# Simultaneous time imaging, velocity estimation and multiple suppression using local event slopes

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## SUMMARY

We present and discuss the use of local event slopes and their associated attributes (referred to as XTP attributes here) as a way to estimate a time-imaging velocity field and to suppress organized noise including – but not restricted to - multiples. The 4 XTP attributes are: migration velocity, migrated spatial location, migrated zero offset time and stack domain dip. We derive the equations for XTP attributes from the double square root equation which illustrates the strong connection with Kirchhoff time migration. In this paper the XTP attributes are calculated in the shot and receiver domain. The advantages of shot/ receiver domain XTP noise suppression over similar efforts in the CMP and offset domain are discussed.

In a companion presentation (Cooke et al, 2008), we discuss different methods of extracting these local event slopes.


## INTRODUCTION

Our objective is to use the concepts of local event slopes to improve upon conventional migration velocity analysis and noise suppression. Ottolini (1983) first presented the idea of using local slopes for velocity-less time migration. More recently, Fomel (2007) has extended these concepts to perform hyperbolic NMO, DMO and velocity-less PSTM. An excellent question is why do we want to the velocity associated with a 'velocity-less' migration? Ottolini's and Fomel's velocity-less migration is a ray theory migration with no amplitude or phase correction. It maps each input sample to a single output migrated location. We suggest that one can use the Ottolini-Fomel velocity field in a second higher quality conventional time migration. The Ottolini-Fomel technique delivers a fast inexpensive migration velocity field and avoids the expensive traditional method of estimating migration velocities via NMO velocity analysis followed by iterations of migration velocities. Our primary objective however, is to use Otolinni-Fomel migration velocities in multiple and noise suppression. The Ottolini-Fomel migration is actually one of four related attributes that we use for filtering. We call these the XTP attributes.

The term local event slope is synonymous with apparent horizontal slowness or $P$ value. $P$ values are commonly available in the $\tau - P$ domain, but for our purposes here, we need to measure and know $P$ values at all points in the time-space domain. We thus use the acronym XTP as shorthand for space($X$)-time($T$)-local slope($P$). We will use this term XTP to refer to not only the attribute but also the resultant migration/ velocity analysis and coherent noise filtering done with the XTP attributes.

## SOLVING FOR THE XTP ATTRIBUTES

Starting with the familiar double square root equation and its derivatives with respect to the source location and receiver location gives the 3 equations:

$$t = \sqrt{t_0^2 + \frac{(x_r - x_m)^2}{v^2}} + \sqrt{t_0^2 + \frac{(x_s - x_m)^2}{v^2}} \tag{1}$$

$$P_r(x,t) = \frac{\partial t}{\partial x_r} = \frac{x_r - x_m}{v^2\sqrt{t_0^2 + (x_r - x_m)^2/v^2}}$$

$$P_s(x,t) = \frac{\partial t}{\partial x_s} = \frac{x_s - x_m}{v^2\sqrt{t_0^2 + (x_s - x_m)^2/v^2}}$$

Where $x_m$ is the $x$ coordinate of the reflecting/ diffracting point and $x_r$ and $x_s$ are the locations of the source and receiver. $P_s(x,t)$ is a *shot* gather $P$ value and $P_r(x,t)$ is the *receiver* gather $P$ value for the same time and trace (we assume that reciprocal shot-receiver pairs are available). If we can measure $P_s$ and $P_r$, we will have 3 equations and 3 unknowns. Solving for the unknowns gives the first 3 XTP attributes:

$$x_m = x_s - dP_s \frac{t - dP_r}{t(P_r - P_s) + 2dP_sP_r}, \tag{2}$$

$$v^2 = \frac{x_s - x_m}{tP_s} + \frac{x_r - x_m}{tP_r}, \tag{3}$$

$$t_0 = \frac{|x_s - x_m|}{v}\frac{\sqrt{1/v^2 - P_s^2}}{|P_s|}, \tag{4}$$

where $d = x_r - x_s$ is the known source receiver distance. As per Clairbout (1985) an additional XTP attribute is the stack dip:

$$\text{stack dip} = \frac{P_s + P_r}{2}$$

Fomel (2007) does not start with the DSR equation, but he derives similar equations for $P$ values in the CMP and offset domain. As pointed out by Fomel, the solutions for $t_0$ and $x_m$ allow one to do 'velocity-less' time migration. Note that there is a strong connection here with the familiar Kirchhoff time migration as Kirchhoff migration is another solution to equation Yilmaz(1983).

