

The Curvelet Transform

[A review of recent applications]

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Multiresolution methods are deeply related to image processing, biological and computer vision, and scientific computing. The curvelet transform is a multiscale directional transform that allows an almost optimal nonadaptive sparse representation of objects with edges. It has generated increasing interest in the community of applied mathematics and signal processing over the years. In this article, we present a review on the curvelet transform, including its history beginning from wavelets, its logical relationship to other multiresolution multidirectional methods like contourlets and shearlets, its basic theory and discrete algorithm. Further, we consider recent applications in image/video processing, seismic exploration, fluid mechanics, simulation of partial differential equations, and compressed sensing.

INTRODUCTION

Most natural images/signals exhibit line-like edges, i.e., discontinuities across curves (so-called line or curve singularities). Although applications of wavelets have become increasingly popular in scientific and engineering fields, traditional wavelets perform well only at representing point singularities since they ignore the geometric properties of structures and do not exploit the regularity of edges. Therefore, wavelet-based compression, denoising, or structure extraction become computationally inefficient for geometric features with line and surface singularities. In fluid mechanics, discrete wavelet thresholding often leads to oscillations along edges of the coherent eddies and, consequently, to the deterioration of the vortex tube structures, which in turn

Digital Object Identifier 10.1109/MSP.2009.935453

can cause an unphysical leak of energy into neighboring scales producing an artificial “cascade” of energy.

Multiscale methods are also deeply related with biological and computer vision. Since Olshausen and Field’s work in *Nature* [55], researchers in biological vision have reiterated the similarity between vision and multiscale image processing. It has been recognized that the receptive fields of simple cells in a mammalian primary visual cortex can be characterized as being spatially localized, oriented, and bandpass (selective to structure at different spatial scales). However, wavelets do not supply a good direction selectivity, which is also an important response property of simple cells and neurons at stages of the visual pathway. Therefore, a directional multiscale sparse coding is desirable in this field.

One of the primary tasks in computer vision is to extract features from an image or a sequence of images. The features can be points, lines, edges, and textures. A given feature is characterized by position, direction, scale, and other property parameters. The most common technique, used in early vision for extraction of such features, is linear filtering, which is also reflected in models used in biological visual systems, i.e., human visual motion sensing. Objects at different scales can arise from distinct physical processes. This leads to the use of scale-space filtering and multiresolution wavelet transform in this field. An important motivation for computer vision is to obtain directional representations that capture anisotropic lines and edges while providing sparse decompositions.

To overcome the missing directional selectivity of conventional two-dimensional (2-D) discrete wavelet transforms (DWTs), a multiresolution geometric analysis (MGA), named curvelet transform, was proposed [7]–[12]. In the 2-D case, the curvelet transform allows an almost optimal sparse representation of objects with singularities along smooth curves. For a smooth object f with discontinuities along C^2 -continuous curves, the best N -term approximation \tilde{f}_N that is a linear combination of only N elements of the curvelet frame obeys $\|f - \tilde{f}_N\|_2^2 \leq CN^{-2} (\log N)^3$, while for wavelets the decay rate is only N^{-1} . Combined with other methods, excellent performance of the curvelet transform has been shown in image processing; see e.g., [49], [45], [60], and [61]. Unlike the isotropic elements of wavelets, the needle-shaped elements of the curvelet transform possess very high directional sensitivity and anisotropy (see Figure 1 for the 2-D case). Such elements are very efficient in representing line-like edges. Recently, the curvelet transform has been extended to three dimensions by Ying et al. [7], [68].

Let us roughly compare the curvelet system with the conventional Fourier and wavelet analysis. The short-time Fourier transform uses a shape-fixed rectangle in frequency domain, and conventional wavelets use shape-changing (dilated) but area-fixed windows. By contrast, the curvelet transform uses angled polar wedges or angled trapezoid windows in frequency domain to resolve directional features.

