

Multifocusing Stack Technique for Subsurface Imaging*

Sunjay Sunjay¹

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¹Exploration Geophysics, BHU, Varanasi-221005, India (Sunjay_sunjay@rediffmail.com/hotmail.com/yahoo.com)

Abstract

The soul goal of exploration seismology, precise subsurface imaging, can be done in different ways and in different domains: time or depth. Although depth migration has become almost mandatory in areas of complex geology, because it accounts for travel time non-hyperbolic moveout, it has in fact quite a limited purpose - to convert seismic data from one form to another for a *given velocity model*. Time imaging provides sufficient information for a subsurface of moderate complexity. Moreover, even for complex areas that require depth migration for correct subsurface imaging, time imaging usually constitutes a key first step that facilitates the estimation of a velocity model for depth imaging. For these reasons, improving the quality of time imaging is a focus of intensive research. A recent advance is multifocusing (MF), a method with the potential to greatly improve the quality of time imaging.

Theory - Introduction

Multifocusing stack is a new method of zero-offset time imaging proposed by Boris Gelchinsky (Gelchinsky et al., 1997; Berkovitch et al., 1998). The principle goal of multifocusing is the same as for NMO-DMO stack: to create an accurate approximation of the zero-offset section with high signal-to-noise ratio. In multifocusing, this goal is achieved by applying the moveout correction to large super-gathers comprising a large number of traces which need not belong to the same CMP gather, but whose sources and receivers are within a certain vicinity of the image point. Since the traces being stacked no longer belong to the same CMP gather, such a procedure requires a more general moveout correction than the one used in the conventional CMP stacking. Analytical expressions (based on the spherical representation of wavefronts) describe the moveout correction for a given source-receiver pair with respect to a zero-offset image trace by three parameters measured at the image point. In other words, the moveout correction expressed by the multifocusing formulas is a three-parameter expansion of the travel time in the vicinity of the image point. In this sense it is closely

related to the paraxial ray approximation (Tygel et al., 1997). The three parameters are: Emergence angle β , Radius of curvature of the wavefront of the Normal-Incidence-Point wave (NIP-wave radius R_{NIP}), and Radius of curvature of the wavefront of the normal wave (N-wave radius R_N), all parameters being measured at the image point. The Normal-Incidence-Point (NIP) wave front is formed by a point source placed at the point where the zero-offset ray emitted from the image point hits the reflector (Figure 1). The wavefront of the Normal (N) wave is formed by normal rays emitted by different points on the reflector (like in an "exploding reflector" scenario, Figure 2).

Exploding Reflector

Huygens principle states that wave motion can be described by exploding secondary sources along the wavefront. The envelope of the resulting spheres constitute successive wavefronts which progress in time. This fundamental concept elucidates the nature of wave motion for virtually any field, such as electromagnetism, optics, acoustics and elasticity. We have deviated slightly from Huygens principle, advocating that the explosions take place not along the wavefronts, but rather on the reflectors of the medium where the wave propagates. The magnitude of each explosion is directly proportional to the reflection coefficient of that reflector. Each explosion point emits particles at each reflector point of the receivers yields the wavefields. If the reflection coefficient vanishes, no additional explosion occurs at this point of time and space.

Multifocusing formulas not only provide an adequate representation of the arrival times for arbitrary source-receiver configurations just like the conventional NMO correction does for CMP gathers, but is in fact more accurate for various earth models. In particular, the multifocusing formulas are very accurate for a spherical reflector under a homogeneous overburden, and also for a smoothly curved dome-like reflector (Tygel et al., 1997). For a single CMP gather the multifocusing moveout correction reduces to the "shifted hyperbola" of de Bazelaire (1989), which is known to give a superior approximation of the travel time for a horizontally layered medium than the classical Dix NMO equation (Castle, 1994).

Multifocusing Moveout Correction

Let us consider the ray diagram in Figure 3. The central ray starts at point X_0 with angle β to the vertical, hits the reflector Σ at NIP and returns again at X_0 . A paraxial ray from the source S intersects the central ray at point P and arrives back to the surface at point G . These two rays define a fictitious focusing wave which starts with the wave front Σ_S , focuses at P , is reflected at the reflector Σ and emerges again at X_0 with the wave front Σ_G . Following the formulae of Gelchinsky et al. (1997), we can write the expression for moveout correction in the form:

$$\Delta\tau = \frac{\sqrt{(R^+)^2 + 2R^+\Delta X^+ \sin\beta + (\Delta X^+)^2} - R^+}{V_0} + \frac{\sqrt{(R^-)^2 + 2R^-\Delta X^- \sin\beta + (\Delta X^-)^2} - R^-}{V_0}$$

where

$$R^\pm = \frac{1 \pm \sigma}{\frac{1}{R_{CEE}} \pm \frac{\sigma}{R_{CRE}}}$$

and σ is the so-called focusing parameter given by:

$$\sigma = \frac{\Delta X^+ - \Delta X^-}{\Delta X^+ + \Delta X^- + 2 \frac{\Delta X^+ \Delta X^-}{R_{CRE}} \sin\beta};$$

where ΔX^+ and ΔX^- are the source and receiver offsets of an arbitrary ray with respect to the central ray, R^+ and R^- are the wave front curvatures of the fictitious waves Σ_S and Σ_G , respectively, and V_0 is the near surface velocity.

Quantities R^+ and R^- involved in equation (1) are curvature radii of the fictitious wave fronts Σ_S and Σ_G . It is clear from Figure 3 that, for a given central ray, the radii R^+ and R^- depend on the position of the source and receiver that define the paraxial ray (or, more precisely, on the position of the point P where the paraxial ray intersects with the central ray). Equation (2) expresses the radii of the fictitious wavefronts R^+ and R^- through the fundamental curvature radii R_{NIP} and R_N , which are defined by the central ray only and are the same for all the source-receiver pairs in the vicinity of the central ray. The dependence of the radii R^+ and R^- on the position of source and receiver (or on the position of the point P on the central ray) is contained in the focusing parameter σ which has a very clear physical interpretation. In particular, $\sigma = 0$ means that $R^+ = R^- = R_N$, which implies that point P coincides with the radius of curvature of the normal wave (or of the reflector), and corresponds to the case of coinciding source and receiver (zero-offset

configuration). The cases $\sigma = \infty$ and $\sigma = -1$ imply $R^- = 0$ and $R^+ = 0$, and correspond to the common-source and common-receiver configurations. The case $\sigma = \infty$ leads to $R^+ = R^- = R_{NIP}$, and corresponds to the situation where the focusing point P coincides with NIP.

Moveout correction defined by equations (1)-(3) can be applied to arbitrary source and receiver offsets as long as the arcs of the fictitious wave fronts Σ_S and Σ_G can be considered spherical in shape. The moveout correction in equation (1) is a sum of two hyperbolas. However, for all familiar source-receiver distributions this correction reduces to a single hyperbola. For a common source (common receiver) gather this can be readily seen after substituting $\Delta X^+ = 0$ ($\Delta X^- = 0$) in equation (1). For a CMP gather which shows that for a single CMP gather and $R_N = \infty$ the multifocusing moveout formula (1) reduces to the "shifted hyperbola" of de Bazelaire (1988), which is the most general practical NMO equation (Castle, 1994).

The multifocusing moveout correction as defined by equations (1)-(3) can be applied to any trace if its source and receiver are in some vicinity of the image point, for which we want to obtain the zero-offset trace. Thus, the multifocusing moveout correction can be applied to large super-gathers without any loss of the spatial resolution. In multifocusing, a super-gather is any set of traces whose sources and receivers are in some vicinity of the image point. Examples of super-gathers are shown in [Figure 4](#).

Benefits of MFS

Potential benefits of the multifocusing as compared to the more traditional methods of time imaging (NMO+DMO) can be explained as follows: 1) Stacking a large number of traces belonging to different CMP gathers can increase signal-to-noise ratio by attenuating noise originating at a target depth; 2) For a flat reflector under a homogeneous overburden the NIP radius depends on the distance between the image point and the reflector and is independent of the reflector dip. For an inhomogeneous overburden R_{NIP} represents the distance between the image point and the reflector in a reference medium (homogeneous medium with reference velocity V_0 equal to the velocity in the uppermost layer near the observation surface), again, independent of the dip; 3) Simultaneous determination of curvatures and emergence angle makes it possible to recover dip-independent RMS velocities V_{RMS} through a simple algebraic transformation,

$$V_{RMS} = \left(\frac{2V_0 R_{CRE}}{t_0} \right)^{1/2}$$

where t_0 is the zero-offset arrival time at the image point. These velocities may be then used for migration; 4) The multifocusing moveout correction for a given sample of the image trace at t_0 depends on the incidence angle and on curvatures measured on seismograms, and does not involve the value of t_0 itself. Thus all samples belonging to the same event would have the same parameters and hence the same moveout correction. Thus, the multifocusing moveout correction does not cause stretch of the signal.