## OBTAINING THE P VALUES

We use a combination of 2D instantaneous frequencies and a curvelet-like FK wedge filter to obtain the required shot and receiver domain $P$ values. An example of $P$ values is shown in figure 5A. Our solution for $P$ values is discussed in more detail in a companions presentation (Cooke et al, 2008b). For most samples in a shot or receiver gather, it is sufficient to calculate a single $P$ value. But as pointed out in figure 2A, there are some locations with multiple arrivals with different slopes. One of the key challenges then in XTP analysis to extract and use multiple $P$ values where multiple and conflicting dips occur. We use the terminology *instantaneous* $P$ values to denote that all samples in a gather have a single corresponding $P$ value and the term *spectral* $P$ values to indicate that all samples have a spectrum of $P$ solutions.

## EXAMPLE OF MIGRATION VELOCITY ESTIMATION

Figure 1A shows our interval velocity model used to generate 92 finite difference shot gathers. Figure 1B shows our XTP migration of those shot gathers using equations 2 and 4. Figure 2A shows one of the input shot gathers. Figure 2B shows a migrated common image point gather and 2C shows the XTP velocity attribute for that migrated gather. Figure 3A shows the XTP velocity attribute for figure 1B. Figure 3B shows the expected velocity answer; this is the RMS average of the interval velocities in figure 1A. Overall, there is a considerable difference between the XTP velocity attribute (3A) and the expected result (3B). These differences are caused by the following:

- due to the acquisition geometry, the source-receiver offsets drop to zero at the model edges;
- the fold drops to zero at the model edges;
- The XTP velocity will not be correct for a reflector's wavelet side lobes. Side lobes have the same P value as the center lobe, but are advanced or delayed in time. This effect is shown in figure 5A where *Ps* values are in constant 'bands' that track reflections. Because *Ps* is constant as time varies for this band, the resulting XTP velocity changes. Note that this same effect is observed on high quality NMO velocity spectra. Also not that this phenomena would be minimized with more and closer spaced reflectors in our model.
- The vertical axis is time in 3A and is depth in 3B.

The center portion of figure 3A above 1.6 seconds contains full fold primary reflections; note that the XTP velocity result here matches the expected velocity at the reflector wavelet's center lobes

## XTP VELOCITY WORK FLOW COMPARED TO CONVENTIONAL NMO-MIGRATION VELOCITY ANALYSIS.

Modern migration velocities analysis work flow is iterative (that is slow and manpower intensive) because it starts with NMO (stacking) velocities which have two types of 'errors': they are located in the unmigrated spatial location and they are distorted by a 1/cos(dip) factor. The iterative nature of conventional NMO & migration velocity analysis is needed to correct these errors. Note that these errors do not exist for above XTP velocity analysis. Additionally, NMO velocities frequently need to be manually interpreted to avoid stacking multiples. The section below shows how XTP attributes have the potential to simultaneously solve for the velocities of primaries reflections and noise (including multiples) which allows a filtering step that rejects the noise based on its XTP attributes.

## APLICATION OF XTP COHERENT NOISE FILTERING

The arrow in figure 2A points to a region containing 3 separate arrivals: a diffraction from a fault in our input velocity model, organized noise (actually a reflection from the model boundary) and multiples. In order to apply equations 2 and 3 at the arrow, a single $P_s$ value is needed (as well as a single $P_r$ value from the appropriate receiver gather) is needed - not 3 $P$ values. This dilemma was solved in the XTP migration of figure 1B by averaging the $P$ values of these 3 arrivals – not a desirable solution as the average is not exactly representative of the slope of any of the 3 arrivals. We now attempt to remove the shot gather noise annotated in figure 2A by using the higher resolution *spectral P* values (as opposed to *instantaneous P* values).

