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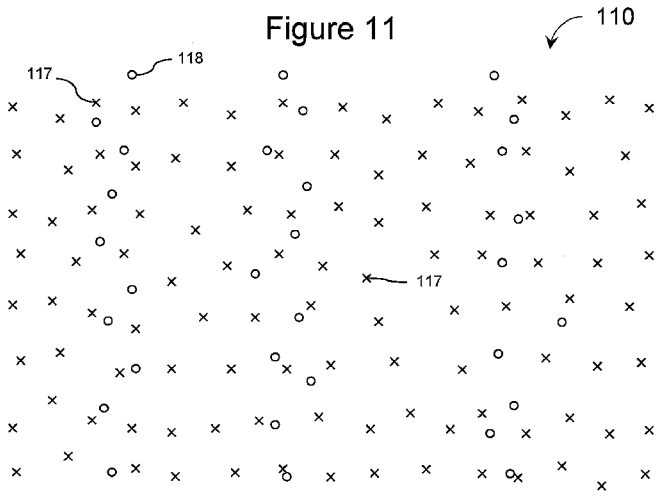
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(54) **Title**: SEISMIC DATA ACQUISITION USING DESIGNED NON-UNIFORM RECEIVER SPACING

Figure 11



(57) **Abstract**: The invention relates to an arrangement for seismic acquisition the spacing between each adjacent pairs of receiver and sources lines is not all the same. Some receiver and/or source lines and/or receiver and/or source spacings are larger and some are smaller to provide a higher quality wavefield reconstruction when covering a larger total area or for a similar total area of seismic data acquisition while providing a wavefield that is optimally sampled by the receivers and sources so that the wavefield reconstruction is suitable for subsurface imaging needs.

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SEISMIC DATA ACQUISITION USING DESIGNED NON-UNIFORM RECEIVER SPACING

FIELD OF THE INVENTION

[0001] This invention relates to seismic data acquisition of geologic structures in the earth and processing the data that is useful in interpreting the geologic structures.

BACKGROUND OF THE INVENTION

[0002] Seismic data is acquired to investigate and map the structures and character of geological formations under the earth. Seismic data is typically gathered by laying out seismic receivers (e.g., geophones or similar sensors) in a survey area and directing one or more seismic sources such as vibrator trucks to move from shot point to shot point and direct seismic energy into the ground. As the seismic sources direct seismic energy into the earth where they are reflected and/or refracted by interfaces between subsurface geological formations the seismic receivers sense the resulting reflected and/or refracted energy, thereby acquiring seismic data that provides information about the geological formations under the ground. Basically a seismic source emits a wavefield that propagates down through the earth and is reflected and/or refracted by interfaces between subsurface geological formations then propagates back to the surface where the receivers detect and discretely sample the returning, ascending or upcoming wavefield.

[0003] Typically, thousands of discrete seismic receivers are used to gather seismic data. The seismic receivers are generally laid out in lines that are substantially parallel and laterally spaced at equal distances and uniformly spaced down the line. In this configuration, uniform coverage of the subsurface is achieved. It is conventional that receiver spacing along the lines is closer than the spacing between the lines and that, therefore, the wavefield detected by the sensors is less well sampled in the lateral direction (perpendicular to the receiver lines) in most seismic surveys. The normal ratio of the station spacing to the line spacing runs between 2 and 30 to 1. This means that the spacing of the receivers along the line is between half and one thirtieth the spacing between parallel receiver lines. This is normally due to the costs and expense of adding additional receiver lines that can dramatically increase the expense of the survey to achieve a better sampling of the returning, ascending or upcoming wavefield.

SUMMARY OF THE INVENTION

[0004] The invention more particularly includes a method of acquiring seismic data including deploying receivers in a survey area where each receiver is laterally spaced from one another in two horizontal directions wherein the lateral spacing in at least one horizontal direction is deliberately non-uniform and wherein the spacing between any two seismic receivers in the deliberately non-uniform direction varies by a distance of at least five percent between the largest spacing and smallest spacing. The method further includes directing seismic energy into the ground and recording reflected and/or refracted seismic data with the deployed seismic receivers, recovering the measured data from the deployed seismic receivers, and reconstructing the wavefield from the recovered data.

[0005] The invention also relates to a method of acquiring seismic data including deploying receivers in a survey area and identifying seismic source points within the survey area where each source point is laterally spaced from one another in two horizontal directions wherein the lateral spacing in at least one horizontal direction is deliberately non-uniform and wherein the spacing between any two seismic source points in the deliberately non-uniform direction varies by a distance of at least five percent between the largest spacing and smallest spacing. The method further includes directing seismic energy into the ground at the source points and recording reflected and/or refracted seismic data with the deployed seismic receivers, recovering the measured data from the deployed seismic receivers, and reconstructing the wavefield from the recovered data.

[0006] A particular preferred embodiment of the present invention relates to a method of acquiring seismic data including deploying receivers in a survey area where each receiver is laterally spaced from one another in two horizontal directions and identifying source points wherein each source point is laterally spaced from one another wherein the lateral spacing for each of the source points and for each of the receivers is deliberately non-uniform in at least one horizontal direction and wherein the horizontal spacing between any two seismic receivers in the deliberately non-uniform direction varies by a distance of at least five percent between the largest spacing and smallest spacing and further wherein the horizontal spacing between any two seismic source points in the deliberately non-uniform direction varies by a distance of at least five

percent between the largest spacing and smallest spacing. The method further includes directing seismic energy into the ground from the source points and recording reflected and/or refracted seismic data with the deployed seismic receivers, recovering the measured data from the deployed seismic receivers, and reconstructing the wavefield from the recovered data.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The invention, together with further advantages thereof, may best be understood by reference to the following description taken in conjunction with the accompanying drawings in which:

[0008] Figure 1 is schematic top view of a portion of a seismic survey area showing a conventional arrangement of lines of seismic receivers with shot points;

[0009] Figure 2 is schematic top view of a portion of a seismic survey area showing one inventive arrangement of lines of seismic receivers with shot points;

[0010] Figure 3 is schematic top view of a portion of a seismic survey area showing a second inventive arrangement of lines of seismic receivers with shot points;

[0011] Figure 4 is schematic top view of a portion of a seismic survey area showing a third alternative inventive arrangement of lines of seismic receivers with shot points;

[0012] Figure 5 is schematic top view of a portion of a seismic survey area showing a fourth alternative inventive arrangement of lines of seismic receivers with shot points;

[0013] Figure 6 is schematic top view of a portion of a seismic survey area showing a fifth alternative inventive arrangement of lines of seismic receivers with variably spaced shotpoints;

[0014] Figure 7 is a is schematic top view of a portion of a seismic survey area showing a sixth alternative inventive arrangement of lines of seismic receivers with shot points;

[0015] Figure 8 is schematic top view of a portion of a seismic survey area showing a seventh alternative inventive arrangement of lines of seismic receivers with shot points;

[0016] Figure 9 is schematic top view of a portion of a seismic survey area showing a eighth alternative inventive arrangement of lines of seismic receivers with shot points;

[0017] Figure 10 is schematic top view of a portion of a seismic survey area showing a ninth alternative inventive arrangement of lines of seismic receivers with shot points; and

[0018] Figure 11 is schematic top view of a portion of a seismic survey area showing a tenth alternative inventive arrangement of lines of seismic receivers with shot points.

DETAILED DESCRIPTION OF THE INVENTION

[0019] Turning now to the preferred arrangement for the present invention, reference is made to the drawings to enable a more clear understanding of the invention. However, it is to be understood that the inventive features and concept may be manifested in other arrangements and that the scope of the invention is not limited to the embodiments described or illustrated. The scope of the invention is intended only to be limited by the scope of the claims that follow.

[0020] An exemplary conventional seismic data acquisition system is indicated by the arrow 10 in Figure 1. The seismic data acquisition system 10 comprises lines of receivers where eight such lines are shown and labeled 15A, 15B, 15C, 15D, 15E, 15F, 15G and 15H. The receiver lines are arranged substantially parallel to one another and are commonly spaced a common and uniform distance apart. Along each receiver line are a number of generally evenly spaced receivers 17, indicated by "x's". Also shown with small circles are shot points 18 at which the seismic sources would generate and direct seismic energy into the ground. As arranged, the total system width of the system 10 is S_1. The width-wise or lateral receiver line spacing between each adjacent pair of receiver lines is one seventh of S_1 and indicated as 19_{ab}, 19_{bc}, 19_{cd}, 19_{de}, 19_{ef}, 19_{fg} and 19_{gh}. In Figure 1, the receiver line spacing is such that nominally:

[0021] $19_{ab} = 19_{bc} = 19_{cd} = 19_{de} = 19_{ef} = 19_{fg} = 19_{gh}$.

[0022] In accordance with the present invention, it has been found that even or equal receiver line spacing may not be most optimal for acquiring seismic data. Noise in the data set may be most readily identified by even spacing and therefore fairly easily filtered or cancelled in post acquisition processing. But highly non-uniform or irregular spacing may actually provide better results in general. Additionally it has been found that the wavefield sensed in the lateral dimension (perpendicular to the receiver lines) by the

receivers can be better and more accurately reconstructed if the receivers are spaced in a highly non-uniform or irregular spacing.

