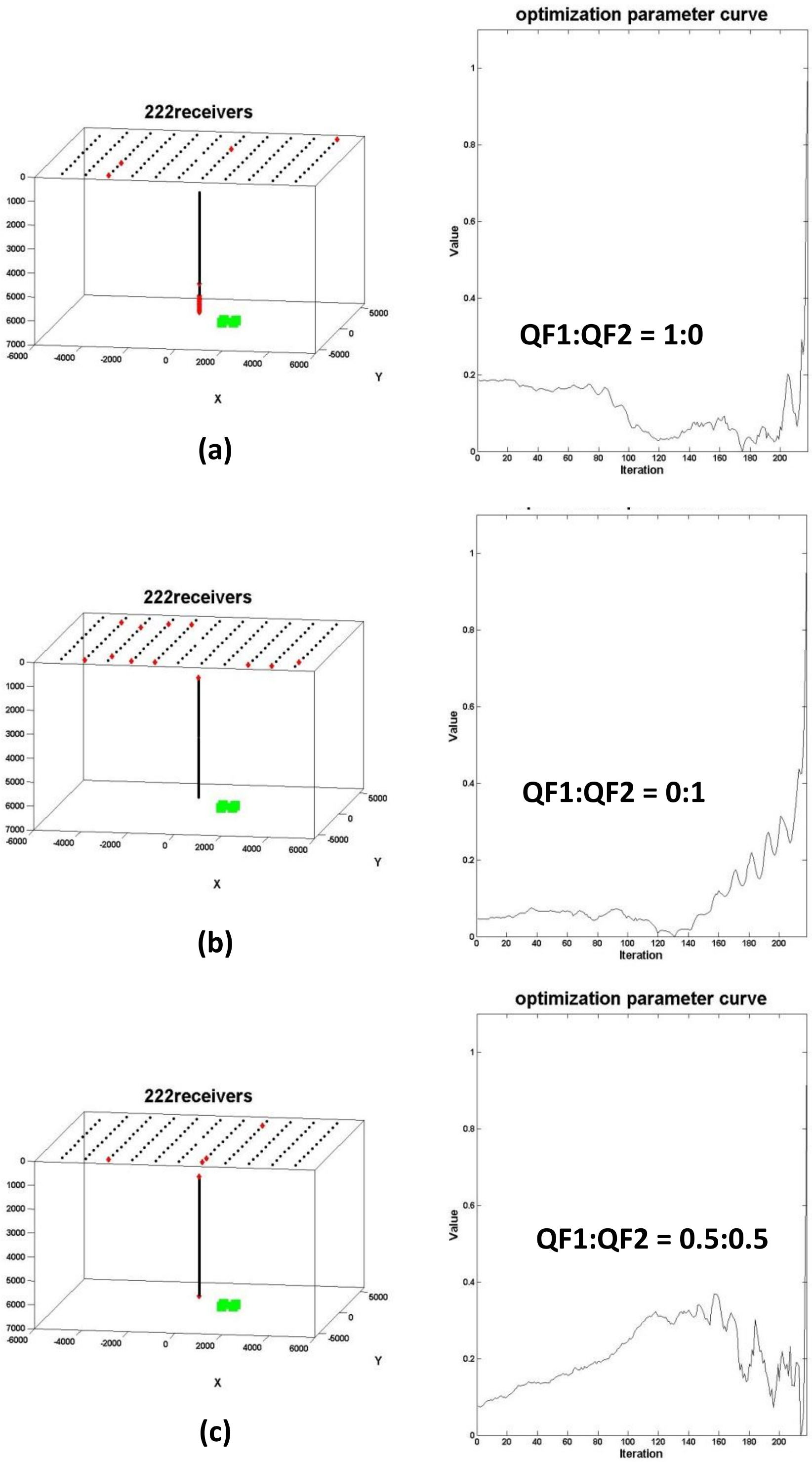

Figure 11: Sample runs with complex velocity model, surface + vertical receiver array and source at lateral offset. (a) shows results with full weight for ray-trace focusing, (b) shows results for full weight on moment tensor inversion and (c) shows results with equal weight assigned to the two components. Red dotted locations are those finally selected based on parameter.