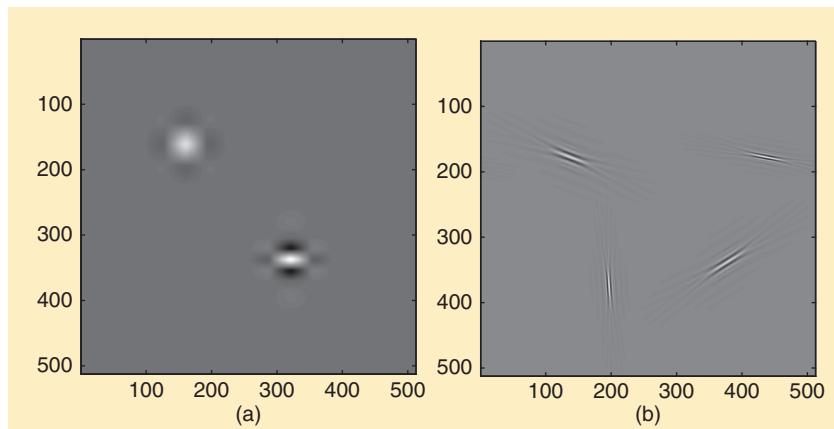
The theoretic concept of curvelets is easy to understand, but how to achieve the discrete algorithms for practical applications is challenging. In this article, we first address a brief history of curvelets starting from classical wavelets. We also mention some other wavelet-like constructions that aim to improve the representation of oriented features towards visual reception and image processing. Then we shall derive the discrete curvelet frame and the corresponding fast algorithm for the discrete curvelet transform in the 2-D case. Finally, we show some recent applications of the discrete curvelet transform in image and seismic processing, fluid mechanics, numerical treatment of partial differential equations, and compressed sensing.

FROM CLASSICAL WAVELETS TO CURVELETS

As outlined in the introduction, although the DWTs has established an impressive reputation as a tool for mathematical analysis and signal processing, it has the disadvantage of poor directionality, which has undermined its usage in many applications. Significant progress in the development of directional wavelets has been made in recent years. The complex wavelet transform is one way to improve directional selectivity. However, the complex wavelet transform has not been widely used in the past, since it is difficult to design complex wavelets with perfect reconstruction properties and good filter characteristics [29], [53]. One popular technique is the dual-tree complex wavelet transform (DT CWT) proposed by Kingsbury [37], [38], which added (almost) perfect reconstruction to the other attractive properties of complex wavelets, including approximate shift invariance, six directional selectivities, limited redundancy and efficient $\mathcal{O}(N)$ computation.

The 2-D complex wavelets are essentially constructed by using tensor-product one-dimensional (1-D) wavelets. The directional selectivity provided by complex wavelets (six directions) is much better than that obtained by the classical DWTs (three directions), but is still limited.

In 1999, an anisotropic geometric wavelet transform, named ridgelet transform, was proposed by Candès and Donoho [4], [8]. The ridgelet transform is optimal at representing straight-line



[FIG1] The elements of (a) wavelets and (b) curvelets on various scales, directions, and translations in the spatial domain. Note that the tensor-product 2-D wavelets are not strictly isotropic but prefer axes directions.

singularities. Unfortunately, global straight-line singularities are rarely observed in real applications. To analyze local line or curve singularities, a natural idea is to consider a partition of the image, and then to apply the ridgelet transform to the obtained sub-images. This block ridgelet-based transform, which is named curvelet transform, was first proposed by Candès and Donoho in 2000, see [9]. Apart from the blocking effects, however, the application of this so-called first-generation curvelet transform is limited because the geometry of ridgelets is itself unclear, as they are not true ridge functions in digital images. Later, a considerably simpler second-generation curvelet transform based on a frequency partition technique was proposed by the same authors; see [10]–[12]. Recently, a variant of the second-generation curvelet transform was proposed to handle image boundaries by mirror extension (ME) [19]. Previous versions of the transform treated image boundaries by periodization. Here, the main modifications are to tile the discrete cosine domain instead of the discrete Fourier domain and to adequately reorganize the data. The obtained algorithm has the same computational complexity as the standard curvelet transform.