Figure 4 shows a model based decomposition of figure 2A. The sum of the 3 panels in figure 4 exactly equals figure 2A. The decomposition is based on having $P$ values more negative, equal to, or greater than $P$ values based on a predefined model (see Cooke et al, 2008b). XTP attributes are calculated for each of the 3 shots in figure 4. Figure 5A shows example $P_s$ values calculated from the center panel of figure 4 and used to calculate XTP attributes. Figure 5B shows the XTP $t_0$ attribute for the right panel in figure 4, and figure 5C shows a filter mask generated from this $t_0$ attribute. The mask for $t_0$ requires that $t_0$ lie between 0 and 2 seconds. The $x_\mathrm{m}$ mask (not shown) requires that $0<x_m<2500$m. The velocity mask (not shown) requires that 1400<vel< 2400m/sec. The shots post-masking are summed to give figure 6B. Figure 6A shows a similar XTP but it is based on instantaneous $P$ values, not the decomposition based on spectral P values that come from figure 4 .

## NOISE SUPPRESSION DISCUSSION

The XTP*(instantaneous P)* result in figure 6A indiscriminately removed noise and signal at the arrow; the resulting shot has been muted where the dipping events were. The XTP*(spectral P)* result in figure 6B however, has removed only the noise dipping from the right because it does not fit the double-square-root model that XTP attributes are based on. The arrival dipping from the left is a valid fault diffraction. The XTP attributes recognized this diffraction as a valid arrival and thus it was not filtered.

The Radon transform is one of our most powerful tools for suppressing multiples and noise. The Radon transform requires that all modeled primaries and multiples have their apex at source-receiver offset=0, and thus Radon noise suppression must be applied in the CMP domain. An alternative to CMP-Radon noise suppression is shot and/or receiver XTP noise suppression. Two advantages of doing this noise suppression in the shot and or receiver domain are:

- Dip discrimination between signal and noise can be greater in the shot domain than in the CMP domain. This is especially true when the apex of signal arrivals and noise arrivals are at different source-receiver offsets - a common occurrence for deep water diffracted multiples.
- The shot domain usually has denser offset sampling than the CMP domain which leads to better dip resolution and improved noise suppression capabilities.

## SUMMARY AND CONCLUSIONS

We have shown how local event slopes and XTP attributes can be used for velocity analysis and organized noise suppression. XTP velocities may offer an advantage over NMO velocities because XTP velocities are in the migrated spatial location and do not have a 1/cos(dip) scale factor. XTP noise suppression may offer an advantage over CMP-Radon noise suppression because XTP noise suppression can be done in the shot and/or receive domain where there can be some offset sampling and dip discrimination advantages.

All of the examples here are developed for synthetic data. These concepts need to be tested with real seismic data.

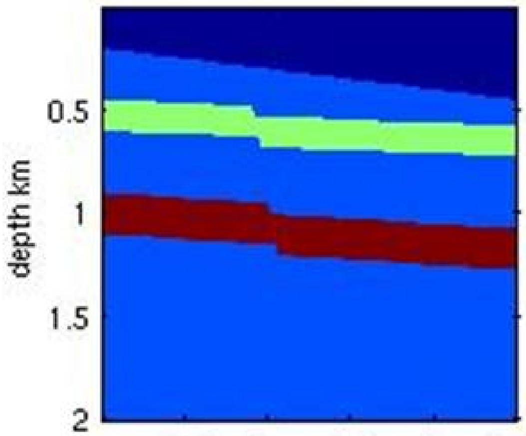


Figure 1A: Interval velocity model used to generate 92 finite difference shot gathers as in figure 2A.

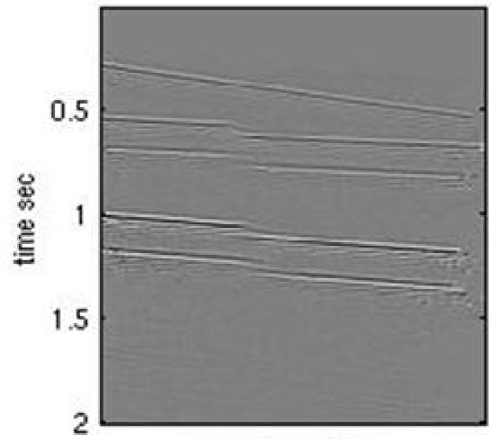


Figure 1B: XTP preStack time migration of those 92 gathers.

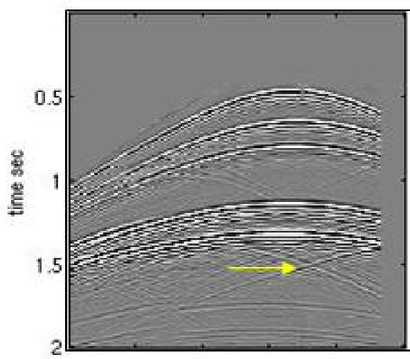


Figure 2A: One of the input shot gathers. Arrow denotes region with 3 different local slopes.