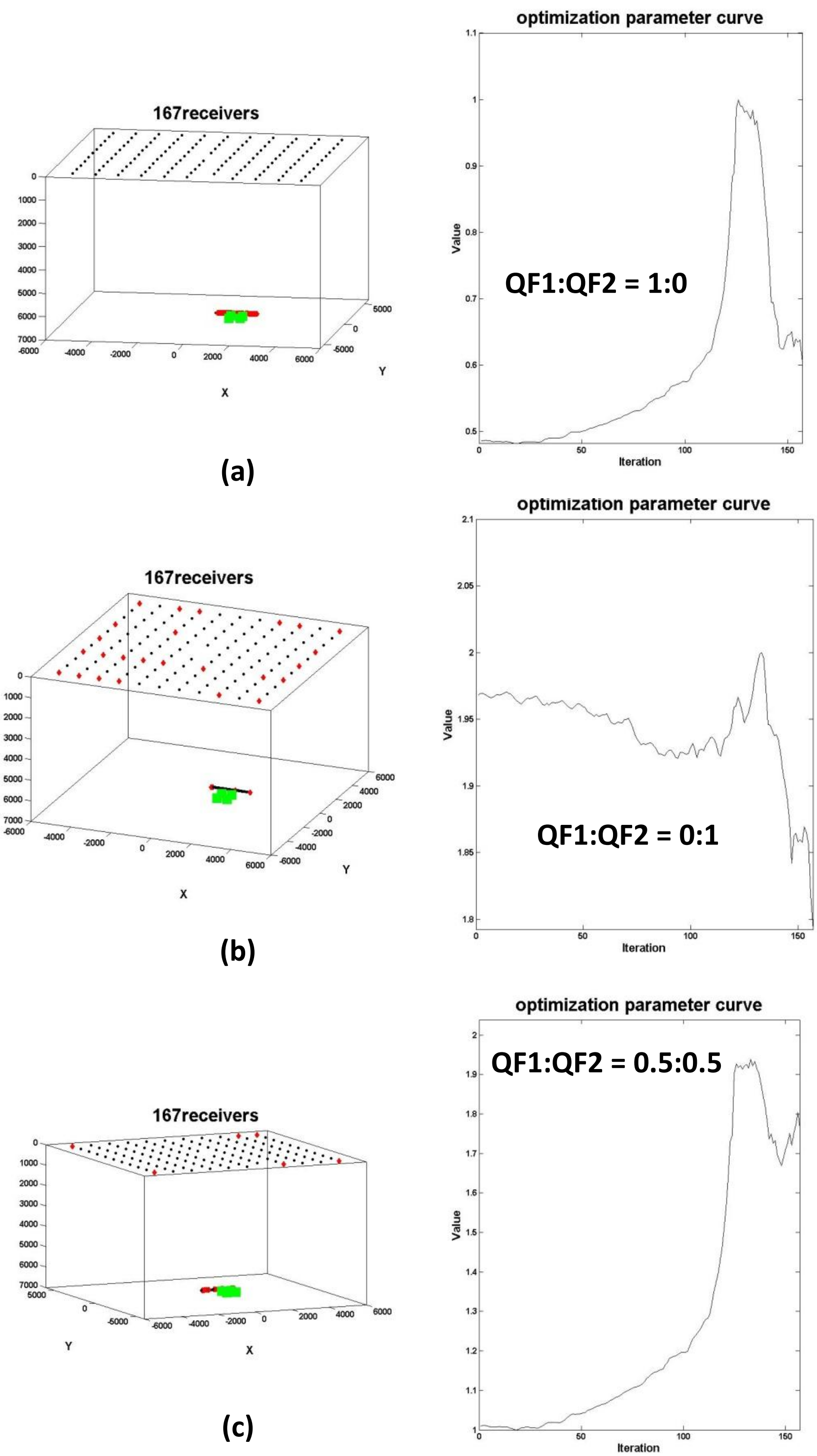

Figure 12: Sample runs with complex velocity model, surface + horizontal receiver array and source at lateral offset. (a) shows results with full weight for ray-trace focusing, (b) shows results for full weight on moment tensor inversion and (c) shows results with equal weight assigned to the two components. Red dotted locations are those finally selected based on parameter.