The second-generation curvelet transform [10]–[12] has been shown to be a very efficient tool for many different applications in image processing, seismic data exploration, fluid mechanics, and solving partial differential equations (PDEs). In this survey, we will focus on this successful approach and show its theoretical and numerical aspects as well as the different applications of curvelets. From the mathematical point of view, the strength of the curvelet approach is their ability to formulate strong theorems in approximation and operator theory. The discrete curvelet transform is very efficient in representing curve-like edges. But the current curvelet systems still have two main drawbacks: 1) they are not optimal for sparse approximation of curve features beyond C^2 -singularities, and 2) the discrete curvelet transform is highly redundant. The currently available implementations of the discrete curvelet transform (see www.curvelet.org) aim to reduce the redundancy smartly. However, independently from the good theoretical results on N -term approximation by curvelets, the discrete curvelet transform is not appropriate for image compression. The question of how to construct an orthogonal curvelet-like transform is still open.

RELATIONSHIP OF CURVELETS TO OTHER DIRECTIONAL WAVELETS

There have been several other developments of directional wavelet systems in recent years with the same goal, namely a better analysis and an optimal representation of directional features of signals in higher dimensions. None of these approaches has reached the same publicity as the curvelet transform. However, we want to mention shortly some of these developments and also describe their relationship to curvelets.

Steerable wavelets [28], [59], Gabor wavelets [40], wedgelets [23], beamlets [24], bandlets [51], [54], contourlets [21], shearlets [39], [31], wave atoms [20], platelets [67], and surfacelets [42] have been proposed independently to identify and restore geometric features. These geometric wavelets or directional wavelets are uniformly called X-lets.

The steerable wavelets [28], [59] and Gabor wavelets [40] can be seen as early directional wavelets. The steerable wavelets were built based on directional derivative operators (i.e., the second derivative of a Gaussian), while the Gabor wavelets were produced by a Gabor kernel that is a product of an elliptical Gaussian and a complex plane wave. In comparison to separable orthonormal wavelets, the steerable wavelets provide translation-invariant and rotation-invariant representations of the position and the orientation of considered image structures. This feature is paid by high redundancy. Applications of Gabor wavelets focused on image classification and texture analysis. Gabor wavelets have also been used for modeling the receptive field profiles of cortical simple cells. Applications of Gabor wavelets suggested that the precision in resolution achieved through redundancy may be a relevant issue in brain modeling, and that orientation plays a key role in the primary visual cortex. The main differences between steerable wavelets/Gabor wavelets and other X-lets is that the early methods do not allow for a different number of directions at each scale.

Contourlets, as proposed by Do and Vetterli [21], form a discrete filter bank structure that can deal effectively with piecewise smooth images with smooth contours. This discrete transform can be connected to curvelet-like structures in the continuous domain. Hence, the contourlet transform [21] can be seen as a discrete form of a particular curvelet transform. Curvelet constructions require a rotation operation and correspond to a partition of the 2-D frequency plane based on polar coordinates; see the section “The Discrete Curvelet Frame.” This property makes the curvelet idea simple in the continuous case but causes problems in the implementation for discrete images. In particular, approaching critical sampling seems difficult in discretized constructions of curvelets. For contourlets, critically sampling is easy to implement. There exists an orthogonal version of the contourlet transform that is faster than current discrete curvelet algorithms [7]. The directional filter bank, as a key component of contourlets, has a convenient tree-structure, where aliasing is allowed to exist and will be canceled by carefully designed filters. Thus, the key difference between contourlets and curvelets is that the contourlet transform is directly defined on digital-friendly discrete rectangular grids. Unfortunately, contourlet functions have less clear directional geometry/features than curvelets (i.e., more oscillations along the needle-like elements) leading to artifacts in denoising and compression.

Surfacelets [42] are 3-D extensions of the 2-D contourlets that are obtained by a higher-dimensional directional filter bank and a multiscale pyramid. They can be used to efficiently capture and represent surface-like singularities in multidimensional volumetric data involving biomedical imaging, seismic imaging, video processing and computer vision. Surfacelets and the 3-D curvelets (see the section “Three-Dimensional Curvelet Transform”) aim at the same frequency partitioning, but the two transforms achieve this goal with different approaches as we described above in the 2-D case. The surfacelet transform is less redundant than the 3-D curvelet transform, and this advantage is payed by a certain loss of directional features.