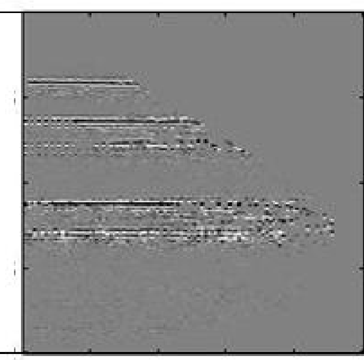

Figure 2B: XTP migrated shot gather.

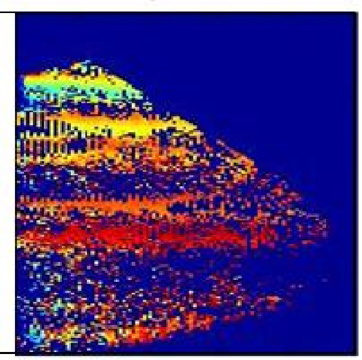

Figure 2C: XTP velocity attribute associated with figure 2B.

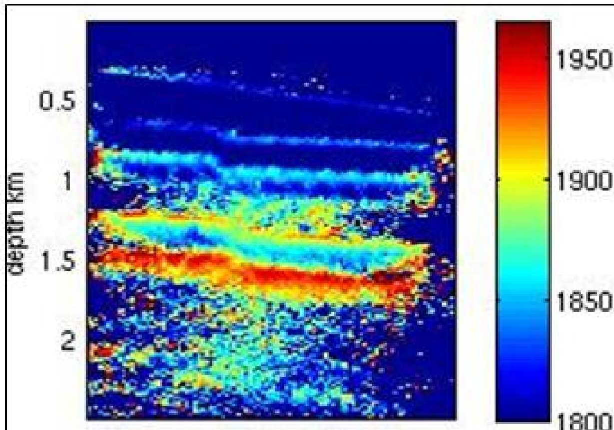


Figure 3A: Migrated and stacked XTP velocity. Vertical axis = km. Color bar is velocity in m/s and applies to both 3A and 3B.

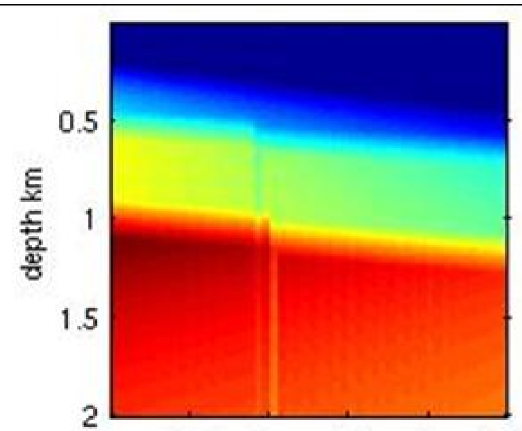


Figure 3B: Vrms calculated from figure 1A. Vertical axis = seconds

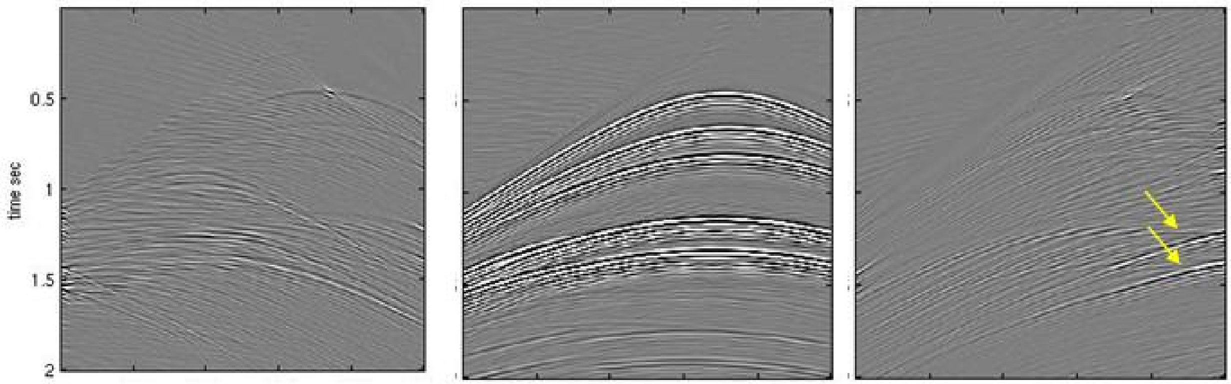


Figure 4: Result of decomposing the shot in figure 2A into 3 different 'P Band' pass regions. Center panel contains slopes that fit a pre-defined model. Left panel has P values more negative than center. Right panel has P values more positive than the center panel. Sum of all 3 panels exactly equals figure 2A.