Final configuration tested for involves both horizontal as well as surface arrays (Figure 12). The horizontal array was configured as parallel (laterally offset but at same depth from reference sources). Again the receivers in the wellbore got preference when ray focusing based optimization had the highest weighted impact on design. Within wellbore, those receivers closest to the zone get pruned first and the process seems to spread away from the center (zone) towards the periphery of the receiver array. Optimized runs tended to select some sources at the surface as well (as moment tensor inversion based optimization requires laterally separated receivers creating relatively large solid angle which is not possible with a single horizontal wellbore array. Thus the presence of wellbore array again indicates that a relatively small surface array may suffice (few well positioned receivers based on design considerations).

Based on the results obtained for various configurations, we also extracted receiver locations for local optimum for few test cases in order to verify their possible use as candidate receiver configurations. This exercise is recommended and is particularly useful in case we have highly irregular and unconditioned outputs in order to make an optimal choice. Figure 13 shows examples of such locally optimal solutions for two sample runs.

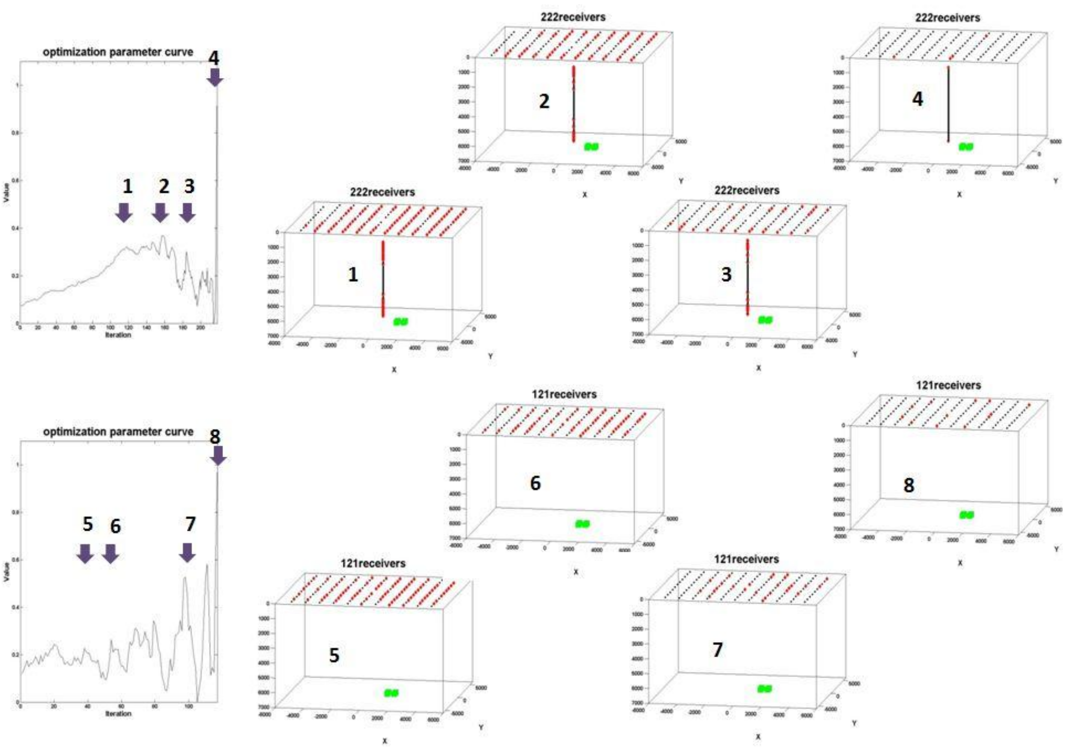

Figure 13: Local maximums from optimized parameter curve as potential design solutions.