Unlike curvelets, the shearlets [39], [31] form an affine system with a single generating mother shearlet function parameterized

by a scaling, a shear, and a translation parameter, where the shear parameter captures the direction of singularities. It has been shown that both the curvelet and shearlet transforms are (at least theoretically) similarly well suited for approximation of piece-wise smooth images with singularities along smooth curves [12], [31]. Indeed, using the fast curvelet transform based on transition to Cartesian arrays, described in the section “Transition to Cartesian Arrays,” the discrete implementations of the two transforms are very similar [7].

The bandlet transform [51], [54] is, in contrast with the previously mentioned transforms, based on adaptive techniques and has a good performance for images with textures beyond C^2 -singularities, but it has to pay much higher computational cost for its adaptation.

In this article, we are not able to give a more detailed overview on all these approaches and refer to the given references for further information.

THE DISCRETE CURVELET FRAME

In this section, we want to consider the construction of a discrete curvelet frame. Recalling the structure of 1-D wavelets being well localized in frequency domain, we consider the question how these ideas can suitably be transferred to construct a curvelet frame that is an (almost) rotation-invariant function frame in two dimensions. Finally, we summarize the properties of the obtained curvelet elements.

WHAT CAN BE LEARNED FROM THE 1-D WAVELET TRANSFORM?

Using the 1-D dyadic wavelet transform in signal analysis, one considers a family of dilated and translated functions $\{\psi_{j,k} := 2^{j/2}\psi(2^j \cdot -k) : j, k \in \mathbb{Z}\}$, generated by one mother wavelet $\psi \in L^2(\mathbb{R})$, and being an orthonormal basis of $L^2(\mathbb{R})$. Then, each signal $f \in L^2(\mathbb{R})$ can be uniquely represented in a wavelet expansion

$$f = \sum_{j, k} c_{j, k}(f) \psi_{j, k},$$

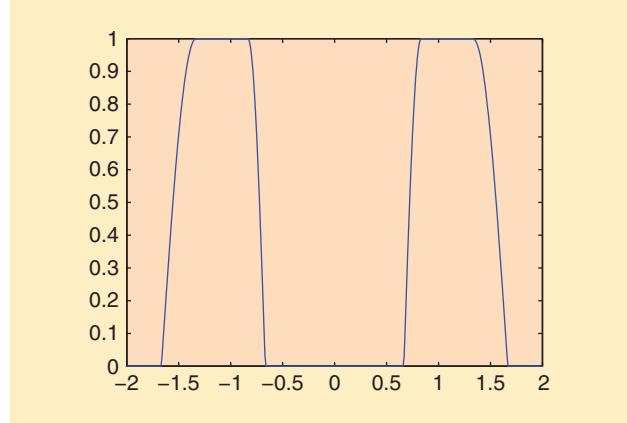
where $c_{j, k}(f) := \langle f, \psi_{j, k} \rangle$ are the wavelet coefficients. Here $\langle \cdot, \cdot \rangle$ denotes the scalar product in $L^2(\mathbb{R})$. Observe that the Fourier transformed elements of the wavelet basis have the form

$$\hat{\psi}_{j, k}(\xi) = 2^{-j/2} e^{-i2^{-j}\xi k} \hat{\psi}(2^{-j}\xi),$$

i.e., dilation by 2^j in space domain corresponds to dilation by 2^{-j} in frequency domain, and the translation corresponds to a phase shift.

For a good frequency localization of the wavelet basis, the main idea is to construct a wavelet basis that provides a partition of the frequency axis into (almost) disjoint frequency bands (or octaves). Such a partition can be ensured if the Fourier transform of the dyadic wavelet $\hat{\psi}$ has a localized or even compact support and satisfies the admissibility condition

$$\sum_{j=-\infty}^{\infty} |\hat{\psi}(2^{-j}\xi)|^2 = 1, \quad \xi \in \mathbb{R} \text{ a.e..} \quad (1)$$



[FIG2] Plot of a Meyer wavelet $\hat{\psi}(\xi)$ in frequency domain.

This admissibility condition also ensures the typical wavelet property $\hat{\psi}(0) = \int_{-\infty}^{\infty} \hat{\psi}(x) dx = 0$.