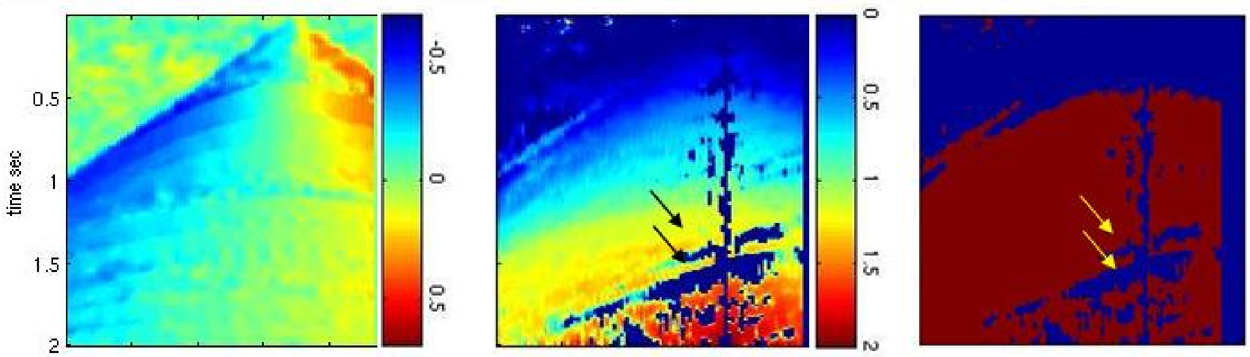


Figure 5A: $P_s$ values calculated from shot gather in figure 4, middle panel. Color = km/sec.

Figure 5B: XTP $t_0$ attribute for figure 4, right panel. Color = XTP $t_0$ attribute. Organised noise at arrows has XTP $t_0$ = 0 (blue)

Figure 5C: XTP $t_0$ filter mask. Red = 1(pass) and blue = 0 (reject). Each input decomposed shot above is multiplied by the 3 XTP filter masks.

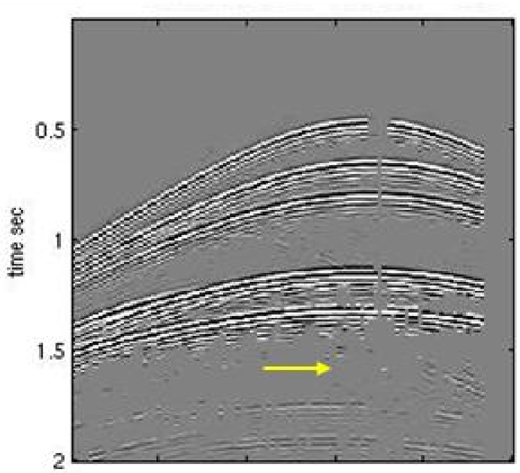


Figure 6A: Shot from figure 2A filtered using XTP attributes based on instantaneous P values.

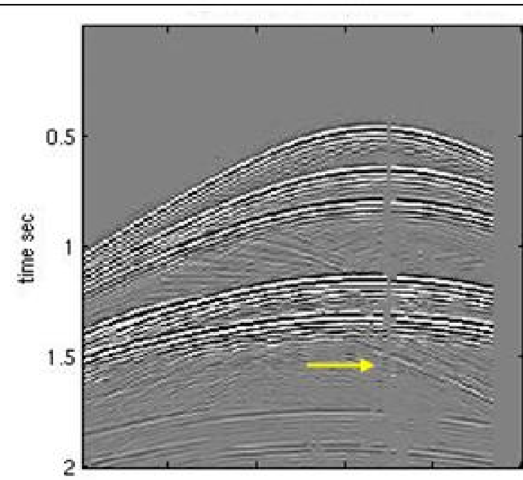


Figure 6B: Shot from figure 2A filtered using XTP attributes based on spectral P values.