Conclusion and Implementation

The combination of generality and accuracy makes the multifocusing formulas an appealing basis for an imaging procedure. However, despite the potential advantages of the multifocusing approach, its practical use in processing of real data has been held back partly by the difficulties of implementation. Indeed, implementation of the multifocusing method has an inherent difficulty associated with the need to determine, for each t_0 on each image trace, three imaging parameters: σ , R_{NIP} and R_N instead of a single parameter (stacking velocity) in the conventional NMO stack. For the NMO stack, the stacking velocity is usually determined by means of the interactive velocity analysis, consisting of displaying a panel of correlation measures (e.g. semblance) as a function of t_0 and velocity, and manual picking of the appropriate correlation maxima as a function of t_0 . For the multifocusing parameters a similar procedure is out of the question for two reasons. First, the cost of calculating the correlation measure for all possible combinations of three parameters over a large gather of traces is prohibitively high. Secondly, even if such computation was possible, an interactive procedure would have to involve displaying and picking of maxima of the correlation measure as a function of four variables (t_0 and three imaging parameters), which does not look feasible. Thus, the determination of the imaging parameters must involve some kind of automation based on automatic optimization methods. This, in turn, brings about all sorts of problems associated with automatic correlation/stacking procedures, which have been encountered before in numerous attempts to construct an automatic NMO stack. A basic problem here is that automatic imaging procedures optimally stack useful signal as well as noise, especially spatially correlated noise. The correlation measure as a function of parameters may not be unimodal, thus requiring a global optimization strategy. However, even the global maximum may be related to the noise rather than signal.

For example, strong multiple reflections may have higher correlation measure than weaker primary events. In the interactive correlation procedures this ambiguity is resolved manually by picking right maxima on the basis of a priori velocity information. In the automatic procedure the only way is to impose constraints on the imaging parameters. Such a constrained optimization procedure has been employed in our implementation of the multifocusing method. Implementation of the multifocusing method is based on a phase correlation of the signal on the observed seismic traces. The data are moveout corrected along different travel time curves to find the curve closest to the travel time curve of the signal. The unknown parameters β , R_{NIP} , and R_N are estimated by finding a set of parameters which maximizes the semblance function calculated for all seismic traces in a chosen offset range around a central trace in a time window along the travel time curve defined by expression (1). Maximization of the semblance is achieved by a nonlinear global

optimization method. The correlation procedure described above is repeated for each central image point and for each time sample forming a multifocusing time section (MFS). Each sample on MFS represents the optimal stacked value corresponding to the optimal parameters of β , R_{NIP} and R_N and it is close to an accurate zero-offset section. Estimated sets of parameters can also be represented in the time section forming a so-called anglegram $\beta(x,t)$ and radius-grams $R_{NIP}(x,t_0)$, $R_N(x,t_0)$. These three additional sections together with MFS may be used for structural and lithological inversion because, in fact, they include all possible information contained in the observed wave fields within the framework of the ray theory.