Solid angle analysis can also be carried out to validate observations made from optimized array designs or as one of the selection criteria for optimal design from multiple potential candidate designs. The best method is to encode maximum solid angle calculation for designs within the optimization algorithm and use it as an additional element of selection. While this has not been implemented within the optimization algorithm at this point, some initial solid angle analysis has been carried out for typical receiver configurations (based on selected end points within receiver patch). Figure 14 shows two such configurations and Table 1 shows the results for test cases. The solid angle is computed as per the following equation which should work for n dimensional patch at the surface:

$$\tan\left(\frac{\Omega}{\mathrm{n}}\right) = \sqrt{\tan\left(\frac{\theta_s}{2}\right)\prod_{i=1}^{n}\tan\left(\frac{\theta_s-\theta_i}{2}\right)} \qquad \text{where } \theta_s = \frac{1}{2}\times\sum_{j=1}^{n}\theta_i \qquad \text{and } \theta_i \text{ are the vertex angles}$$

A thorough investigation should involve solid angle analysis for all possible receiver combinations (for a receiver patch on a pseudo surface).

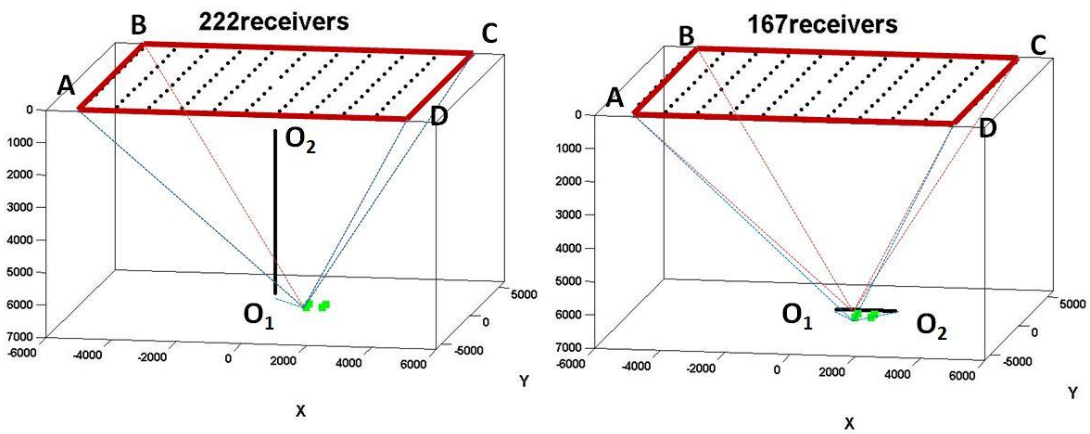

Figure 14: Sample solid angle calculations for reference.

Receiver array design	Vertex angles	Solid angle (Ω)
Surface	57°, 62°, 64°, 59°	~ 179
Vertical	61°, 97°	0
Horizontal	58°, 66°	0
Surface + Vertical (A,D,C,O_1)	39°, 27°, 61°	~53
Surface + Vertical (A,D,C,O_2)	59°, 27°, 84°	~ 274
Surface + Horizontal (A,D,C,O_1)	58°, 41°, 74°	~ 24
Surface + Horizontal (A,D,C,O_2)	91°, 41°, 129°	~ 23

Table 1: Sample solid angle results for selected receivers from designs for reference.

Observations & Recommendations

1. Surface array is highly sensitive to subtle changes in the subsurface structure of the reservoir. (Sensitivity would normally follow the sequence surface > vertical > horizontal due to large velocity variations with depth compared with lateral variations). This is further validated by the unstable design solutions observed.

2. For vertical arrays, it seems to be best to have the sensors closest to the actual zone of interest (which also makes intuitive sense as this would reduce estimation uncertainties). However, if vertical/ horizontal wells are the only observation wells, it is necessary to place a few surface sensors taking solid angle criteria into account. The other way is to have multiple wellbore arrays distributed around the zone of interest.