[0023] The reason for this is the method of wavefield sampling. A uniform grid or series of lines is much like a tree farm with trees neatly laid out in rows with a common, but close spacing of each tree within a row. The gaps between the trees represent gaps in seismic data that are literally large enough to drive a tractor through it. We don't know what is in the gaps and since they extend so far, there may be something fairly large. However, where the trees are lined up, the seismic data is oversampled as a recorder may actually be turned off and the two adjacent receivers will almost certainly provide sufficient data to accurately predict what the silent recorder would have captured. What should be disturbing is that the gaps are not just between two rows, but there are gaps running at 45 degree angles and 90 degree angles to the rows. Consider the views within Arlington National Cemetery where one is seeing all of the headstones that are perfectly aligned. Many headstones are somewhat hidden by the perfect alignment in quite a few orientations. This arrangement of headstones is good for demonstrating military precision and honoring fallen soldiers, but not as good for getting as much information about the geologic subsurface with the receivers available. While a random arrangement of receivers or sources is not desired, the point of a desired non-uniform arrangement may be visualized while standing in the middle of a dense forest where one has the impression of seeing an impenetrable array of trees. From any location, there are enough trees in view to be seen in a composite as an impenetrable forest. In a tree farm that may actually have more trees than the forest allows long views that are wide enough for tractors to easily drive. The rows of trees make the hidden trees seem redundant.

[0024] The critical question is how variable can we space the lines and stations and still recover our wavefield accurately. With knowledge of the likely complexity of the subsurface, synthetic surveys may be constructed and run on computers using varying arrays of receivers and sources. Using the data acquired by the synthetic survey, a wavefield reconstruction is created and compared to the underlying model. A variety of such tests will provide guidance to designing the various spacings in the actual survey. Clearly, a sparser survey is a less expensive survey and if accuracy can be obtained at

lower cost, then a sparser survey will be undertaken that will provide the accuracy or precision needed.

[0025] Essentially, geophysicists are able to process and interpret seismic data to map the various interfaces between formations based on individual data points established by the time delay of the signal returned from the formation. The data actually forms a large plurality of interface points. The points may be seen to form a nearly continuous line along each of the interfaces in the direction of the vessel travel. Closely spaced "lines" of receivers provides higher three dimensional definition, but at considerably higher cost. Simply put, it takes a certain amount of time to deploy a line of seismic receivers and recover it from the field. Therefore, close lateral spacing of receiver lines means more labor cost and time performing the survey. While it would be preferred to properly sample the wavefield containing the echo returns with close spacing of lines and receivers, the costs associated with such a proper survey can be very costly to cost prohibitive.

[0026] Currently, geoscientists interpolate the shape of the geological interfaces in the gaps between points by using the data received by seismic receivers that are close to the gaps in question. Most interpolation algorithms are simple mathematical processes, such as basic averaging of the nearby data. With the missing information supplied by the interpolation, the data is provided to seismic processors to create an image of the geological subsurface. However, according to the present invention, it is better to reconstruct the entire wavefield in one realization. Wavefield reconstruction involves statistical linear regression analysis where a model wavefield is created from prior knowledge of the geological subsurface and is iteratively refined based on actual measured data from the seismic survey. Through the regression analysis, the L0 and L1 norms are calculated for each comparison between the model wavefield and the actual data such that the model wavefield is iteratively corrected until calculated L0 and L1 norms are minimized. At L0 and L1 norm minimization, the model wavefield is believed to most accurately represent the actual wavefield that would have ascended from the geological subsurface if data could have been recorded at every possible location. Thus, at this point, the model wavefield or reconstructed wavefield may provide data from the entire surveyed area including all gaps between points and from any point or points

within the survey area. Data from the reconstructed wavefield is then processed in the conventional manner to create a three dimensional image of the subsurface structures. With an accurately reconstructed wavefield, the shape of the geological interfaces can be more properly imaged. It should be recognized that wavefield reconstruction utilizes data from receivers well distant from gaps as the iterative process attempts to "fit" the model wavefield to the larger data set. Wavefield reconstruction algorithms model the wavefield based upon its components and the physical properties of the survey area being sampled. In the present invention, prior knowledge of the geological substructures in the design of the receiver array and especially the non-uniform spacing of the receiver array enhances and enlarges the strength of such algorithms to obtain a more accurate reconstructed wavefield with the same number or fewer data points. Wavefield reconstruction also takes advantage of the truism that the simplest model of the earth that accurately fits the measured data is likely the most correct model. Thus, by minimizing the L0 and L1 norms, the complexity of the geologic model that accurately matches the measured data is also minimized and provides a very useful reconstructed wavefield for imaging.

[0027] The wavefield reconstruction fidelity is dependent on the receiver spacings used in the sampling of the wavefield. It has been found that the wavefield sensed in the lateral dimension (perpendicular to the line of receivers) by the receivers can be better reconstructed if the receivers are spaced in a non-uniform or irregular spacing. The estimation can typically be quite accurate depending on the complexity of the geological interface. A flat interface is quite easy.

[0028] Consider the situation where someone desires to determine the contour of the bottom of a back yard pond where the water is dark and the person does not want to get wet. Since we know before hand that a pool normally has a generally flat or rounded bottom with some small variation in depth from one end to the other and that the deepest points will be away from the edges and somewhere centered within the pool, we can use this knowledge to take some short cuts. Using this knowledge, we can determine that a solution would be to take a yard stick and dip it into the pond at various places in the pond and develop a rough, but fairly accurate model of the bottom of the pond. This use of prior knowledge of the general type and nature of the pool allows us to model the

problem and determine a method that would sample less densely and just a few profiles allow us to determine a very accurate representation of the pool bottom.

[0029] Next, let us consider what would happen if the pool is now a murky fishing pond. Now we can not make the assumption that the pool bottom is flat or smooth in fact more then likely the bottom is quite rough with rocks logs and other trash. If we look around the area on the surface we might conclude the bottom could have logs, brush or rocks. In this case, if the bottom is a very rough surface or unpredictable surface, the contour of the bottom is much more complicated and challenging to survey with few samples. Now a more densely sampled survey with more sampling profiles would be needed to accurately measure the subsurface. This kind of complication routinely occurs in seismic surveys.

[0030] The present invention uses some relatively simple logic to provide quality subsurface maps, models or images of geological interfaces, but creates such maps, models or images from data that can be acquired in a more efficient manner than current techniques using interpolation methods that are currently available. Returning to the backyard fishing pond example, the present invention would be practiced in a very small scale but analogous example where the surveyor would make several depth measurements fairly close together to determine how smooth or continuous the bottom is. The surveyor would then combine this knowledge with a review of the observations from the surface and determine the likelihood of debris and logs or rocks in the pond. If the bottom were to be smooth or flat, then the remainder of the measurements may be few and spread out. The depth between actual measurements may be confidently interpolated. For example, the depth at a point half way between two actual measurements two feet apart that are 16 inches and 18 inches may be confidently interpolated to be 17 inches. One need NOT make the actual measurement, especially if the time or cost to make such measurement is substantial. On the other hand, an efficient survey design could be developed that would provide a reasonably accurate model of a more complicated bottom structure, but the measurements would be closer together. The critical difference is between the concepts of interpolation and reconstruction. Interpolation is a mathematical process that does not use prior knowledge of what is being sampled to calculate the new value. In our example, most algorithms will come up

with 17 inches regardless of the subsurface because that is the average of the two measurements. Interpolation takes no account of the prior knowledge of what is being sampled. This works with a pool bottom that is smoothly varying but if we consider a rough bottom of brush, rocks and logs, then we cannot confidently interpolate the answer. In this case we must reconstruct the bottom through using prior knowledge of the likeliness of the roughness on the bottom and proper sampling of the data we do sample.

[0031] Back to a seismic survey, applying the aforementioned concept becomes much more complicated for seismic data acquisition in that portions of the survey area may be simpler geological structures and other portions may have more complicated structures. Typically, a seismic data survey will survey an area where some data has already been collected, but the data is not sufficiently rich to resolve potential hydrocarbon deposits for drilling. This data from prior surveys maybe sparse 3D or 2D seismic data or even from well logs or other geological observations. Data from prior surveys may provide enough information to determine the complexity of the geological structures and create models of the substructures sufficient to analyze the "spacing" of actual data necessary to get a sufficiently accurate image of the geological substructures that are sufficient to justify the risk for spending millions of dollars on exploration wells. So, this invention is about getting sufficient volumes or density of seismic data to decide and plan a drilling program while minimizing the cost of gathering the seismic data.