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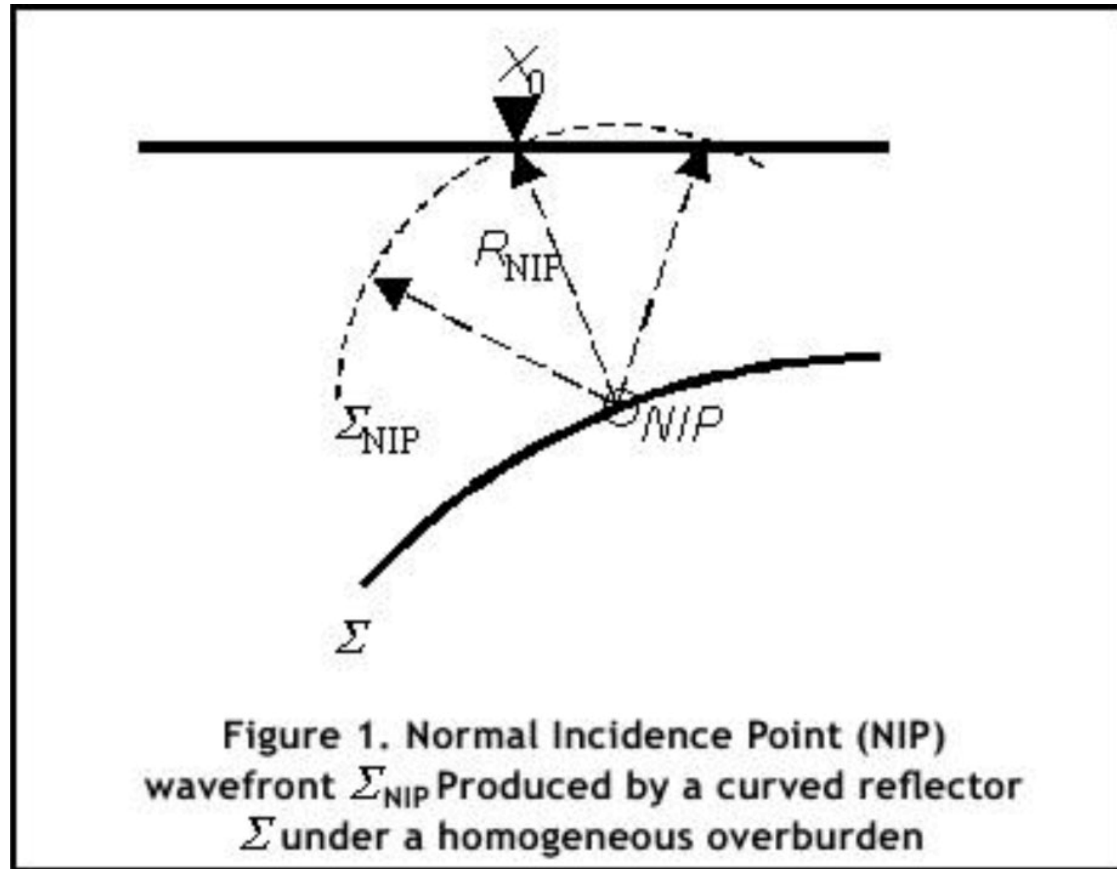


Figure 1. Normal incidence point (NIP) wavefront Σ_{NIP} produced by a curved reflector Σ under a homogeneous overburden.

