HOW DO WE DESIGN 3D SURVEYS?

ROBIN R. WYE
VP Geophysics, GAPS Ltd.
Bogotá, Colombia

SUMMARY

The following paper shows a set of design routines applied in the analysis of seismic targets. It trends to be just an approximation to better key parameters determination and calculation to optimize the cost-benefit ratio of a well-programmed seismic survey.

There are several experiences in field design, associated to the integration of several technical information supplied by exploration companies, which have given good results in both imaging and work efficiency. For this reason, we understand the importance of a detailed analysis of parameters to obtain the best possible 3D image of the current target and its overlaid strata.

INTRODUCTION

Although it is not straight-forward to carry out a seismic design using a standard algorythm, these steps will cover the main variables and parameters to achieve a good analysis, with all necessary and available information.

Step 1 – Design Objectives

"The objective of the 3D survey is to map the structural/stratigraphic XX horizon(s) to a resolution of VV metres vertically and horizontally. To do this we also require imaging of structural dips of up to YY degrees, and we require a full fold, fully migrated area of ZZ sq kms. The objective of the mapping is to achieve costs savings by.......(economic exploration objective)."

"Key processes that will be used on the data will be ....stack, DMO, FK demultiple, PSTM, PSDM, AVO, Inversion, ... etc."

From these objective statements all other factors are derived – with the help of a little additional data and some analysis.

Step 2 – Key Parameters Determination

1. MIGRATION APERTURE (MA):

This analysis could be performed using 4 methods:

A. **Straight ray calculation**: assumes homogeneous earth, therefore is normally wrong. OK if velocity only changes very slowly with depth.

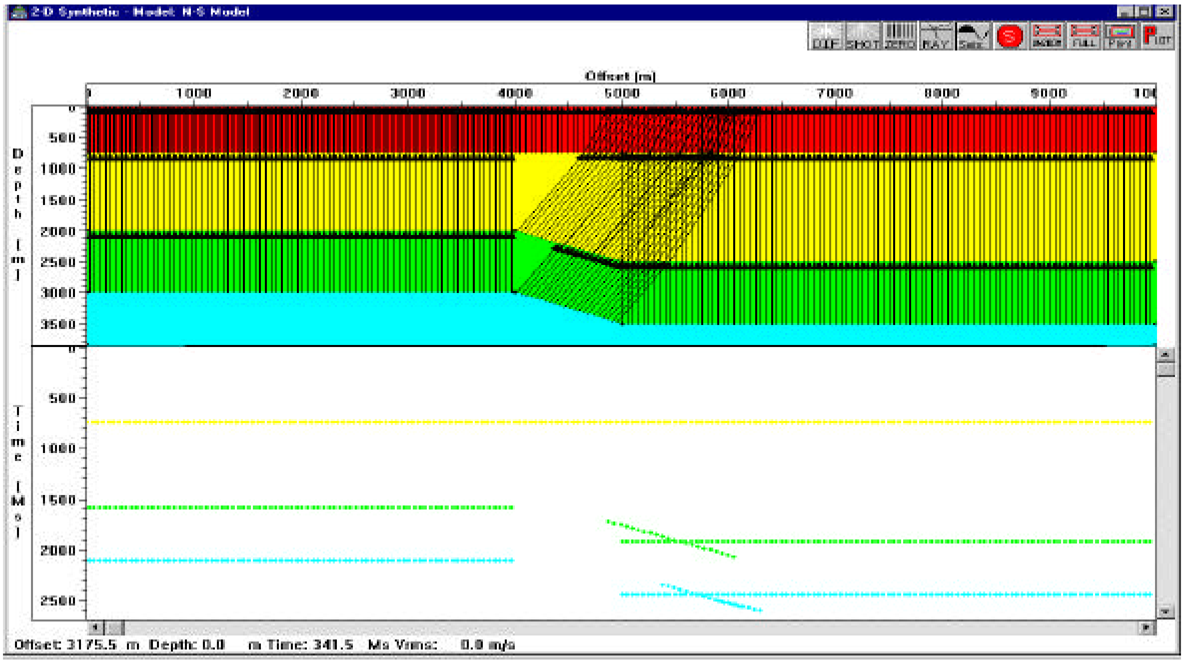
$$MA = Z_{obj} * \tan(q_{\max}) \qquad \text{(Ec. 1)}$$

B. **Curved ray equation**: assumes a linear increase in interval velocity with depth. Works in sedimentary basins where burial compaction gives approximately linear velocity/depth approximations Vz = Vo + kZ
(Vo = velocity at Z=0, Z=depth below surface). Then the curved ray migration aperture can be calculated by:

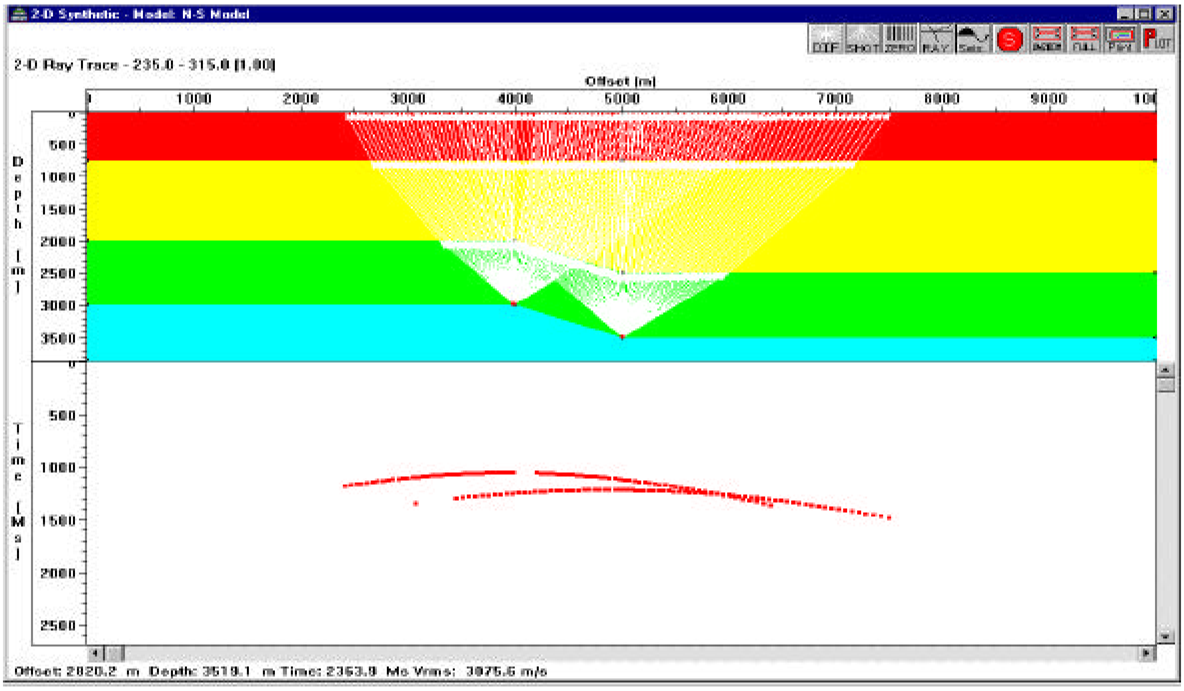
$$MA = \sqrt{\left[\frac{Z_{obj} + \frac{V_o}{k}}{\sin q}\right]^2 - \left[\frac{V_o}{k}\right]^2} - \left[\frac{Z_{obj}}{\tan q} + \frac{V_o}{k \tan q}\right] \qquad \text{(Ec. 2)}$$

C. **Modelling:** produce 2D or 3D depth models and raytrace reflectors and diffractions to find aperture. Works well with simple models, but raytracing is not reliable in very complex models.