[0032] Referring now to Figure 2, a seismic data acquisition system is indicated by the arrow 20 where eight receiver lines comparable to the eight receiver lines of Figure 1. However, the receiver lines 25A, 25B, 25C, 25D, 25E, 25F, 25G and 25H are arranged to be spaced from one another by an uncommon or irregular spacing. Along each receiver line are a number of generally evenly spaced seismic receivers 27. As deployed for seismic data collection in Figure 2, the total system width S_2, is wider than S_1. As with system 10 in Figure 1, each pair of receiver lines have an individual receiver line spacing indicated as 29_{ab}, 29_{bc}, 29_{cd}, 29_{de}, 29_{ef}, 29_{fg} and 29_{gh}. While one or more receiver line spacings may be the same as other receiver line spacings, not all are the same. Preferably, at least one receiver line spacing 29 is equal to or less that the receiver line spacing 19 of the system 10 shown in Figure 1. Specifically, spacing 29_{cd} is the same as spacing 19_{cd} while spacing 19_{ab} is slightly larger than spacing 19_{ab} and spacing 29_{bc} is

quite a bit larger than spacing 19_{bc}. At least one receiver line spacing must be less than or equal to or very close to equal to the receiver line spacing 19 of the System 10 in Figure 1 in order to provide the accuracy of the data collected by inventive system 20. Since S_2 is wider than S_1, the area to be surveyed will be surveyed in less time at lower cost with an inventive system 20 configuration as compared to a conventional system 10 configuration as the survey area will be covered by fewer receiver lines overall. The range at which a configuration may be made wider without losing comparable accuracy depends on the complexity of the subsurface structures in the area to be surveyed. Based upon current studies, comparable accuracy may be obtained with S_2 being 10 to 20 percent wider and current estimates are that 35% wider provides data that is accurately processible. The same current analysis indicates that above 35% may create unacceptable holes in the data in certain complex substructures, but upwards of 50% and as high as 90% is possible and likely in fairly simple geologic structures and in seismically benign areas.

[0033] Turning now to Figure 3, the inventive technique of the present invention may be used to another and perhaps opposite end. The first end was to create an accurate model of the geological substructures with a sparser array of receiver lines. The opposite end is to provide a much more precise model of the geological substructures without giving up productivity. In Figure 3, a system 30 is shown where eight receiver lines comparable to the eight receiver lines of Figure 1 and of Figure 2. Like system 20, the receiver lines 35A, 35B, 35C, 35D, 35E, 35F, 35G and 35H are arranged to be spaced from one another and by an uncommon or irregular spacing. However, the lateral width S_3 of system 30 is approximately the same as S_1, the width of conventional system 10. Along each receiver line is a number of generally evenly spaced seismic receivers 37. Like in System 10 in Figure 1, each pair of receiver lines have an individual receiver line spacing indicated as 39_{ab}, 39_{bc}, 39_{cd}, 39_{de}, 39_{ef}, 39_{fg} and 39_{gh}. While one or more receiver line spacings may be the same as other receiver line spacings, not all are the same. Preferably, at least one receiver line spacing 39 is less that the receiver line spacing 19 of system 10 shown in Figure 1 while one or more receiver line spacings 39 are larger than the common receiver line spacing 19. However, since S_3 is essentially the same as S_1, the area to be surveyed will take about the same number of receiver lines and about the same amount of time with the inventive system 30 configuration as compared to the

conventional system 10 configuration. What is key is that having one or two or three receiver line spacings 39 being less than the common receiver line spacing 19 provides greater wavefield reconstruction accuracy. The closely spaced receiver line spacings 39_{ab} and 39_{ef} provide accurate data and provide details for the wavefield reconstruction algorithms and processors to more accurately estimate the shape of the geological interfaces in the larger gaps represented by spacings 39_{bc} and 39_{de}. System 30 essentially provides higher detail without higher cost.

[0034] In other more preferred embodiments, the receivers themselves do not have to be equally spaced along the receiver lines. As shown in Figures 4 and 5, the receiver lines are unequally spaced in the same manner and spacing as system 20 in Figure 2. In Figure 4, the system 40 the spacing of the receivers along a receiver line is shown to be non-uniform. It should be seen that all of the receiver lines have the same common, but unequal spacing. Thus, the receivers are all in common lines or straight columns from top to bottom of the drawing. In Figure 5, the system 50 has the same non-uniform receiver line spacing as system 20 in Figure 2, but the spacing of the receivers along the receiver line is not only non-uniform, but not the same from receiver line to receiver line. In other words, the receivers do not line up in straight columns.

[0035] In Figure 6, the system 60 does not include alignment in any direction and are two dimensionally non-uniform. It should be noted that the sources through all of the embodiments from system 20 to system 60 include sources that have been maintained in common regular spacing. Referring to Figure 7, the system 70 at first appears to be exactly the same as system 20. All of the receivers are aligned and ordered in the same common spacing. However, a closer inspection reveals that the center column of sources are closer to the left column and further from the right column. Essentially, system 70 shows that the sources may also be arranged in the non-uniform arrangements of the receivers.

[0036] Referring to Figure 8, the next level of complication of source spacing is demonstrated by system 80 which includes varied spacing vertically, but all columns have the same non-uniform spacing.

[0037] Referring to Figure 9, system 90 shows a slightly more complicated arrangement for the sources where they remain in straight columns, but the columns are

non-uniformly spaced, the spacing vertically within the columns is no-uniform and each column is differently non-uniformly spaced.

[0038] System 100 in Figure 10 shows an additional bit of complexity where the sources are fully varied in both vertically and horizontally in the Figure, but on the ground in both the x and y directions.

[0039] What should be recognized in systems 70 through 100 is that the receivers have all be uniform in both directions. Many combinations of non-uniform spacings for both the sources and receivers are possible. The permutations of a few combinations of spacings for both sources and receivers have been described above. The most complicated combination is shown in Figure 11 where system 110 includes the sources have full two dimensional non-uniformity and the receivers being fully non-uniform in two dimensions. The following table suggests that more combinations are possible and is presented to avoid presenting many extra drawings that are unnecessary to the understanding of the present invention:

Figure	Source	Receiver
Prior Art Fig 1	Uniform	Uniform
Fig 2 - wider	Uniform	Non-Uniform LINES with uniform spacing along lines
Fig 3 - high definition	Uniform	Non-Uniform LINES with uniform spacing along lines
Fig 4	Uniform	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines
Fig 5	Uniform	Non-Uniform LINES with Irregular Non-Uniform spacing along lines
Fig 6	Uniform	Non-Uniform in 2D
Fig 7	Non-Uniform LINES with uniform spacing along lines	Uniform
	Non-Uniform LINES with	Non-Uniform LINES

	uniform spacing along lines	with uniform spacing along lines
	Non-Uniform LINES with uniform spacing along lines	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines
	Non-Uniform LINES with uniform spacing along lines	Non-Uniform LINES with Irregular Non-Uniform spacing along lines
	Non-Uniform LINES with uniform spacing along lines	Non-Uniform in 2D
Fig 8	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines	Uniform
	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines	Non-Uniform LINES with uniform spacing along lines
	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines
	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines	Non-Uniform LINES with IRRegular Non-Uniform spacing along lines
	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines	Non-Uniform in 2D
Fig 9	Non-Uniform LINES with Irregular Non-Uniform spacing along lines	Uniform
	Non-Uniform LINES with Irregular Non-Uniform spacing along lines	Non-Uniform LINES with uniform spacing along lines
	Non-Uniform LINES with Irregular Non-Uniform spacing along lines	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines
	Non-Uniform LINES with Irregular Non-Uniform	Non-Uniform LINES with Irregular

	spacing along lines	Non-Uniform spacing along lines
	Non-Uniform LINES with Irregular Non-Uniform spacing along lines	Non-Uniform in 2D
Figure 10	Non-Uniform in 2D	Uniform
	Non-Uniform in 2D	Non-Uniform LINES with uniform spacing along lines
	Non-Uniform in 2D	Non-Uniform LINES with REGULAR Non-Uniform spacing along lines
	Non-Uniform in 2D	Non-Uniform LINES with Irregular Non-Uniform spacing along lines
Figure 11	Non-Uniform in 2D	Non-Uniform in 2D

[0040] The ability to adequately reconstruct the wavefield will then depend on the design of the source and receiver spacings in both dimensions. Care must be taken in designing such a configuration so that the wavefield does not become under sampled for the subsurface objective being imaged. This can be modeled prior to acquisition of the survey to determine the required station and line spacing.

[0041] It should also be understood that receiver lines and source lines may still be implanted with varying degrees of freedom, but noting that there are no particular requirement that the orientation of the source line and receiver lines be orthogonal for the wavefield reconstruction to work. The lines may be oriented with variations in direction, patterns or layout. Some of the more common in the industry are the brick, zig-zag, slash and inline survey designs. Non-uniform line and station spacing for wavefield reconstruction work equally well with each of these survey technique.

[0042] Finally, the scope of protection for this invention is not limited by the description set out above, but is only limited by the claims which follow. That scope of the invention is intended to include all equivalents of the subject matter of the claims. Each and every claim is incorporated into the specification as an embodiment of the

present invention. Thus, the claims are part of the description and are a further description and are in addition to the preferred embodiments of the present invention. The discussion of any reference is not an admission that it is prior art to the present invention, especially any reference that may have a publication date after the priority date of this application.

CLAIMS

1. A method of acquiring seismic data comprising the steps of:
   a. deploying receivers in a survey area;
   b. identifying seismic source points within the survey area;
   c. directing seismic energy into the ground at the source points and recording reflected and/or refracted seismic data with the deployed seismic receivers;
   d. recovering the measured data from the deployed seismic receivers; and
   e. reconstructing the wavefield from the recovered data;

wherein each source point or each receiver is laterally spaced from adjacent source points or receivers, respectively, in two horizontal directions wherein the lateral spacing in at least one horizontal direction is deliberately non-uniform and wherein the spacing between any two seismic source points or receivers, respectively, in the deliberately non-uniform direction varies by a distance of at least five percent between the largest spacing and smallest spacing.