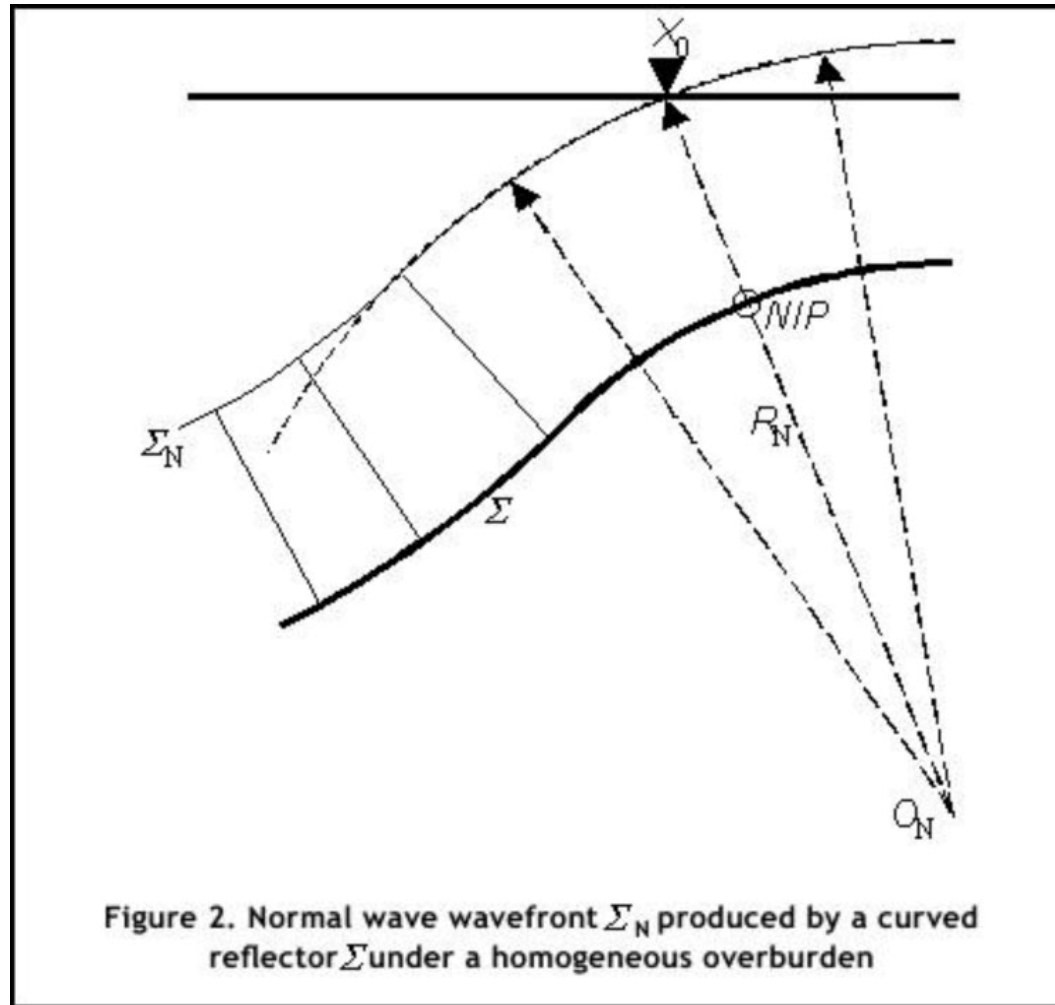


Figure 2. Normal wave wavefront Σ_N produced by a curved reflector Σ under a homogeneous overburden.