Modelled Migration Aperture – 26 degree Dipping Event



Modelled Migration Aperture – 45 degree Diffractions



D. **Empirical processing:** reduce migration aperture and observe effect on data. Can help, but data is often not properly focused by 2D migration anyway, so inferring the required aperture for 3D migration may not be reliable.

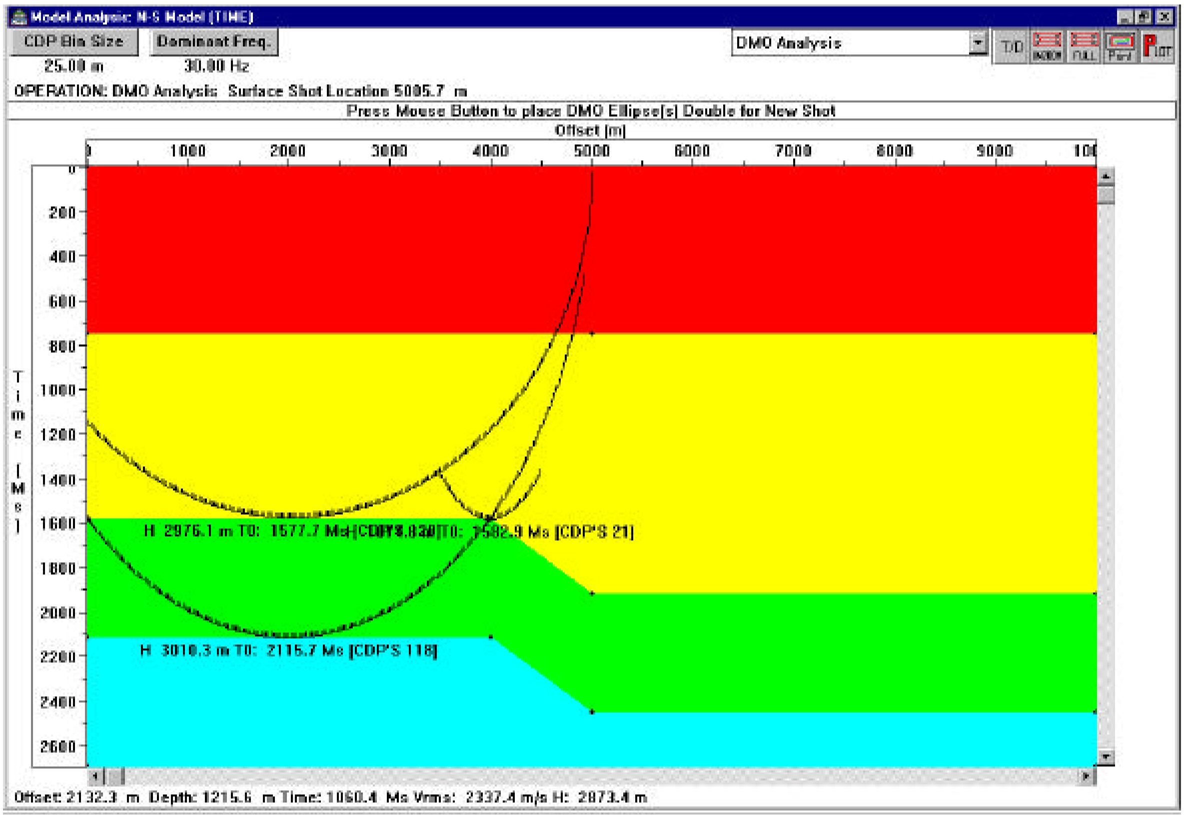
A combination of modelling, empirical, and calculated apertures will give a range of possibilities – select a migration aperture based on confidence, budget, and proximity of key events to the survey boundary AND note it doesn't have to be the same width everywhere!!

Also – if you can live with half fold or less at the edge of your migration aperture, this can save you a lot of money.

2. DMO APERTURE:

If DMO is a key processing step, and especially for very small surveys with shallow, steep, dips, it is worth checking the width of the DMO aperture, and adding this to the migration aperture. The easiest way to do this is to model the aperture, or to use the DMO ellipse equation for the maximum offset at the zone of interest.

DMO Ellipses – Shot at 5000



3. FOLD:

Fold is cost critical. For economic reasons fold of 3D surveys is normally lower than 2D surveys by a factor of 2 to 4. 3D migration acts as a more powerful random noise attenuator than 2D migration – and so lower fold data can still give a good result, even if the stacks are noisy. BUT 3D migration still requires an adequate signal to noise level to work, so beware of shooting at too low a fold! Also – coherent noise often migrates into post-migration background noise and anomalous events. Low fold surveys also tend to have strong variations in trace offset and azimuth distribution between bins, and these variations can be a problem for detailed stratigraphic work, trace inversion, or attribute and waveform tracking. Also – low fold surveys can lead to problems for velocity analysis, demultiple, 3D DMO and AVO processing steps.

The signal to incoherent noise improvement for 2D migration can be defined as:

$$S/N_{2D} = \frac{V_{mig}}{2 \cdot CMP \cdot f_{\max}} \qquad \text{(Ec. 3)}$$

Where –

Vmig = migration velocity
CMP = spatial sample interval (CMP interval)
fmax = maximum signal frequency

The signal to incoherent noise improvement for 3D migration can be defined as:

$$S/N_{3D} = \frac{3 \cdot V_{mig}^{2}}{4 \cdot p \cdot dx \cdot dy \cdot f_{\max}^{2}} \qquad \text{(Ec. 4)}$$

Where -

dx = in-line spatial sample interval (in-line bin dimension)
dy = cross line spatial sample interval (cross line bin dimension)

And hence we can compute equivalent 3D fold, to give the same S/N ratio (for incoherent noise) as a 2D stack

$$Fold_{3D} = \left[\frac{S/N_{2D}}{S/N_{3D}}\right]^{2} \cdot Fold_{2D} \qquad \text{(Ec. 5)}$$

In general it is better to determine fold from examination and decimation of previous 2D data, and examination of the fold levels of previous 3D surveys shot in the same or similar areas, with the same objectives.