A particularly good frequency localization is obtained, if $\hat{\psi}$ is compactly supported in $[-2, -1/2] \cup [1/2, 2]$. Such a construction has been used for Meyer wavelets (see Figure 2). Obviously, the dilated Meyer wavelets $\hat{\psi}(2^{-j}\xi)$ generate a tiling of the frequency axis into frequency bands, where $\hat{\psi}(2^{-j}\xi)$ has its support inside the intervals $[-2^{j+1}, -2^{j-1}] \cup [2^{j-1}, 2^{j+1}]$. In this case, for a fixed $\xi \in \mathbb{R}$, at most two wavelet functions in the sum (1) overlap. We remark that the condition (1) implies even more! It ensures that the function family $\{\psi_{j,k} : j, k \in \mathbb{Z}\}$ forms a tight frame of $L^2(\mathbb{R})$ (see e.g., [50, Theorem 5.1]).

Finally, a localization property of the dyadic wavelet transform in space domain is guaranteed if also ψ is localized, i.e., if $\hat{\psi}$ is smooth.

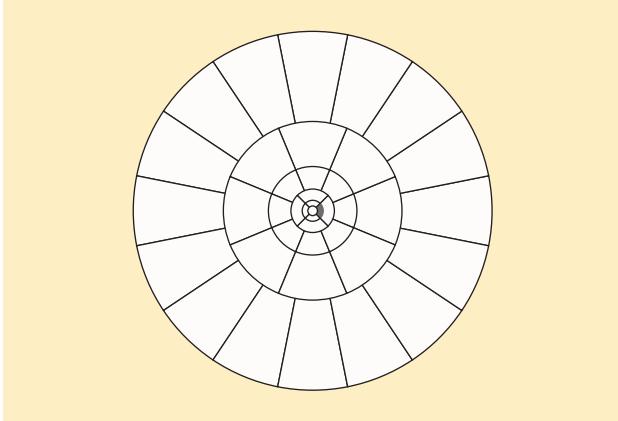
HOW TO TRANSFER THIS IDEA TO THE CURVELET CONSTRUCTION

We wish to transfer this construction principle to the 2-D case for image analysis and incorporate a certain rotation invariance. So, we wish to construct a frame, generated again by one basic element, a basic curvelet ϕ , this time using translations, dilations, and rotations of ϕ . Following the considerations in the 1-D case, the elements of the curvelet family should now provide a tiling of the 2-D frequency space. Therefore the curvelet construction is now based on the following two main ideas [11].

- 1) Consider polar coordinates in frequency domain.
- 2) Construct curvelet elements being locally supported near wedges according to Figure 3, where the number of wedges is $N_j = 4 \cdot 2^{[j/2]}$ at the scale 2^{-j} , i.e., it doubles in each second circular ring. (Here $[x]$ denotes the smallest integer being greater than or equal to x .)

Let now $\xi = (\xi_1, \xi_2)^T$ be the variable in frequency domain. Further, let $r = \sqrt{\xi_1^2 + \xi_2^2}$, $\omega = \arctan \xi_1 / \xi_2$ be the polar coordinates in frequency domain. For the “dilated basic curvelets” in polar coordinates we use the ansatz

$$\phi_{j, 0, 0}(r, \omega) := 2^{-3j/4} W(2^{-j}r) \tilde{V}_{N_j}(\omega), \quad r \geq 0, \omega \in [0, 2\pi), j \in N_0, \quad (2)$$



[FIG3] Tiling of the frequency domain into wedges for curvelet construction.

where we use suitable window functions W and \tilde{V}_{N_j} , and where a rotation of $\phi_{j,0,0}$ corresponds to the translation of a 2π -periodic window function \tilde{V}_{N_j} . The index N_j indicates the number of wedges in the circular ring at scale 2^{-j} (see Figure 3). To construct a (dilated) basic curvelet with compact support near a “basic wedge” (see e.g., the gray wedge in Figure 3 for $j = 0$), the two windows W and \tilde{V}_{N_j} need to have compact support. The idea is to take $W(r)$ similarly as in the 1-D case, to cover the interval $(0, \infty)$ with dilated curvelets, and to take \tilde{V}_{N_j} such that a covering in each circular ring is ensured by translations of \tilde{V}_{N_j} . Here, we have $r \in [0, \infty)$, therefore we cannot take the complete Meyer wavelet to determine W , but only the part that is supported in $[1/2, 2]$ (see Figure 2). Then the admissibility condition (1) yields

$$\sum_{j=-\infty}^{\infty} |W(2^{-j}r)|^2 = 1 \quad (3)$$

for $r \in (0, \infty)$. For an explicit construction of W , see “Window Functions.”