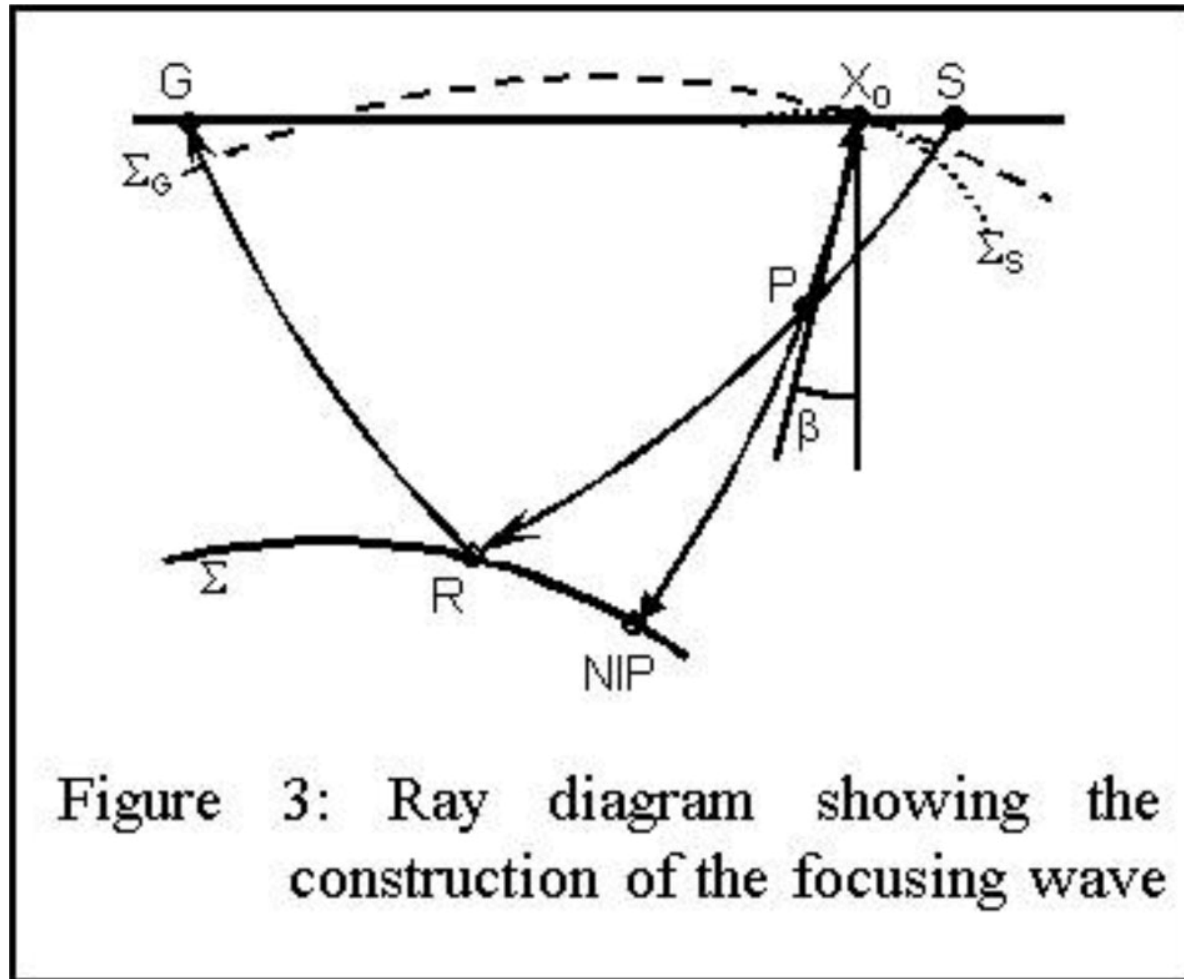


Figure 3: Ray diagram showing the construction of the focusing wave

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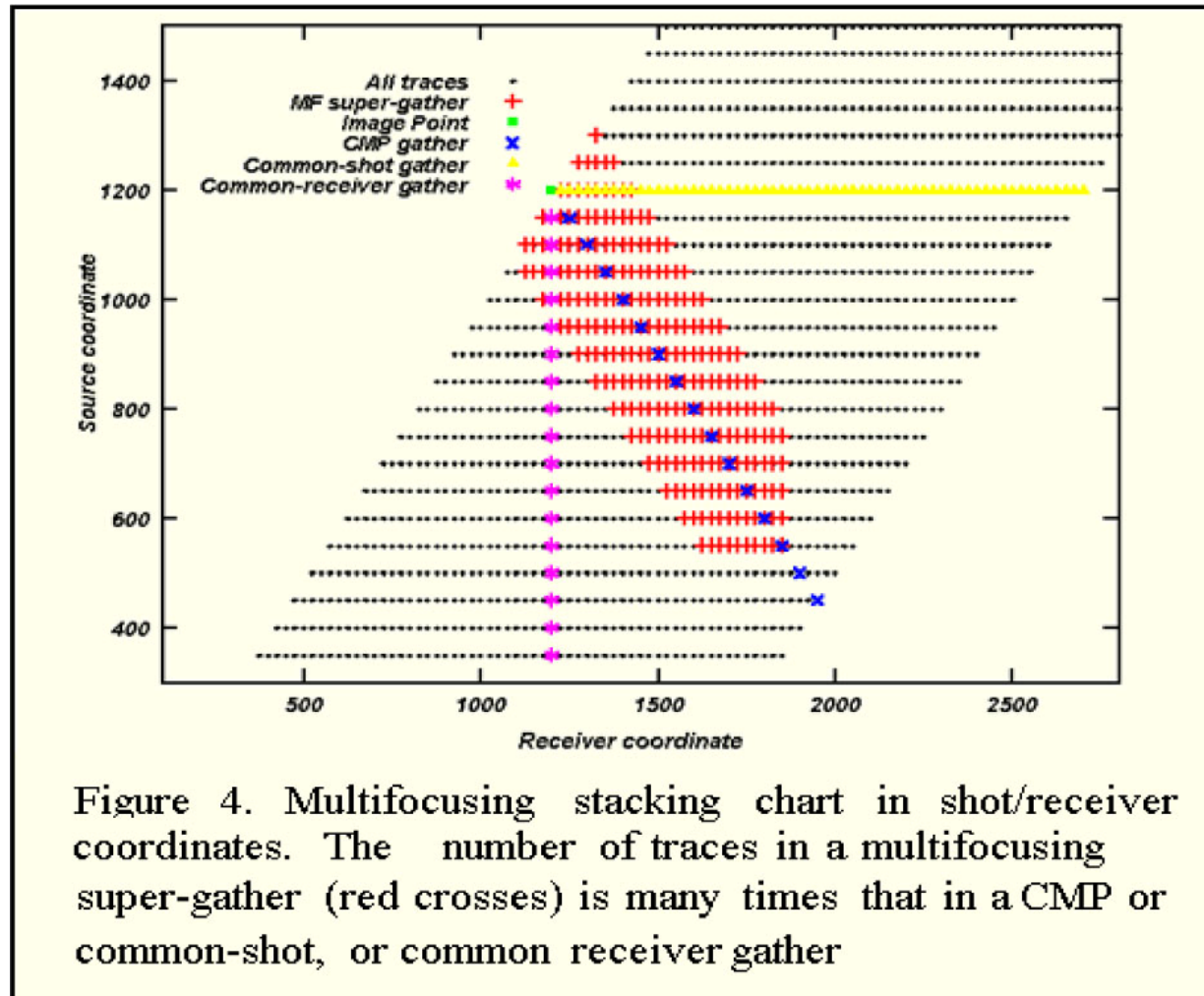


Figure 4. Multifocusing stacking chart in shot/receiver coordinates. The number of traces in a multifocusing super-gather (red crosses) is many times that in a CMP or common-shot, or common receiver gather.