4. BIN SIZE:

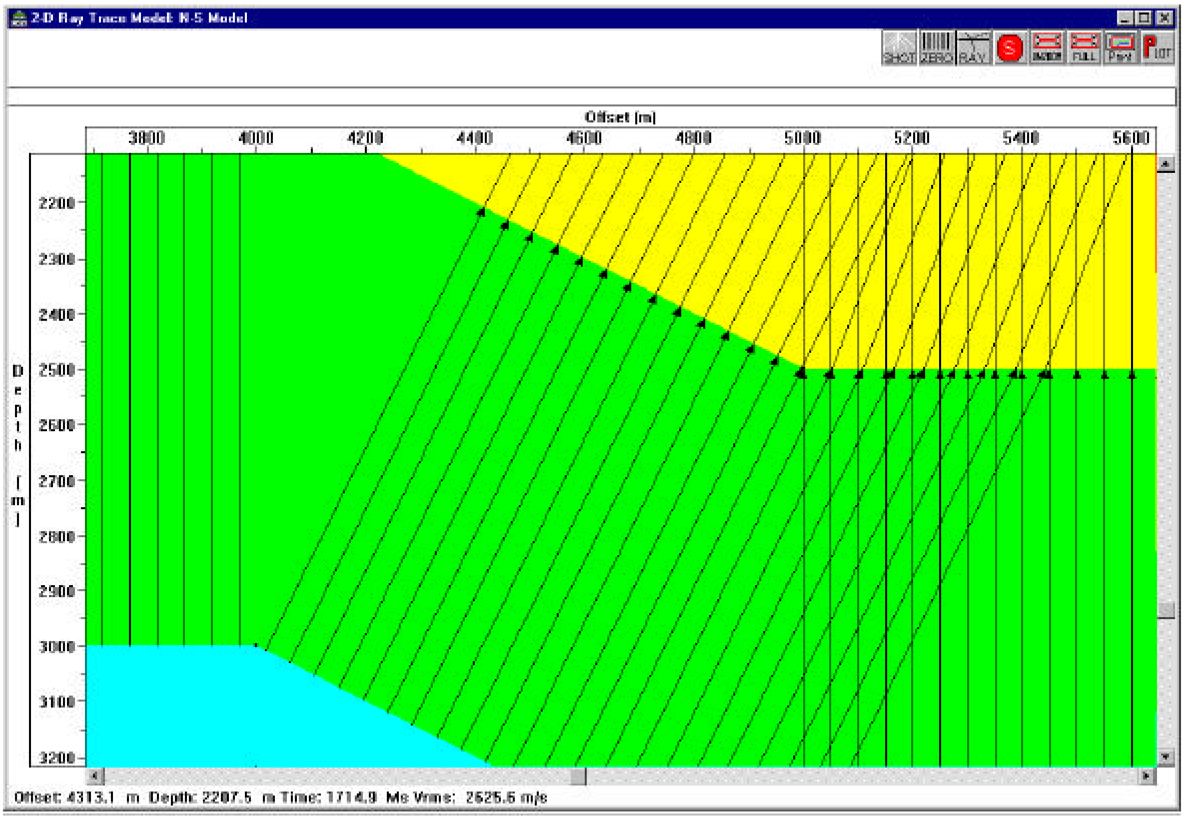
Bin size is generally chosen on the basis of recording the steepest dips of interest without aliasing at the highest frequencies of interest. Note that dips should include both structural dips and diffraction limbs – even in flat areas we need to focus diffraction energy and unless you have strong evidence to the contrary a minimum dip limit of 30 degrees should be used, to sample diffraction energy, even if structural dips are lower.

We normally use Maximum bin size as:

$$Bin = \frac{V}{4 \cdot f \cdot \sin q} \qquad \text{(Ec. 6)}$$

What is V ? – often the average velocity to target is used. But V actually refers to the interval velocity in the interval where there is a difference in path length between adjacent normal incidence rays. This could be the near surface velocity, or the velocity just above target, depending on structure. Examine the structure, draw the rays, and try to decide which velocity to use.

Illustration of Raypath Length Differences In a Layered Media



Also – because of ray bending the path difference tends to be less than the straight ray assumption, so this equation is actually slightly conservative in most real earth situations.

What is f ? – although we normally use the maximum frequency in the data, we really ought to use the maximum frequency required to achieve our resolution requirements, if this is lower.

Post migration resolution (after Vermeer) can be defined as –

$$R_z = \frac{V}{4 \cdot f_{\max}}$$
$$R_x = 2 \cdot R_z \qquad \text{(Ecs. 7,8)}$$

This Rx value is aplied for a 30 degrees minimum migration aperture angle.

Note that Vermeer states that in the presence of noise, this maximum resolution is reduced in many parts of the world by a factor of 3, i.e.

$$R_z = \frac{3 \cdot V}{4 \cdot f_{\max}} \qquad \text{(Ec. 9)}$$

Where v = interval velocity at target.

Therefore, by deciding the required horizontal and vertical resolution it is possible to derive the required maximum frequency, and hence the required bin size.

5. MAXIMUM MINIMUM OFFSET:

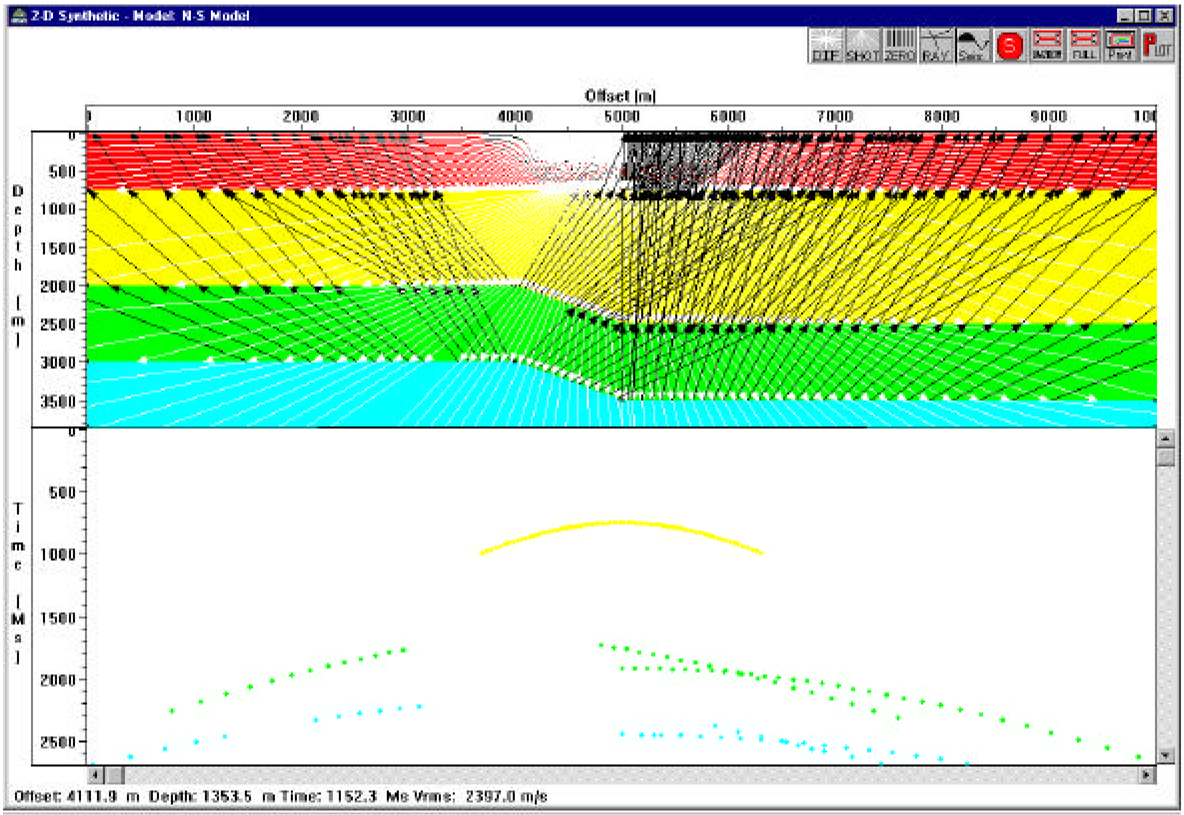
Another cost critical parameter. Why? – because it controls the maximum allowable shot and receiver line intervals. This parameter is controlled by 3 main criteria –

a. Depth of target – shallower targets require more near offsets and hence a smaller maximum minimum offset. Deeper targets are more suitable for designs with a large maximum minimum offset.
b. Depth migration velocities – If you are intending to do depth migration or depth conversion it is important to decide what is the required minimum grid of velocity analyses required, and make sure it is possible to achieve this with the maximum minimum offset specified.
c. Refraction statics – The refractor that will be used for refraction statics computations must be sampled at least twice, and preferably more, in the crossline direction, so the maximum minimum offset must not lead to line separations that are too wide for this, otherwise it will become impossible to find a refraction statics solution.