2. The method according to claim 1, wherein the seismic sources or receivers are spaced in a deliberately non-uniform spacing in both horizontal directions where the largest spacing is at least five percent larger than the smallest spacing in at least one direction.

3. The method according to claim 1, wherein the seismic sources or receivers are spaced in one horizontal direction in a generally uniform spacing, wherein at least eighty percent of the seismic sources or receivers are spaced within one percent of the same spacing along the uniform spacing direction.

4. The method according to claim 1, wherein at least twenty percent of the seismic sources or receivers, optionally at least fifty percent, such as at least seventy percent of the seismic sources or receivers, are spaced more than ten percent,

optionally more than fifteen percent, more than twenty percent, more than twenty-five percent or more than thirty percent, further apart from adjacent seismic sources or receivers, respectively, in the non-uniform spacing direction than the smallest spacing between adjacent seismic sources or receivers, respectively, in the non-uniform direction.

5. A method as claimed in any preceding claim wherein both the receivers and seismic sources are laterally spaced as claimed.

6. A method of acquiring seismic data comprising the steps of:
   a. deploying receivers in a survey area where each receiver is laterally spaced from one another in two horizontal directions wherein the lateral spacing in at least one horizontal direction is deliberately non-uniform and wherein the spacing between any two seismic receivers in the deliberately non-uniform direction varies by a distance of at least five percent between the largest spacing and smallest spacing;
   b. directing seismic energy into the ground and recording reflected and/or refracted seismic data with the deployed seismic receivers;
   c. recovering the measured data from the deployed seismic receivers; and
   d. reconstructing the wavefield from the recovered data.

7. The method according to claim 6, wherein the receivers are spaced in a deliberately non-uniform spacing in both horizontal directions where the largest spacing is at least five percent larger than the smallest spacing in at least one direction.

8. The method according to claim 6, wherein the receivers are spaced in one horizontal direction in a generally uniform spacing, wherein at least eighty

percent of the seismic receivers are spaced within one percent of the same spacing along the uniform spacing direction.

9. The method according to claim 6, wherein at least twenty percent of the deployed receivers, optionally at least fifty percent, such as at least seventy percent of the deployed receivers, are spaced more than ten percent, optionally more than fifteen percent, more than twenty percent, more than twenty-five percent or more than thirty percent, further apart in the non-uniform spacing direction than the smallest spacing between receivers in the non-uniform direction.

10. A method of acquiring seismic data comprising the steps of:
    a. deploying receivers in a survey area and identifying seismic source points within the survey area where each source point is laterally spaced from one another in two horizontal directions wherein the lateral spacing in at least one horizontal direction is deliberately non-uniform and wherein the spacing between any two seismic source points in the deliberately non-uniform direction varies by a distance of at least five percent between the largest spacing and smallest spacing;
    b. directing seismic energy into the ground at the source points and recording reflected and/or refracted seismic data with the deployed seismic receivers;
    c. recovering the measured data from the deployed seismic receivers; and
    d. reconstructing the wavefield from the recovered data.

11. The method according to claim 10, wherein the sources are spaced in a deliberately non-uniform spacing in both horizontal directions where the largest spacing is at least five percent larger than the smallest spacing in at least one direction.

12. The method according to claim 10, wherein the sources are spaced in one horizontal direction in a generally uniform spacing, wherein at least eighty percent of the seismic sources are spaced within one percent of the same spacing along the uniform spacing direction.

13. The method according to claim 10, wherein at least twenty percent of the deployed sources, optionally at least fifty percent, such as at least seventy percent of the deployed sources, are spaced more than ten percent, optionally more than fifteen percent, twenty percent, twenty-five percent or thirty percent, further apart in the non-uniform spacing direction than the smallest spacing between sources in the non-uniform direction.

14. A method of acquiring seismic data comprising the steps of:
    a. deploying receivers in a survey area where each receiver is laterally spaced from one another in two horizontal directions and identifying source points wherein each source point is laterally spaced from one another wherein the lateral spacing for each of the source points and for each of the receivers is deliberately non-uniform in at least one horizontal direction and wherein the horizontal spacing between any two seismic receivers in the deliberately non-uniform direction varies by a distance of at least five percent between the largest spacing and smallest spacing and further wherein the horizontal spacing between any two seismic source points in the deliberately non-uniform direction varies by a distance of at least five percent between the largest spacing and smallest spacing;
    b. directing seismic energy into the ground from the source points and recording reflected and/or refracted seismic data with the deployed seismic receivers;
    c. recovering the measured data from the deployed seismic receivers; and
    d. reconstructing the wavefield from the recovered data.

15. The method according to claim 14, wherein the spacing for adjacent receivers and the spacing for adjacent source points are spaced in a deliberately non-uniform spacing in both horizontal directions where the largest spacing for the receivers and the largest spacing for the source points is at least fifty percent larger than the smallest spacing for each.

16. The method according to claim 14, wherein at least twenty percent, optionally at least fifty percent, such as at least seventy percent, of the deployed receivers and at least twenty percent, optionally at least fifty percent, such as at least seventy percent, of the source points are spaced more than ten percent, optionally more than fifteen percent, twenty percent, twenty-five percent or thirty percent, further apart in the non-uniform spacing direction than the smallest spacing between receivers and sources in the non-uniform direction.

Figure 1

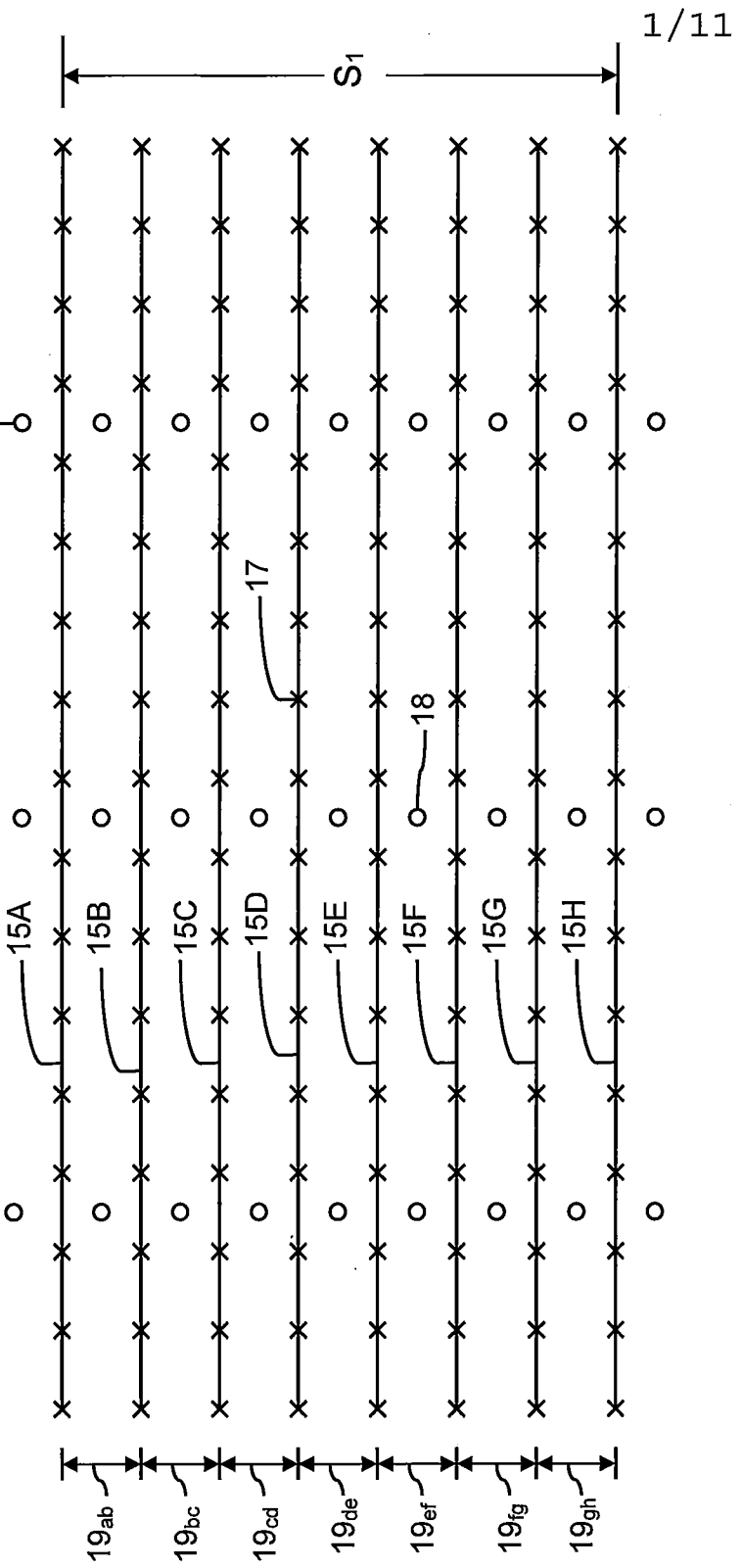

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S_1
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15D
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19_{gh}