Further, for the tiling of a circular ring into N wedges, where N is an arbitrary positive integer, we need a 2π -periodic nonnegative window \tilde{V}_N with support inside $[-2\pi/N, 2\pi/N]$ such that

$$\sum_{l=0}^{N-1} \tilde{V}_N^2 \left(\omega - \frac{2\pi l}{N} \right) = 1 \quad \text{for all } \omega \in [0, 2\pi)$$

is satisfied. Then only two “neighbored” translates of \tilde{V}_N^2 in the sum overlap. Such windows \tilde{V}_N can be simply constructed as 2π -periodizations of a scaled window $V(N\omega/2\pi)$, where V is given in “Window Functions.”

In this way we approach the goal to get a set of curvelet functions with compact support in frequency domain on wedges, where in the circular ring that corresponds to the scale 2^{-j} the sum of the squared rotated curvelet functions depends only on $W(2^{-j}r)$, i.e., it follows that

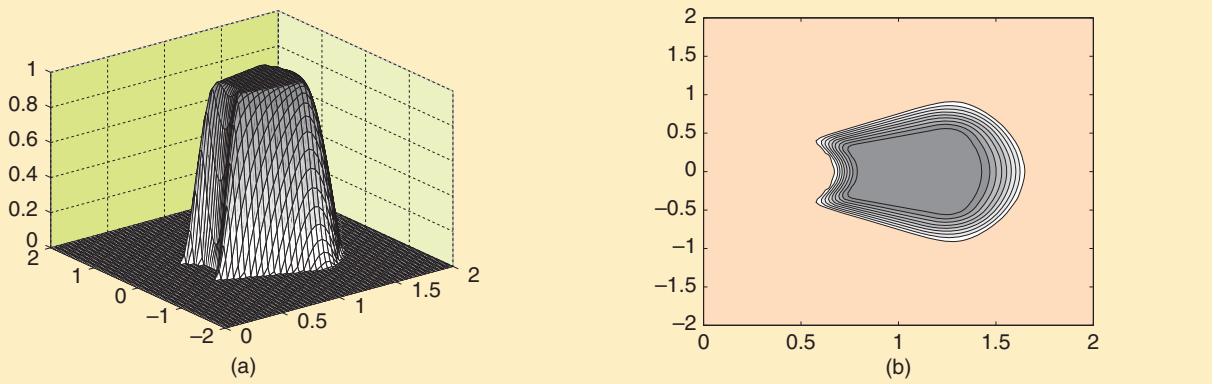
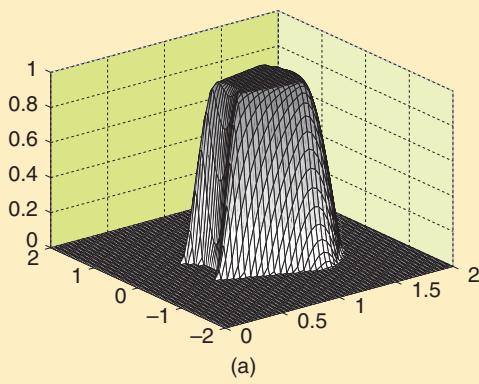
$$\begin{aligned} \sum_{l=0}^{N_j-1} \left| 2^{3j/4} \hat{\phi}_{j,0,0} \left(r, \omega - \frac{2\pi l}{N_j} \right) \right|^2 &= |W(2^{-j}r)|^2 \sum_{l=0}^{N_j-1} \tilde{V}_{N_j}^2 \left(\omega - \frac{2\pi l}{N_j} \right) \\ &= |W(2^{-j}r)|^2. \end{aligned} \quad (4)$$

Together with (3), that means that using the rotations of the dilated basic curvelets $\hat{\phi}_{j,0,0}$, we are able to guarantee an admissibility condition similar to (1) for the 1-D wavelet frame. Remember that the translates of $\phi_{j,0,0}$ have no influence here, since translates in space domain correspond to phase shifts in frequency domain that do not change the support of the Fourier transformed curvelets. The basic curvelet $\hat{\phi}_{j,0,0}$ is illustrated in Figure 4.