To determine the maximum minimum offset –

- Conduct inner trace muting tests on 2D data and observe the effect at target.
- Model shots using ray trace or full waveform modelling, and look at the required offset range at target.
- Look at the minimum offset plots from 3D designs and see if they meet near surface velocity sampling requirements.
- Examine refractors on shot records and determine the offset range required for refraction statics to function.

Modelled Shot Record



6. MAXIMUM OFFSET RANGE:

All 3D designs have varying maximum offset between bins. It is important to determine what the absolute maximum offset will be. The maximum offset can be cost critical because a small maximum offset limits either the number of receiver lines, or the receiver line interval.

Maximum offset can be determined by –

- Far offset muting of 2D data, and observation of the effect at target.
- Examination of shot records or CMP gathers.
- Model shots using ray trace or full waveform modelling – but beware, the base weathering refraction can control the maximum achievable offset – if this effect is left out of the modelling the results might indicate much longer offsets than in reality can be achieved.

7. AZIMUTHAL RANGE:

Azimuthal range is important because a narrow azimuthal range restricts the number or separation or receiver lines, thereby increasing costs. Some factors to consider are –

Narrow azimuthal range reduces problems with velocity anisotropy. If the anisotropy is solely due to reflector dip then 3D DMO, or pre-stack migration, can correct the problem. If it is due to other factors then velocity analysis and correction requires azimuthal velocity analysis and move-out correction, which is normally only achievable by either shooting a narrow azimuth survey or a high fold, wide azimuth, survey that can be separated into azimuth sets during processing.

Low fold, wide azimuth, surveys can lead to problems with 3D DMO, which is an azimuth dependant process.

Wide azimuth surveys give a more symmetrical sampling of the emergent shot wavefield, and theoretically should improve pre-stack imaging (Vermeer).

8. OFFSET REGULARITY:

All 3D survey designs suffer from irregular distribution of offsets within bins, and bin to bin variations. They also tend to cluster offsets in the middle offset range, with relatively few near and far offsets.

Low fold, wide azimuth, designs have the worst regularity of offsets. High fold, narrow azimuth ('pseudo-2D') designs have the best regularity of offsets.

Generally offset regularity is least important for large scale structural interpretations, most important for detailed stratigraphic analysis. However, some areas have variations in signal to noise with offset – so be careful.

Pre-stack migration is often done in offset domain, so irregular offset distribution can affect pre-stack migration.

The best way to examine effects is to take a 2D line and bin it using an offset selection taken from a 3D design. Examination of the stack and migration will show whether the offset irregularity is affecting data continuity and character. Input-Output's CENSUS package contains tools for this. Alternatively a modeled 3D survey can be used to examine effects of offset irregularity – GMG GRiP and GX Technology 3D raytracing packages can be used for 3D modeling.

Step 3 – Survey Parameters Calculation

We now have the key parameters for design –

- Bin Size
- Fold
- Maximum Minimum Offset
- Maximum Offset
- Azimuth Range – wide or narrow

Once we have these the design of the survey becomes more or less automatic.

1. BIN SIZE:

In most designs the bin size is half the perpendicular shot and receiver intervals. [It is possible to 'split' the fold into smaller bins by using bin fractionation techniques – which may offer some benefits for companies having deep and shallow targets. Interested readers should reference papers published by Andreas Corsen and the Gas Research Institute.] This gives us the perpendicular shot and receiver intervals.

2. FOLD:

This consists of in-line and crossline fold. Crossline fold can be calculated as half the number of active receiver lines. Assuming symmetric shooting, inline fold is equal to half the number of active channels divided by the in-line shotline spacing, in channels. Note that this implies that with more active receiver lines the same fold can be achieved with a wider shot line spacing. However, increasing the number of receiver lines may be constrained by the far offset limit, or a narrow azimuth requirement. Increasing the shot line interval may be constrained by the maximum minimum offset required.

A limit is also imposed by the physical constraints of having large quantities of equipment – capital costs rise, and there is a lot more equipment on the ground to maintain in an operating condition every day – resulting in loss of shooting time.

Another design consideration with the receiver / shot trade off is the quantity of recording equipment to move every day – low shot densities imply a large number of receivers to move for every shot, and in rough terrain, especially with helicopter support, the costs of moving recording equipment may start to become greater than shot drilling costs.

3. RECEIVER LINE AND SHOT LINE SPACING:

This is controlled by both far and near offset constraints, and azimuthal constraints. Wide receiver line spacings lead to wider azimuths, larger maximum minimum offsets and longer far offsets. For a given fold, less in-line channels can be 'traded' for more receiver lines, to keep far offset constant, but the maximum minimum offset and azimuth distribution will both tend to increase.

One easy technique is to decide on several different numbers of live receiver lines – say 8, 10 and 12, and calculate number of live channels per line and shot line intervals that meet the required fold and offset requirements.

4. STRAIGHT, BRICK OR DIAGONAL:

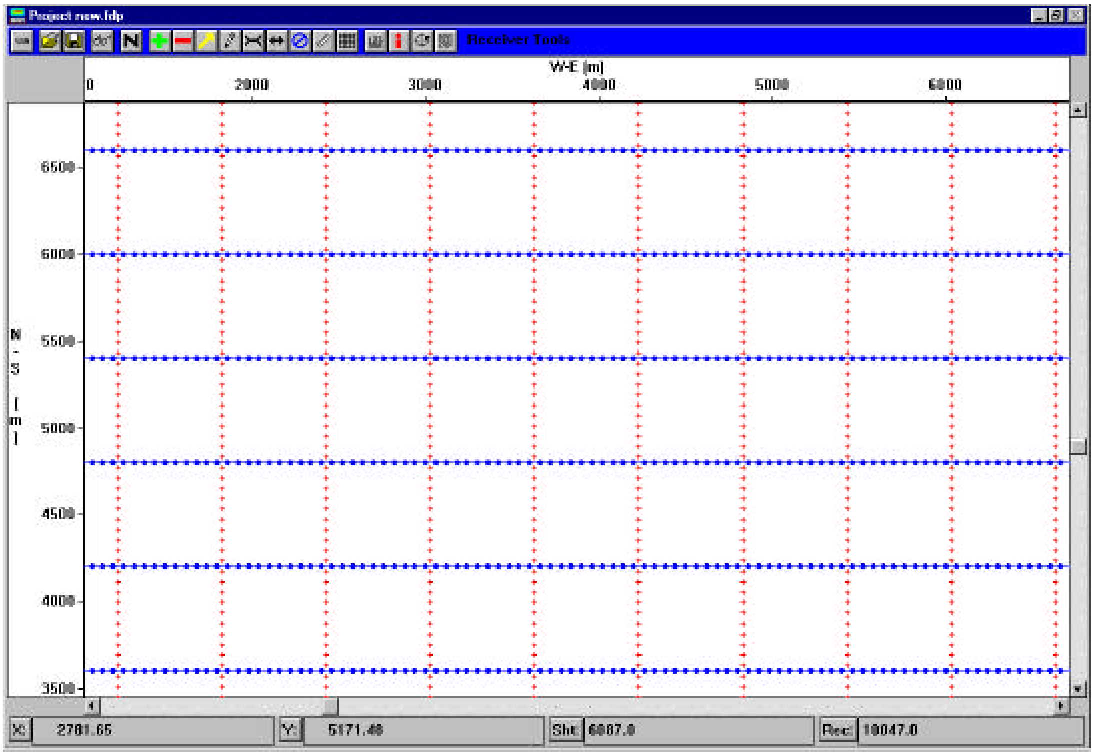
To get true perpendicular cross spreads, which Vermeer recommends for 'true' pre-stack imaging, we need to record the survey with perpendicular shot and receiver lines.