3. Moment tensor inversions for source characterization should be done with boundary elements alone (of the subtended solid angle by the arrays) during final processing/ analysis and with the minimum number of elements possible (taking noise issues into account). However, for the array design and deployment, adequate backup is desired for some degree of redundancy.

4. Actual noise conditions in the field and their impact on sensors is difficult to predict but can have substantial degrading effect and impact design suitability. High noise environments should require built in redundancy in the designs. The algorithm allows us to incorporate specific noise based weighting coefficients to receiver locations before the optimization runs begin to adequately factor it in for the optimization workflow.

5. As already explained, properly designed well arrays can make large surface arrays redundant. However smaller arrays are necessary in case the number of observation wells are limited.

6. More complex cost functions should be tested for to check if the solutions can be improved. However, to the best of our knowledge, this is the first time that an attempt has been made to optimize an array for multiple functions in a holistic manner.

7. For poorly constrained scenarios or badly conditioned solutions, physical constraints may be imposed or multiple solutions may be compared based on local optima and conclusions drawn from such comparisons. Constraints can also provide solutions which are more stable.

8. With regard to horizontal arrays and using updated velocity models based on hydrofrac generated perturbations within velocity field based on stress induced changes from stage to stage, industry seems to be reluctant to focus on working with such changes at this point as it requires very high quality data, increased man hours for processing of the data as well as some more research on newer workflows/ algorithms. However fairly complex lateral velocity models are used (based on available information) to improve results when working with horizontal arrays.

9. While it would seem that the optimal vertical observation array design can remove some of the sensors in the middle section of the well (observations from optimization runs in this work), in the actual field implementations, it is not seen that often as tools have standardized length interconnects and it makes more sense to cover the complete acquisition instead of using a complex array design.

10. While only ray-trace focusing and Moment tensor inversion optimizations have been tested, other factors can also be easily added within the optimization framework. Potential candidates include arrival time differentials (based on moveout), event amplitudes, attenuation pseudo factors,

polarity, etc (Figure 15). Moreover, based on known limitations on the availability of wells, surface conditions, etc, preset arrays can be designed for and included and only those arrays can be set for optimization which provide such flexibility (hasn't been tested).

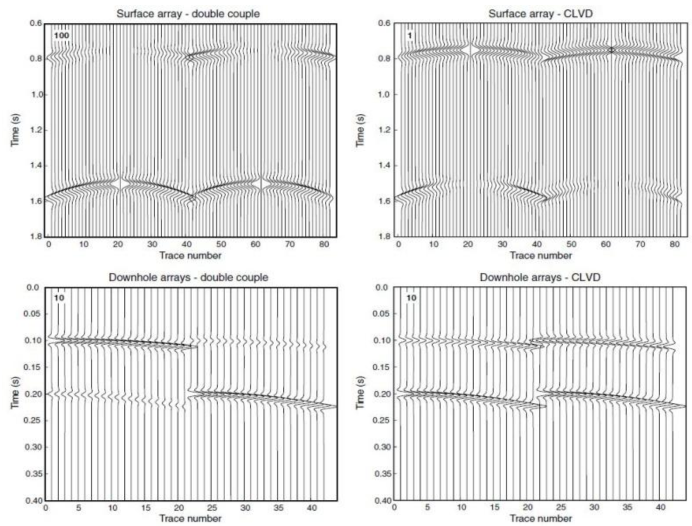

Figure 15: Examples of synthetic seismograms obtained for two different source mechanisms (double couple & compensated linear vector dipole) for surface and wellbore vertical arrays (Eaton et al., 2011).

Future work

Based on the analysis carried out for the test cases, we have adequate confidence on the designed framework and propose testing of the framework for more complex array deployment schemes including multiple down-hole arrays. Moreover, additional inputs within the optimization framework can be looked into to improve the versatility of the designed arrays. Also, tests with real deployments can be conducted with validation based on synthetically generated seismograms for pruned arrays or comparison of actual passive seismic data from deployed arrays (with final selections based on test results). Improved models for inversion algorithms can also allow optimizations based on inversion schemes (with minimization of associated errors). Moreover, increased receiver density can provide better indication of ideal deployment "zones" of interest for receivers.