Figure 2

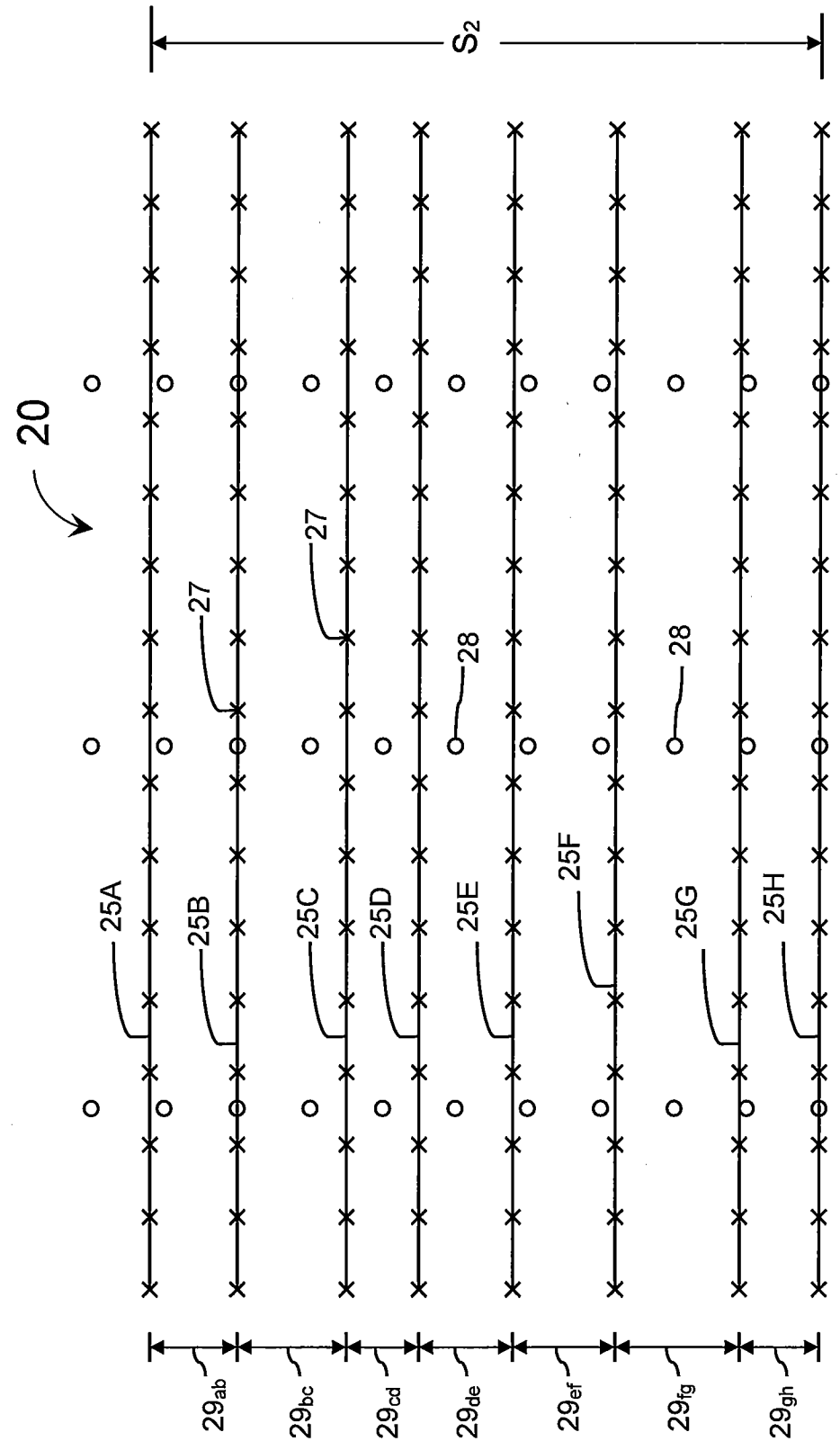

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Figure 3

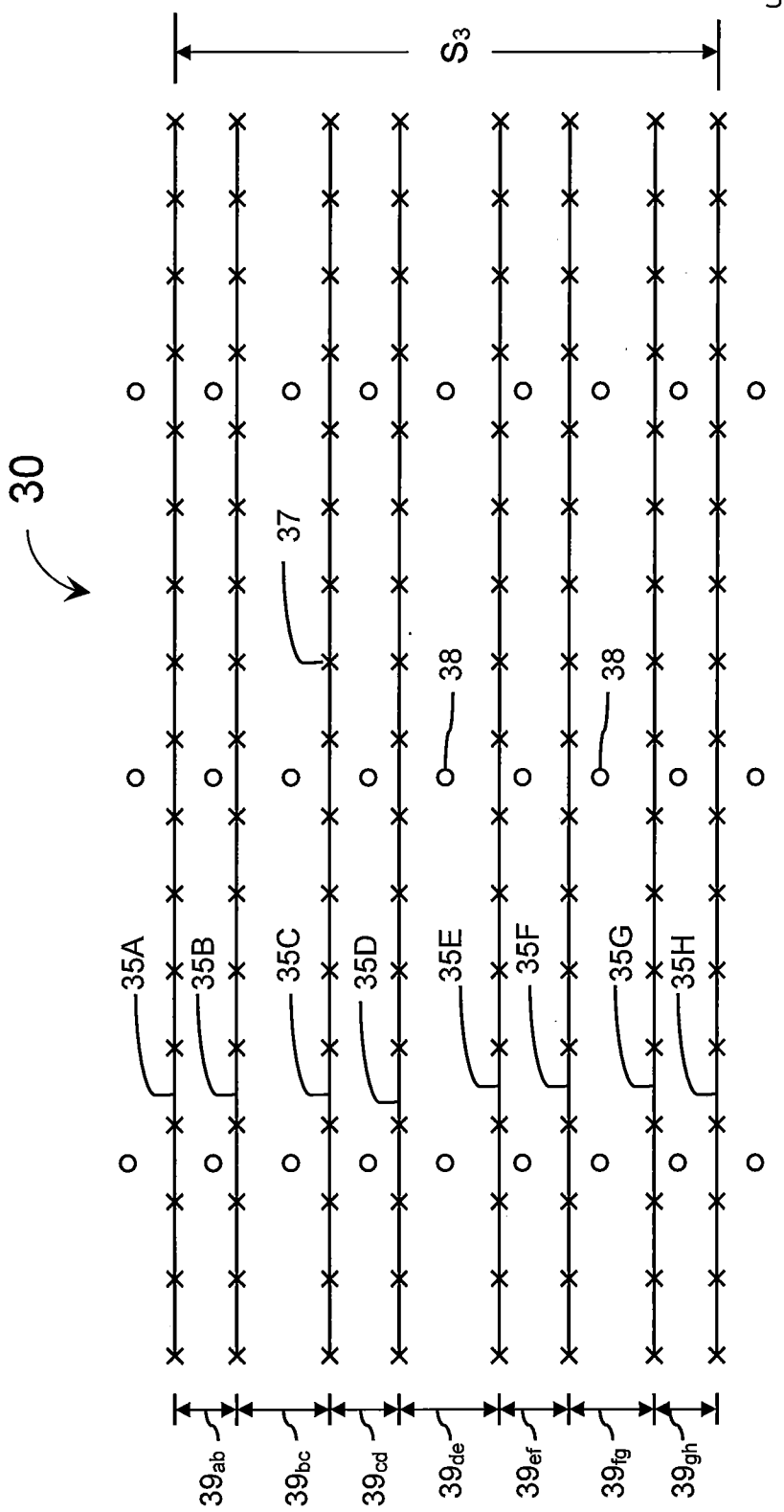

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Figure 4

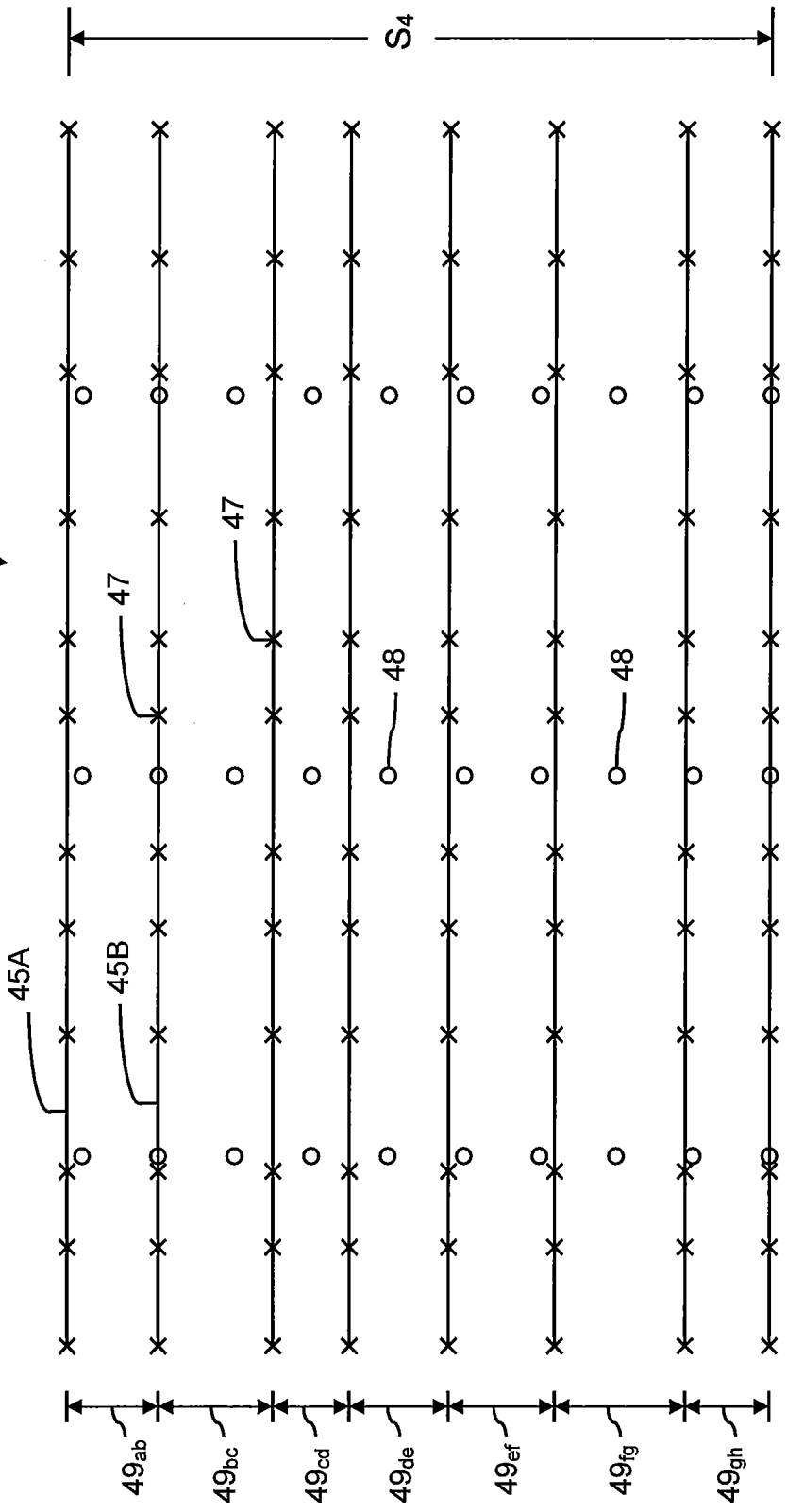


Figure 5

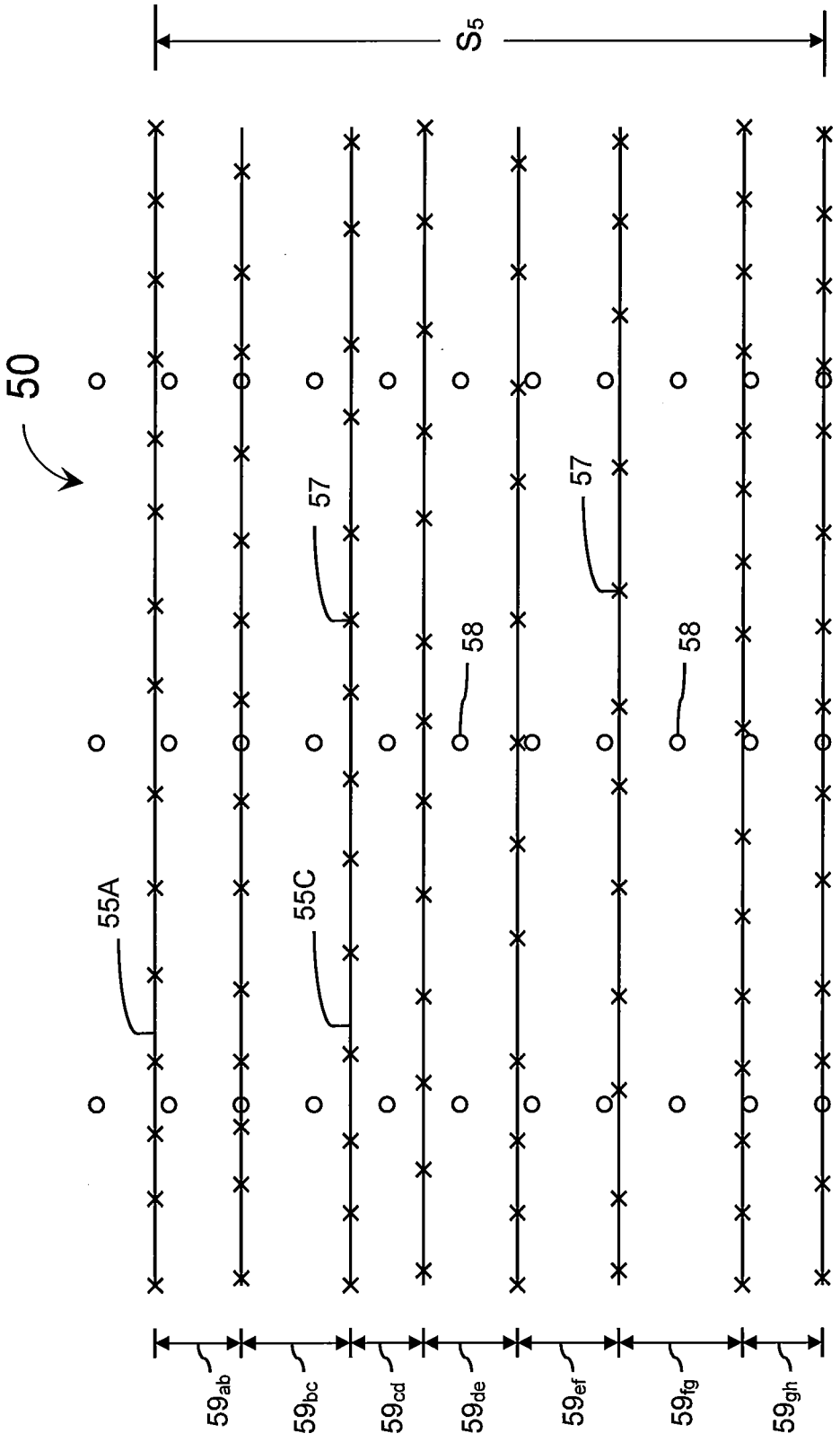


Figure 6

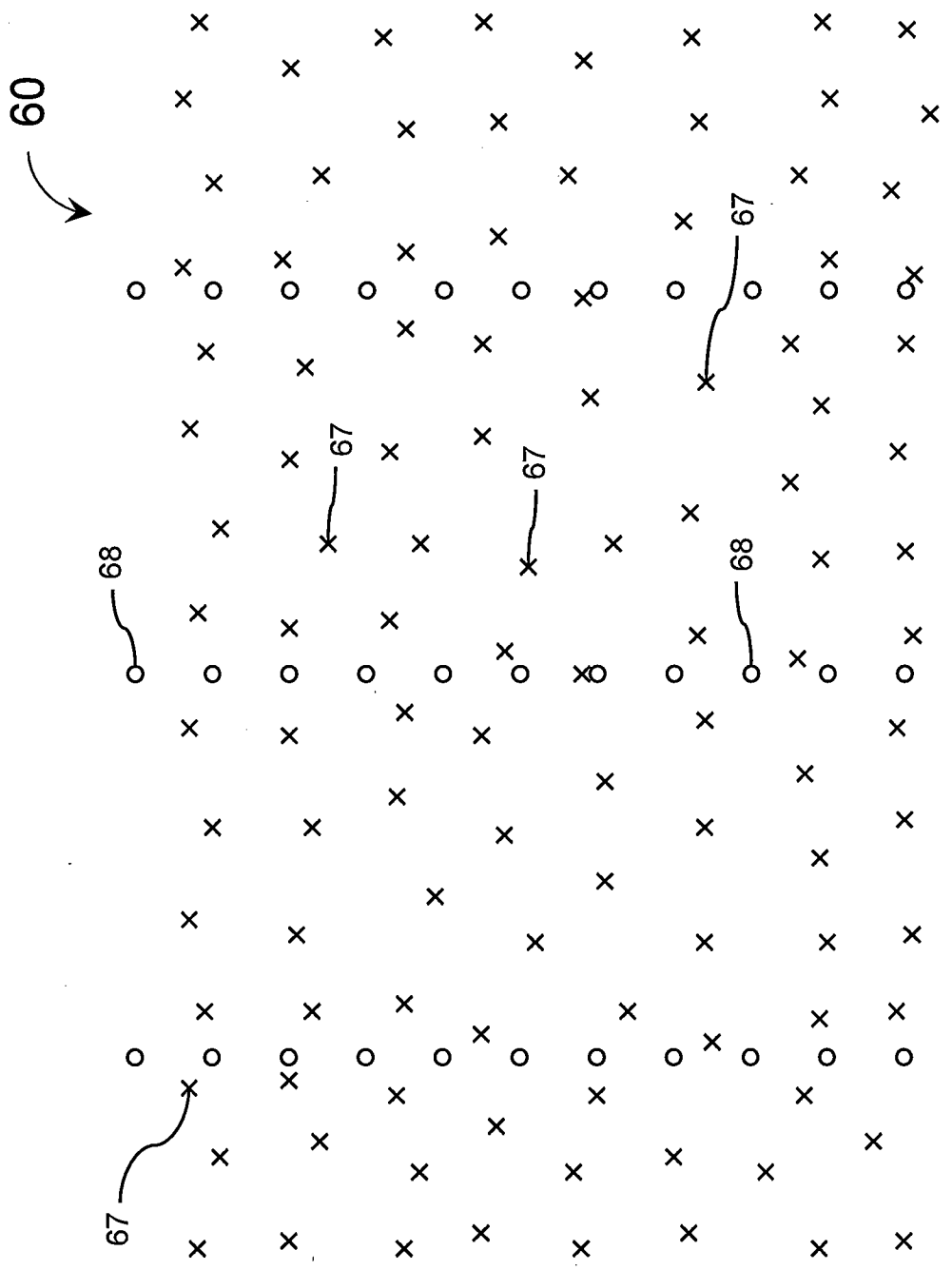


Figure 7