However, the maximum minimum offset can be reduced by 'bricking' shot lines, and therefore has some advantages. BUT if you are trying to apply pre-stack noise attenuation in 3D the brick design gives regular holes in 3D common receiver domain that are not desirable.

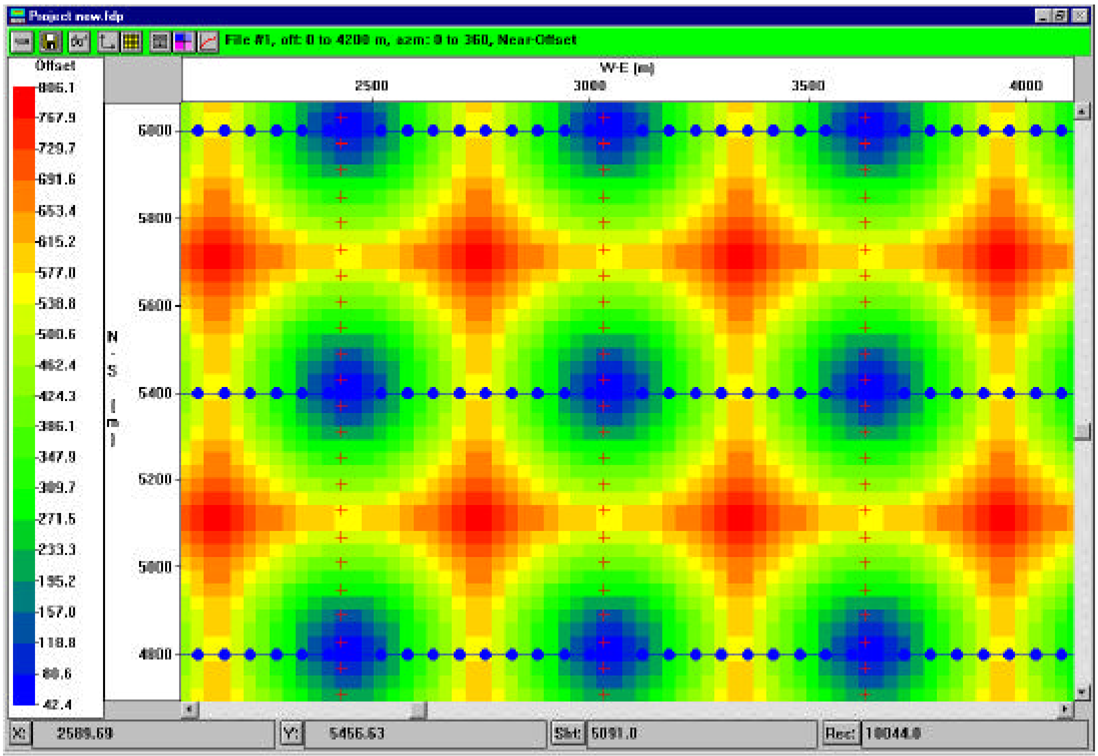
Also, with some parameters a better offset distribution can be obtained by using diagonals, which also have the effect of reducing the maximum minimum offset. However, diagonals increase the along-line distance between shots, slowing drilling and recording production rates, and increasing line cutting and permit costs. Although a 45 degree diagonal is common, because it maintains each shot between receivers, a 26.565 degree diagonal has been used on many surveys as it sometimes gives a worthwhile improvement offset distribution. Diagonals are most suitable for vibroseis surveys, and in-line roll surveys, where continuous shot lines offer operational advantages because they avoid transits between short shot line segments.

Below are some examples for a 600m x 600m shot and receiver grid, 60m shot and receiver interval, 25 fold survey:

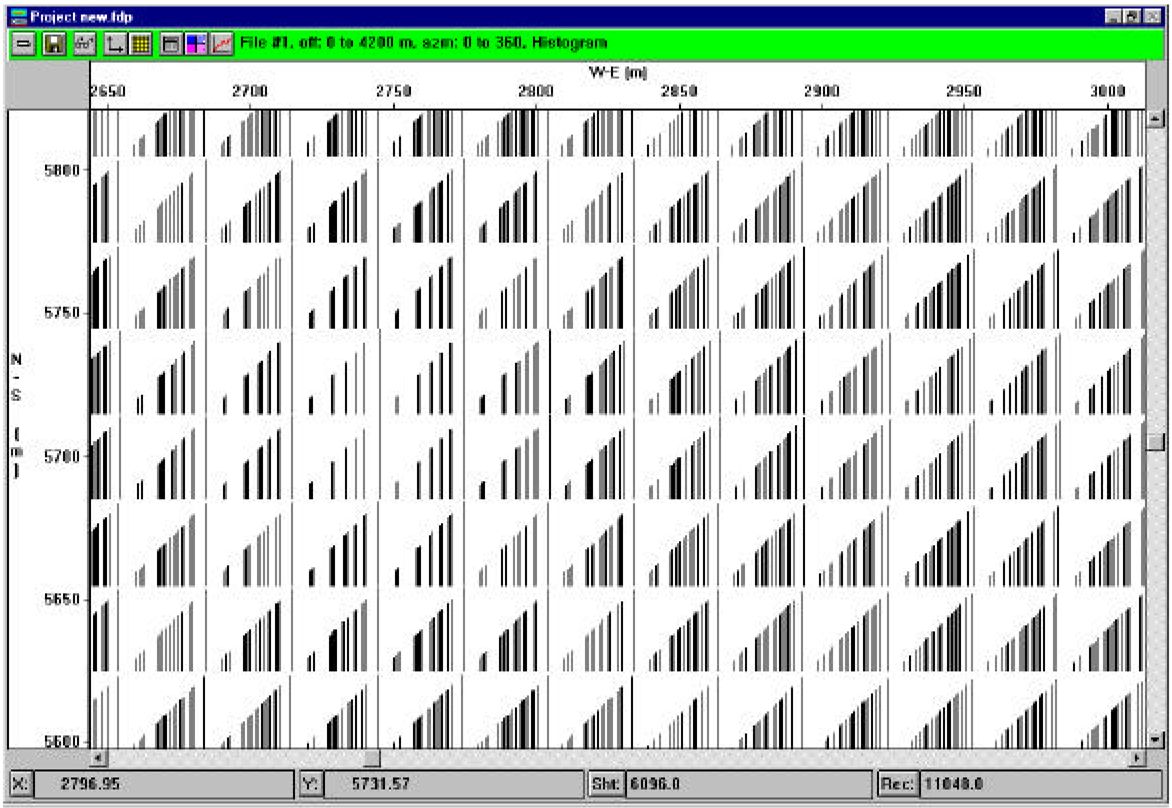
Straight Line Layout



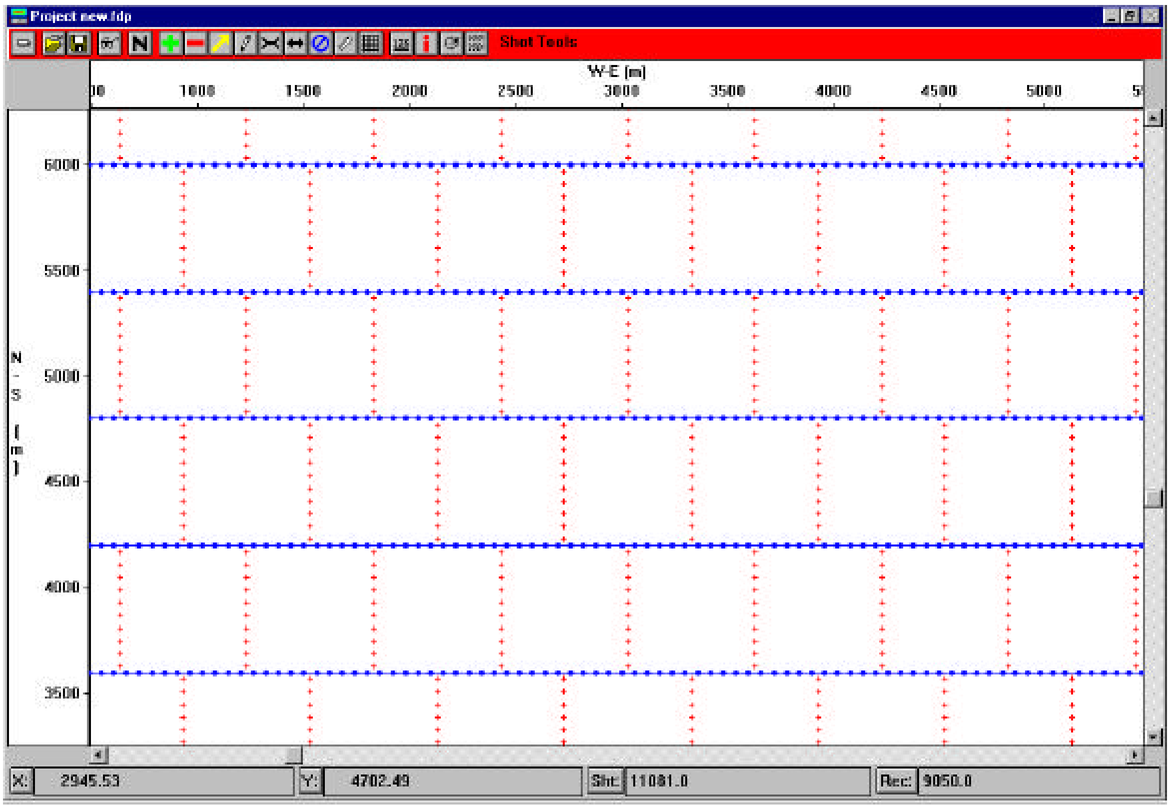
Near Offsets – Straight Line Grid



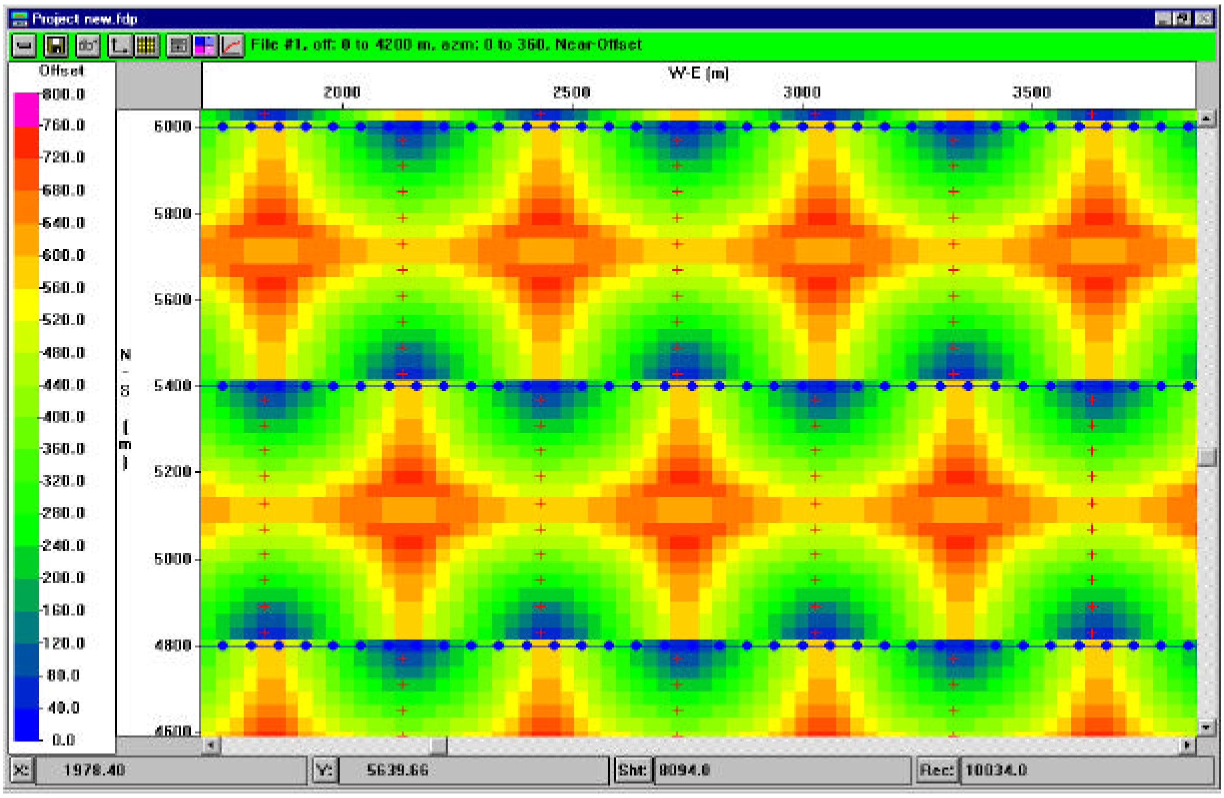
Histograms – Straight Line Grid



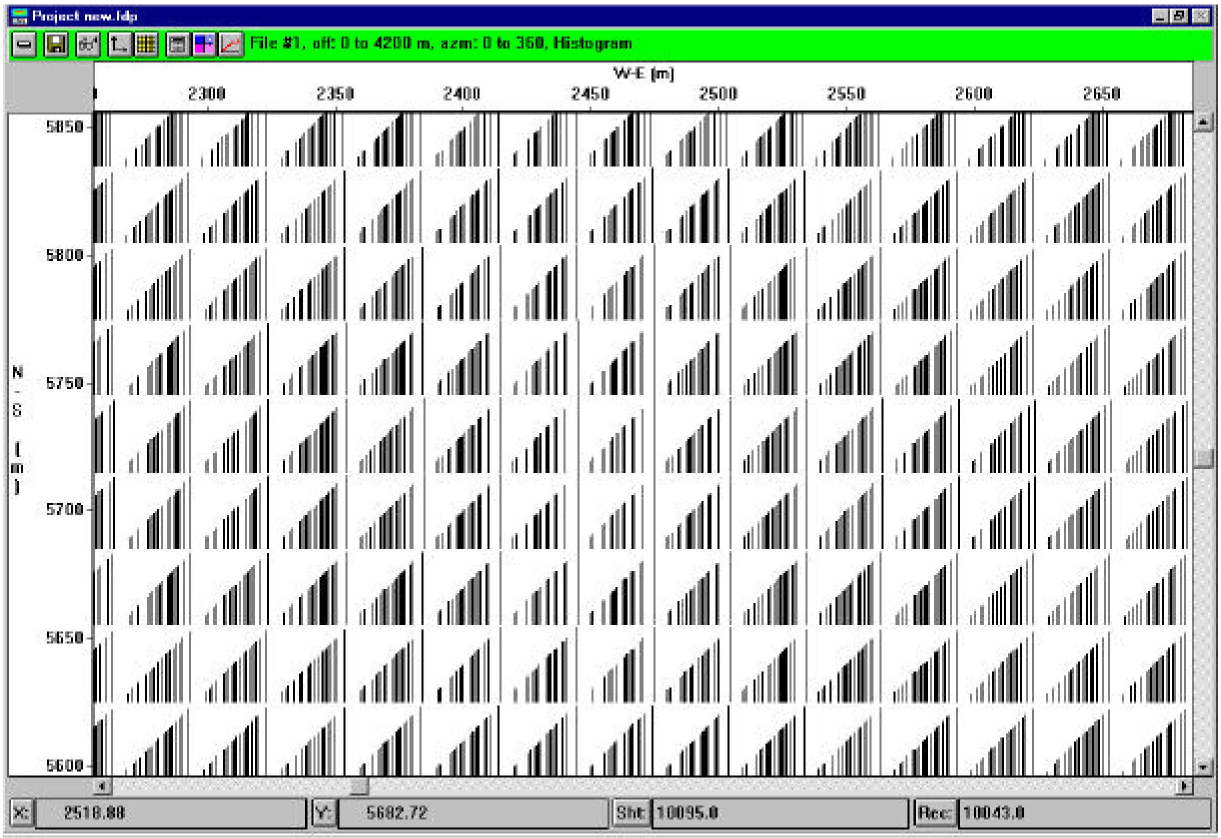
Layout – Bricked Grid



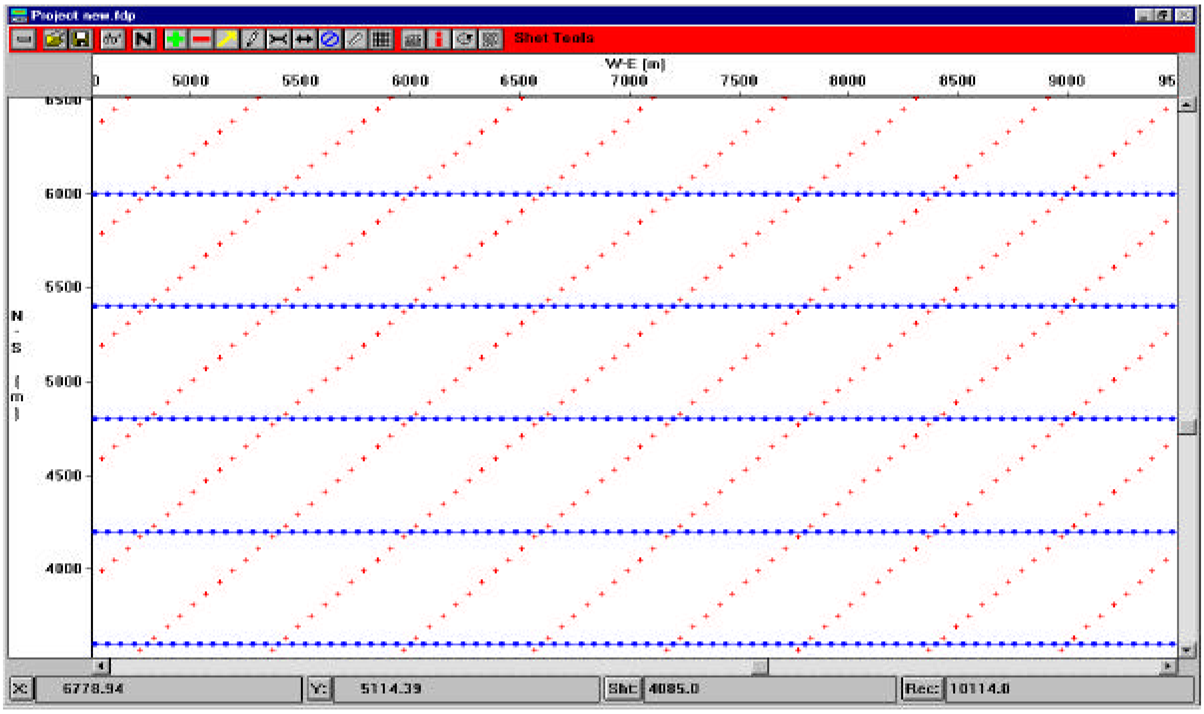
Near Offsets – Bricked Grid



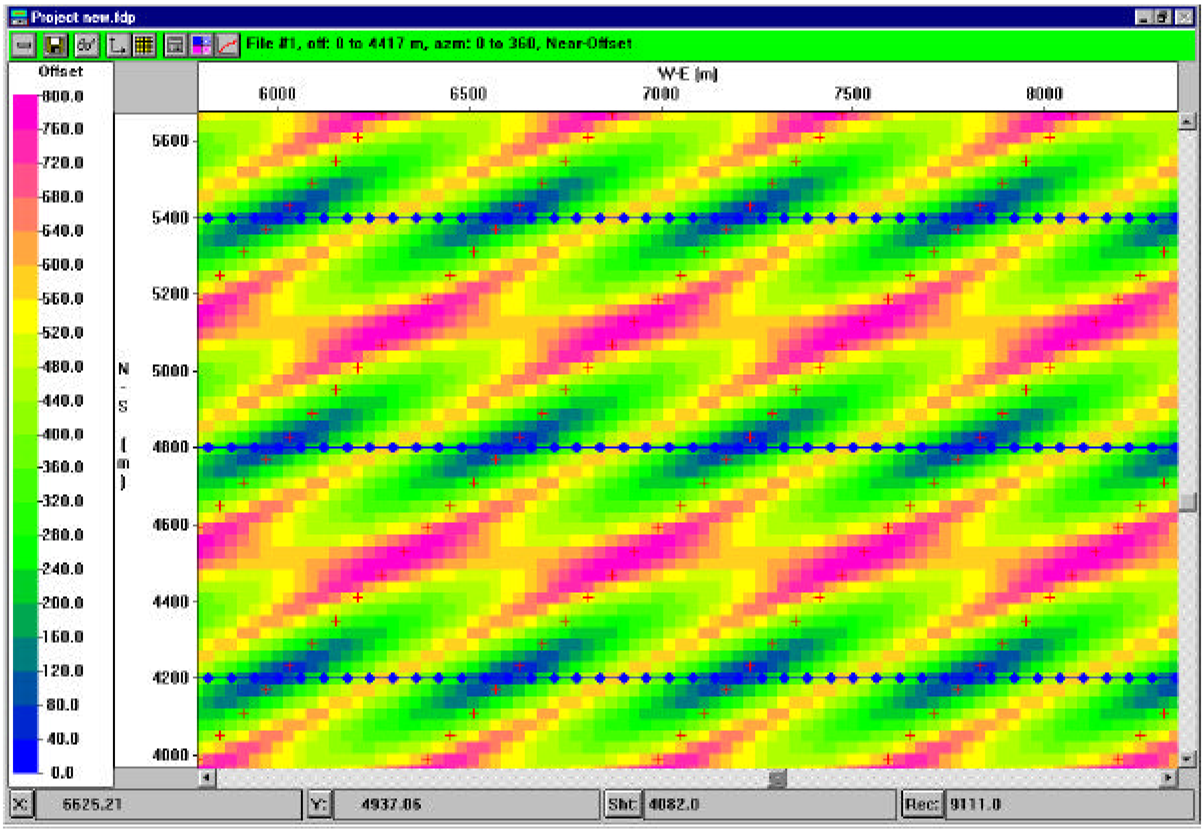
Histogram – Bricked Grid



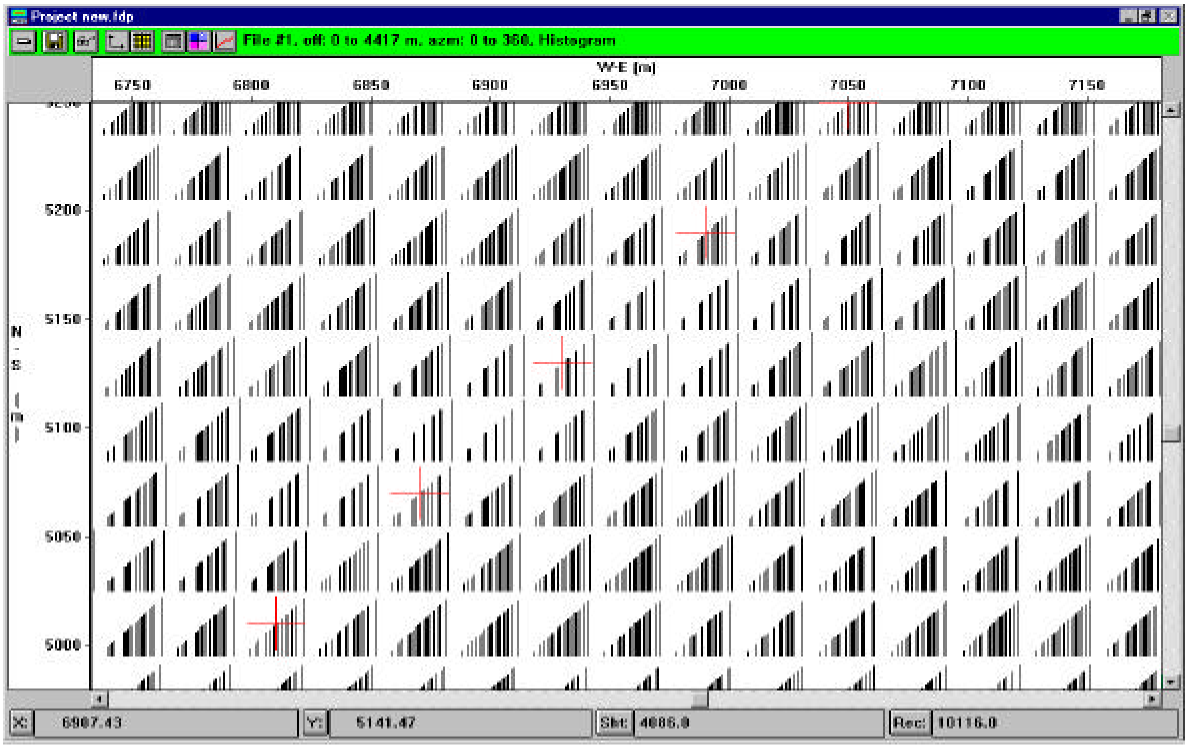
Layout – Diagonal



Near Offsets – Diagonal



Histograms – Diagonals



5. ONE-PASS, ZIPPER, OR IN-LINE ROLL

One pass involves laying receiver lines completely across the survey area, and shooting complete swathes. This has the huge advantage that receivers are only laid once – they are never picked up and re-laid to the same position. To reduce equipment movement the pattern is normally only rolled up one line. Sometimes, to increase productivity, additional lines are laid and two or more swathes recorded at once. Because of the one line roll, in the crossline direction, the receiver statics coupling between swathes is very good. However, it is only suitable for long, thin, survey areas, or 'mini-3D' surveys. Also, if shot densities are very low and receiver line spacing is narrow then shooting with a one line roll becomes less efficient.