Algorithm

A. Read velocity model.
B. Read Source/ Receiver locations and generate ray traces based on velocity model (ray-tracing algorithm).
C. Generate ray-length matrix based on defined 3D gridding.
D. Generate moment tensor inversion matrix based on ray traces and ray lengths.
E. Compute quality factors as defined in previous sections for both elements and normalize the measures before final quality measure for iteration is defined.

F. Remove receiver location with lowest quality measure (as per definition).
G. Store cumulative measure at said iteration as quality parameter.
H. Iterate steps E through G till the number of receivers is down to very low number (user selected minimum).
I. Select array (receiver locations) corresponding to highest measure over all stored iterations as the final selected design.

Note: The effect of pruned locations on subsequent iterations is unknown and therefore this process is not exhaustive. However, at least for the ray trace focusing section of the algorithm, the results are similar to results obtained through either mote exhaustive or more "smart" techniques (Genetic Algorithms).

Acknowledgement

We would like to acknowledge Dr. Iraj Salehi from GTI for his valuable support and suggestions throughout the project. We would also like to acknowledge Dr. Martin Karrenbach from SR2020 for his helpful insights into actual array design and deployment issues in the field as well as access to their proprietary software for generating necessary models and use of appropriate ray tracing algorithms for actual tests. We would also like to thank our sponsors at ISC for their continued support.

References

1. Aki, K., & P. G. Richards, (2002), 'Quantitative Seismology: University Science Books'.
2. Chen, Z., (2006), 'Guidelines for the geometry design or local microseismic arrays', CREWES Research Report - vol. 18.
3. Curtis, A., A. Michelini , D. Leslie & A. Lomax, (2004), 'A deterministic algorithm for experimental design applied to tomographic and microseismic monitoring surveys', Geophys. J. Int., 157.
4. Eaton, D. W., (2011), 'Solid angles and the impact of receiver-array geometry on microseismic moment-tensor inversion', Geophys. J. Int., 76.
5. Eisner, L., B. J. Hulsey, P. Duncan, D. Jurick, H. Werner, & W. Keller, (2010), 'Comparison of surface and borehole locations of induced seismicity. Geophysical Prospecting, doi: 10.1111/j.1365-2487.2010.00867.x.
6. Raymer, D., & Y. Ji, (2004), 'Genetic algorithm design of microseismic injection monitoring networks in the Tengiz field', SEG Annual Meeting, Denver, CO.
7. Sabatier, P. C., (1977), 'On geophysical inverse problems and constraints', Geophys. J. Int., 43.

Appendix A

GTI Proposal for reference:

Introduction

With the increasing use of multiple microseismic arrays in hydraulic fracturing and waste water injection programs, there is a need to look into a standardized scheme of optimizing the design and layout of the different arrays so as to optimize the observations and interpretations which can be made through each of the individual arrays. The aim is to maximize the information that can be collected through these arrays in order to obtain the best possible results during the actual stimulation through improved (high resolution) event mapping, source mechanisms, velocity and other property estimates, etc. This is essential as each monitoring program will have its own unique dynamics which need to be taken into account while designing the arrays. We propose to look at this problem at multiple levels to develop a workflow to design an optimized multi-array survey which works to improve the applicability of the sensor arrays themselves as well as reduce the final deployment costs by taking into account the relevant limits to be placed on the design if the cost benefit analysis requires so. Such a workflow will provide relevant deployment schemes for any future multi-array monitoring experiments and provide the users with a valuable tool to get the best value for money.

Scope of Work

Most hydraulic-fracturing experiments can benefit tremendously with properly designed micro-seismic arrays and their optimum deployment in ways which cover all potential waveform propagation pathways in the subsurface. Moreover, the limitations and advantages associated with different deployment schemes (such as high noise artifacts from surface data, higher deployment costs for relatively deep horizontal arrays, etc) are now well documented. This places a very high premium on the final deployment costs if we were to design arrays which cover all possibilities. Moreover, in order to save costs, most situations demand the placement of arrays in existing wells and surface locations which are more conducive from an "operational" point of view. While there are existing procedures to optimize micro-seismic array design for either surface phones or borehole measurements, simultaneous optimization for both measurements continues to be a challenge.