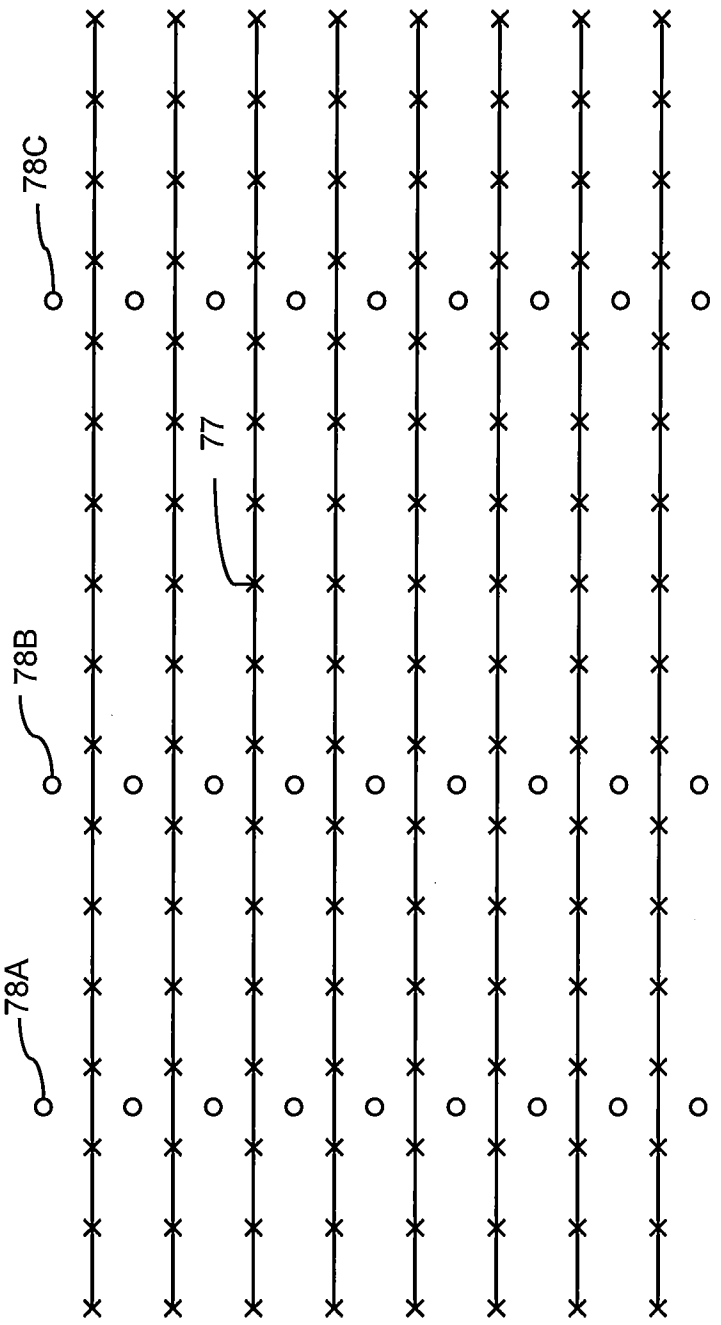


Figure 8

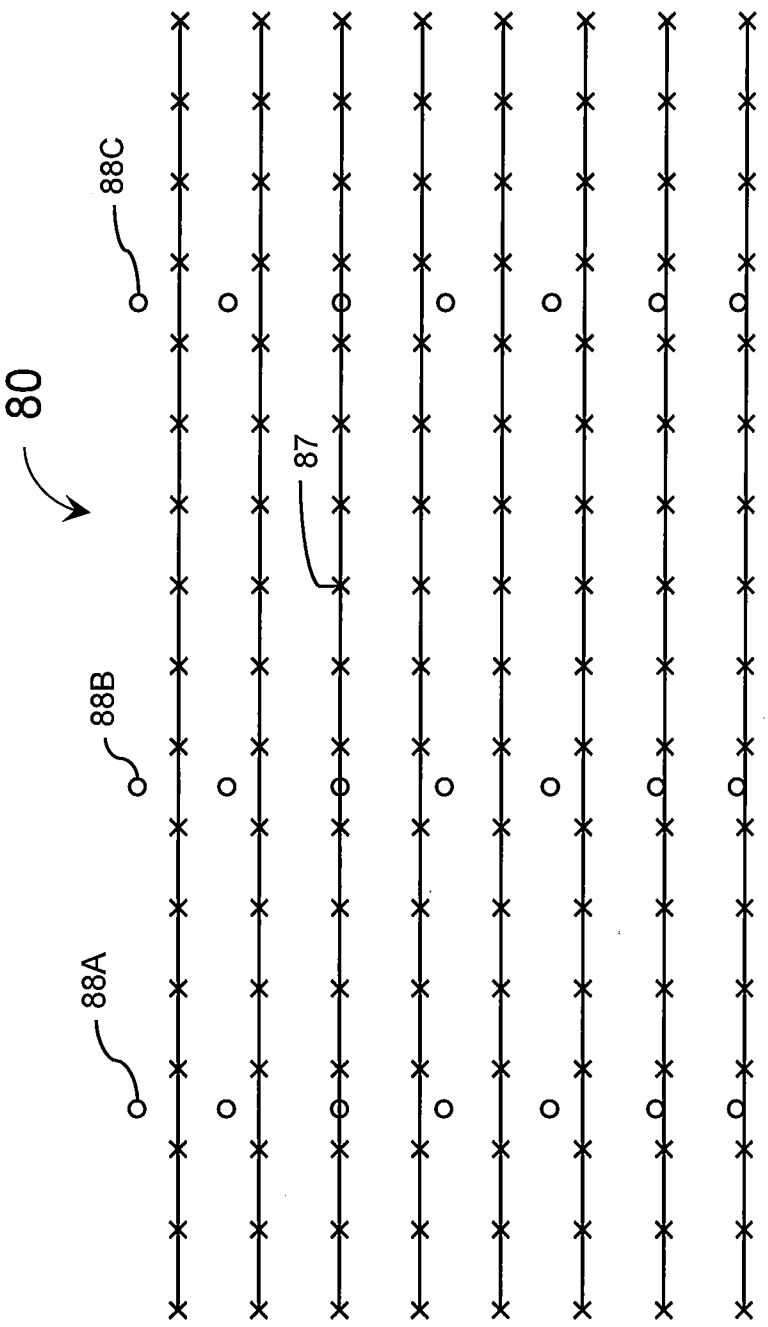


Figure 9

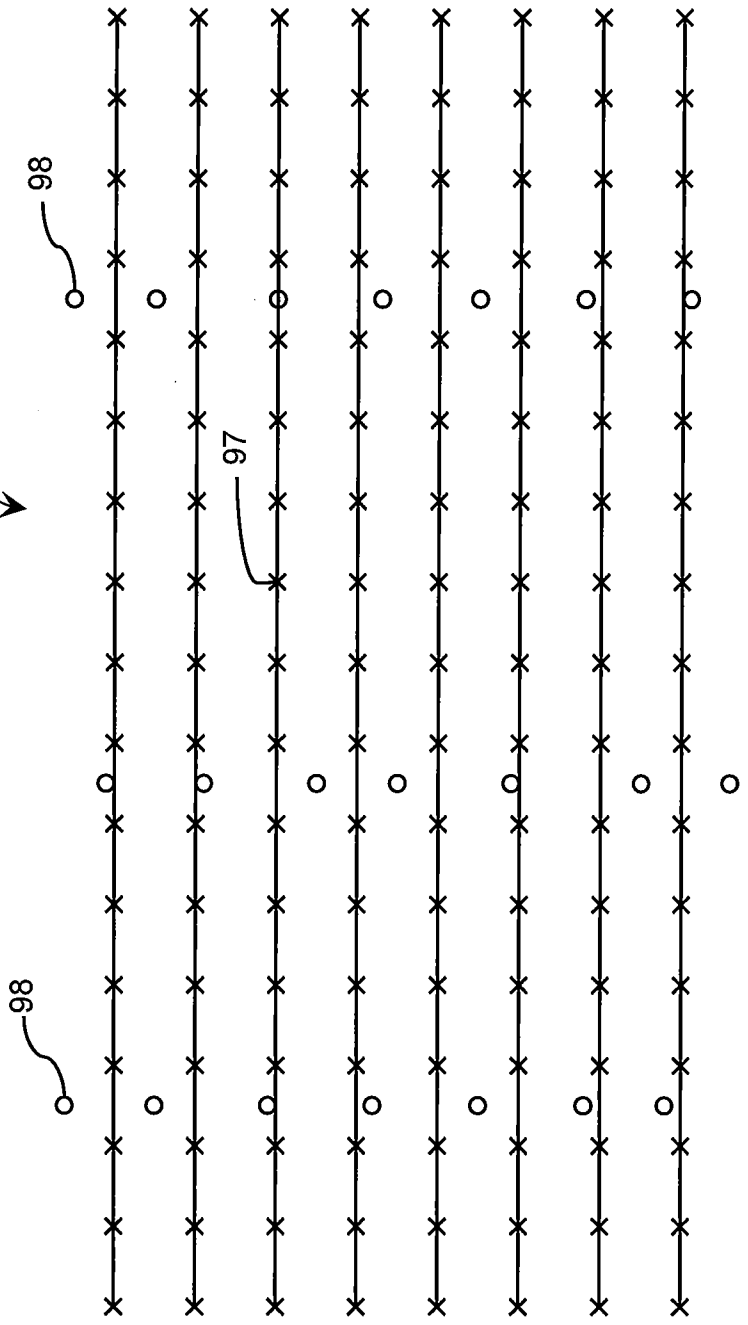


Figure 10

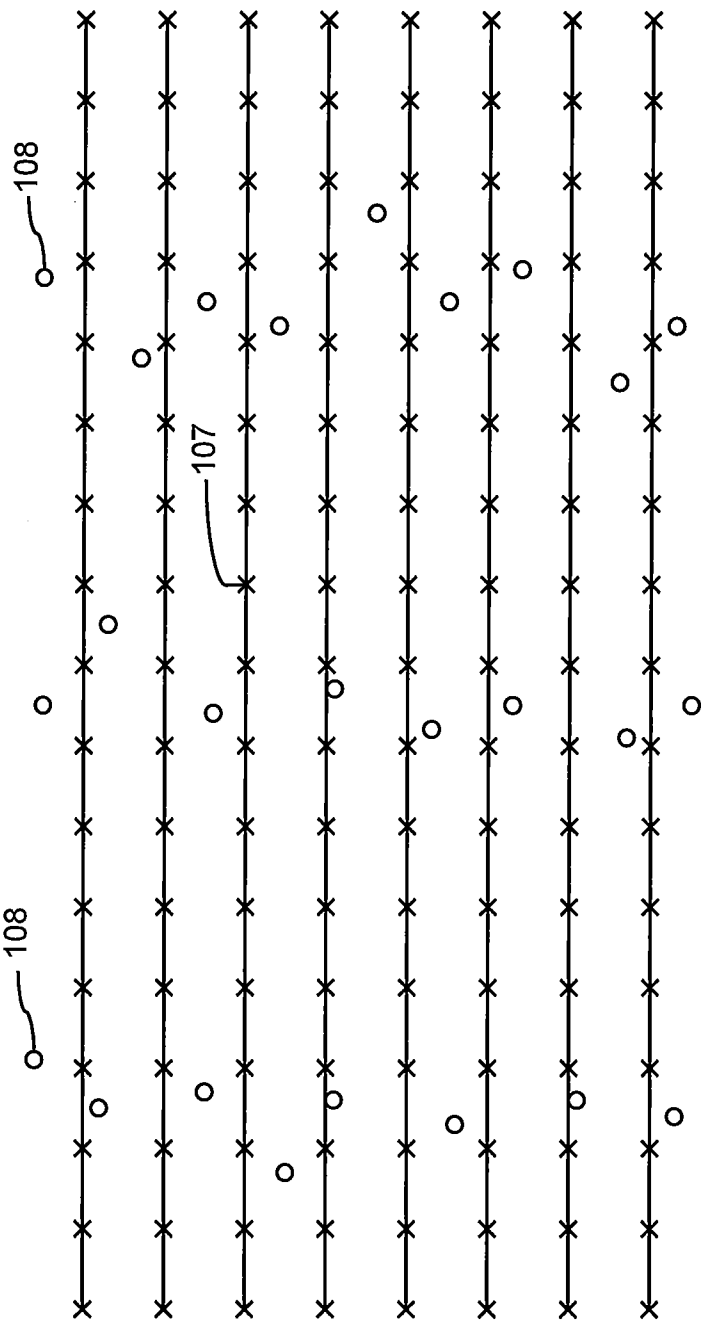
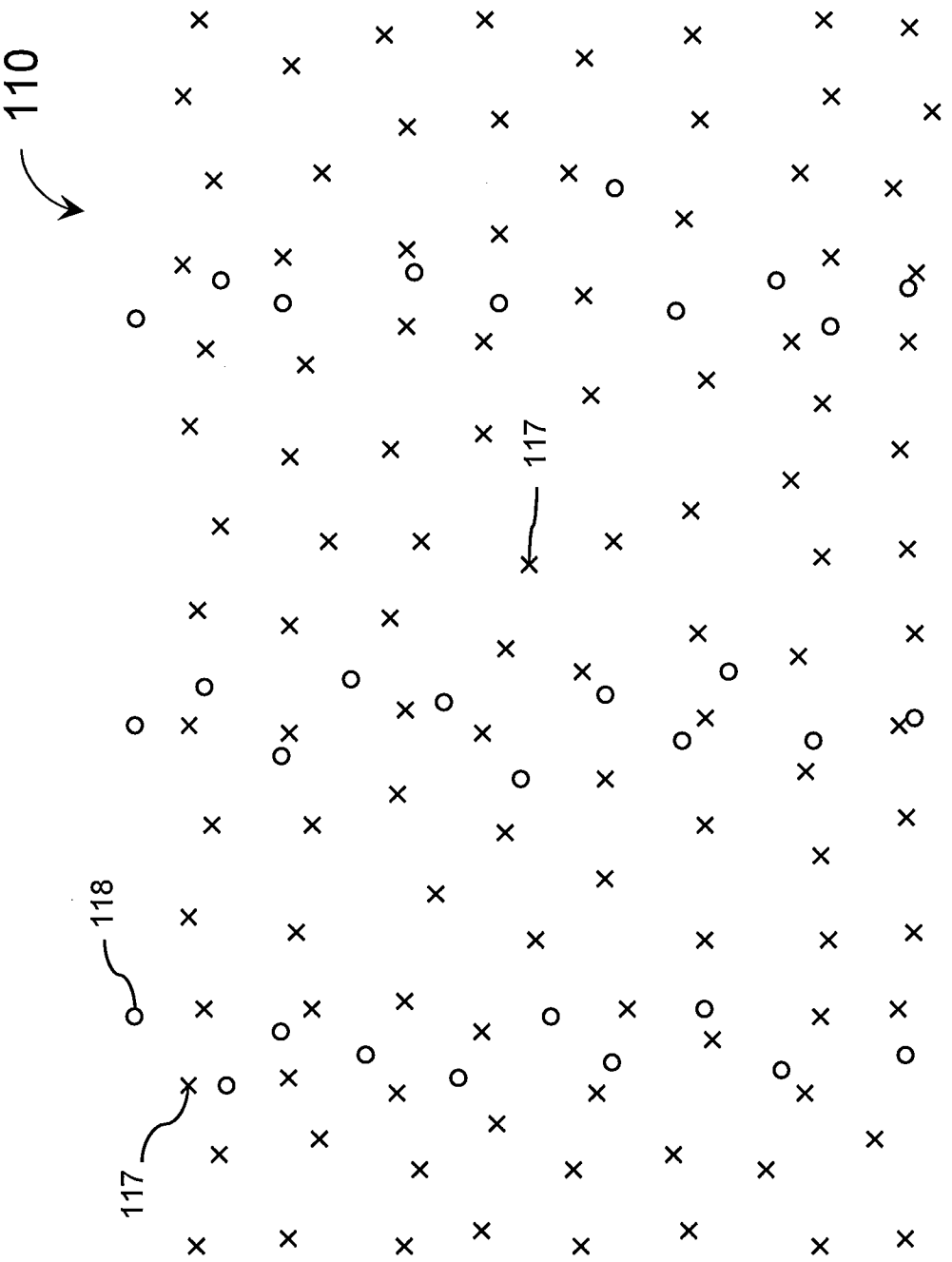


Figure 11



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/039635

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01V 1/20 (2011.01)
USPC - 367/56
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - G01V 1/13, 1/20, 1/28, 1/32, 1/36 (2011.01)
USPC - 343/844; 367/15, 16, 19, 20, 21, 38, 40, 56, 58, 154, 177

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Patbase, Google Patent, Google

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2,906,363 A (CLAY, JR) 29 September 1959 (29.09.1959) entire document	1-16
A	US 7,646,671 B2 (PAN et al.) 12 January 2010 (12.01.2010) col. 5, lines 10-15; col. 4, lines 59-61	1-16
A	US 5,517,463 A (HORNBOSTEL et al.) 14 May 1996 (14.05.1996) col. 5, lines 1-19; Fig.5	1-16
A	US 6,493,636 B1 (DEKOK) 10 December 2002 (10.12.2002) col. 10, lines 56-65; col. 14, lines 56-67	1-16

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
04 October 2011	25 OCT 2011
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)