Zipper is used in areas where the survey is too wide for 'one pass' shooting. The method is the same, but the survey is split vertically into 2 or more blocks, and the recording swathe moves up and down the blocks to obtain total coverage. Because of the need to gain even fold coverage a 'zipper' of half the active spread length is needed on either side of the shot patch, meaning some receivers are re-laid. It still has the advantage of good statics coupling between swathes, but if climatic conditions change, such as heavy rainfall, between two parts of a zipper the receiver statics may also change, which can give processing problems when trying to obtain a good refraction statics solution.

In-line roll involves rolling the spread forward with the shots. For large receiver spreads this can involve moving large numbers of receivers forwards and backwards along the lines. To minimise receiver movement, and hence logistics costs, it is normal to record with a half-swathe crossline roll (e.g. a 5 line roll for a 10 line spread). In some vibroseis designs, and shallow water and OBC airgun shooting, where shot points are relatively cheap then shot lines extend beyond the receiver patch and shots, rather than receivers, are repeated and the swathe does a complete roll without repeating receivers. These designs generally are most suitable when long shot lines are significantly more efficient, such as for vibroseis shooting, and where movement of equipment is easy and cheap.

In general most seismic contractors have 'favorite' ways of shooting surveys based on past experience and their levels of equipment availability. The oil company client will usually get the best deal by specifying the basic parameters (fold, bin size, offset ranges, azimuth preferences) and allowing each contractor to present designs that meet these requirements.

CONCLUSIONS

Successful design of a 3D survey begins with a clear analysis of technical and business objectives. If you don't understand why you are doing it, DON'T DO IT!!

Design to meet your objectives – both now AND in the future. If you only design for exploration, don't be surprised if you need to shoot a second survey for production or tertiary recovery.

Price follows function – if you need high fold, shallow data in a tough terrain area it will cost you a lot more than low fold, deep data in easy terrain. Therefore be careful what you wish for – either way!!

TECHNICAL CONTRIBUTIONS

The easiest way we found to carry out a good job, depends on several facts, such as the state-of-the-art in technologies and resources optimization. It allows us to avoid errors and deliver valuable information faster, and improve the turnaround of our job.

The 3D seismic design has became each day a main step in the upstream business, and the analysis of exploration areas has been better interpreted and understood, as a result of a good selection of key parameters related to seismic acquisition.

Nowadays, it is absolutely mandatory to compare and understand the results of a design, since the hydrocarbon fields demands more details to acquire images of high resolution and good signal-to-noise ratio. It is possible as long as a good model analysis of key parameters guarantee the expected results in what a target imaging concerns.