The aim therefore is to design and implement a monitoring program which makes the best possible use of the available assets (such as wells, etc) and to design the program in such a way so as to optimize the design parameters for both of the planned arrays to get the best possible results. This can be achieved through modeling of the arrays and potential ray-paths using waveform inversion schemes and can be very exhaustive depending on the level of complexity involved. A large number of variables will define these design parameters. These include the crustal or the local velocity structure, major faults and discontinuities, operational factors (such as operational drilling programs, pumping schemes, etc and their proximity), cost/ time/ resource limitations and finally the "desired degree of precision" in the final results.

There are many potential monitoring arrays and their combinations which can be examined. Down-hole (both vertical and horizontal), shallow verticals, surface, etc can all be potentially combined. ISC aims to use linear statistical experiment design techniques to optimize on the relevant parameters associated with the geophysical experiments at hand. Soft computing tools such as genetic algorithms can be used to optimize on specific parameters as desired. Potential data redundancies can be removed depending on the optimized cross-well and surface tomographic designs. It is also important to note that ray-path *coverage alone is poor criterion for designing model parameterizations and therefore holistic model based optimization schemes are necessary if we want to optimize on the basic array designs. In case of highly non linear mapping between the collected and extracted data and the model parameters (which is possible under certain situations requiring optimization), techniques such as "entropy criteria evaluation", Bayesian design, etc can be used.*

The work-plan for the project is defined as follows:

1. *Pre-project study phase: This will include collection of critical information on the field in question including publicly available local velocity fields, exact shales (within Mahantango or other formations) being targeted, typical pumping volumes, etc.*
2. *The next step will be to model for sample stages based on a broad understanding of the stages developed during the provided monitoring experiment. With information on locations of arrays for each cluster of hydrofrac stages, we will generate synthetic datasets to understand the viability of the results as observed through our modeling work by making use of any available information on MEQ orientations, densities, etc. This will include the surface placement as well as the 5 "zippering" geophone placements as was conducted during the provided monitoring experiment.*
3. *Once the models have been validated, the next step would be to modify the arrays (both surface and down-hole) based on identified operational limits to simulate results as obtained from different array configurations. These will include modifying the number and placement of sensors, offsets, etc.*
4. *Optimization will be carried out (for both linear and non-linear mappings) based on preselected criteria. A more detailed description of techniques applicable for specific arrays can be developed and provided as required. Final decision on optimization workflow to be used will depend on the results obtained during the modeling phase.*
5. *Given the fact that simultaneous optimization of borehole and surface measurements will require proper weighting of the each objective, we will run tests and make recommendations on the choice of those weight factors based on different operational considerations.*
6. *Finally, ISC will provide an optimized multi-array design technique based on the observations as discussed above. The complexity of the methods to be used (such as potential full waveform inversion, etc) will be contingent upon mutually agreeable requirements as identified for this project.*

Deliverables

The project deliverables include the following:

1. *Optimized array design procedure for the current industry cooperative research project in Marcellus with a focus on quantifying the potential improvements as obtained through our modeling studies. While the parameters will be optimized for a typical velocity model in the Marcellus shale area, the attempt will be made to easily generalize the results elsewhere.*

2. *Develop a broad workflow for any future array design program including cost effective techniques to optimize multi-array designs and techniques to compare and contrast different array configurations in both qualitative and quantitative manner.*
3. *Project report and multi-array design workflow.*

Duration

The project is envisaged to be spread over a period of 3 months with the deliverables spread over the same duration. The actual model parameter optimizations and optimized array designs will be provided by the beginning of 1Q, 2013.

Cost

The cost to carry out this project is estimated at $75K. The contribution from RPSEA/GTI towards the project cost will be $50K. The remainder ($25K) will be cost share from USC.