There is a last point we have to attend to, namely the “hole” that arises in the frequency plane around zero, since the rotations of the dilated basic curvelets work only in the scales 2^{-j} for $j = 0, 1, 2, \dots$. Taking now all scaled and rotated curvelet elements together with $N_j := 4 \cdot 2^{[j/2]}$ we find for the scales 2^{-j} , $j = 0, 1, \dots$ with (3) and (4)

$$\sum_{j=0}^{\infty} \sum_{l=0}^{N_j-1} \left| 2^{3j/4} \hat{\phi}_{j,0,0} \left(r, \omega - \frac{2\pi l}{N_j} \right) \right|^2 = \sum_{j=0}^{\infty} |W(2^{-j}r)|^2,$$

and this sum is only for $r > 1$ equal to one. For a complete covering of the frequency plane, we therefore need to define a low-pass element



[FIG4] Basic curvelet $\hat{\phi}_{0,0,0}$ in the (a) frequency domain and (b) its support.

WINDOW FUNCTIONS

For constructing the curvelet functions we shall use the following special window functions. Let us consider the scaled Meyer windows (see [18, p. 137])

$$V(\omega) = \begin{cases} 1 & |\omega| \leq 1/3, \\ \cos\left[\frac{\pi}{2}\nu(3|\omega|-1)\right] & 1/3 \leq |\omega| \leq 2/3, \\ 0 & \text{else}, \end{cases}$$

$$W(r) = \begin{cases} \cos\left[\frac{\pi}{2}\nu(5-6r)\right] & 2/3 \leq r \leq 5/6, \\ 1 & 5/6 \leq r \leq 4/3, \\ \cos\left[\frac{\pi}{2}\nu(3r-4)\right] & 4/3 \leq r \leq 5/3, \\ 0 & \text{else}, \end{cases}$$

where ν is a smooth function satisfying

$$\nu(x) = \begin{cases} 0 & x \leq 0, \\ 1 & x \geq 1, \end{cases} \quad \nu(x) + \nu(1-x) = 1, \quad x \in \mathbb{R}.$$

For the simple case $\nu(x) = x$ in $[0, 1]$, the window functions $V(\omega)$ and $W(r)$ are plotted in Figure S1. To obtain smoother functions W and V , we need to take smoother functions ν . We may use the polynomials $\nu(x) = 3x^2 - 2x^3$ or $\nu(x) = 5x^3 - 5x^4 + x^5$ in $[0, 1]$, such that ν is in $C^1(\mathbb{R})$ or in $C^2(\mathbb{R})$. An example of an arbitrarily smooth window ν is given by

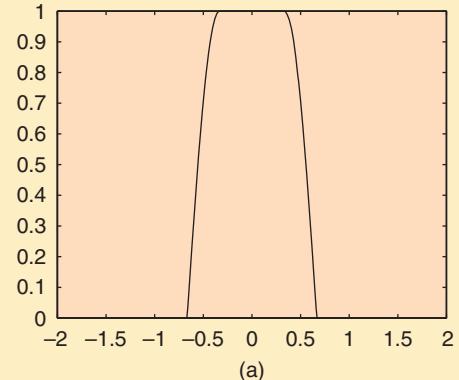
$$\nu(x) = \begin{cases} 0 & x \leq 0, \\ \frac{s(x-1)}{s(x-1) + s(x)} & 0 < x < 1, \\ 1 & x \geq 1 \end{cases}$$

with $s(x) = e^{-\left(\frac{1}{(1+x)^2} + \frac{1}{(1-x)^2}\right)}$.

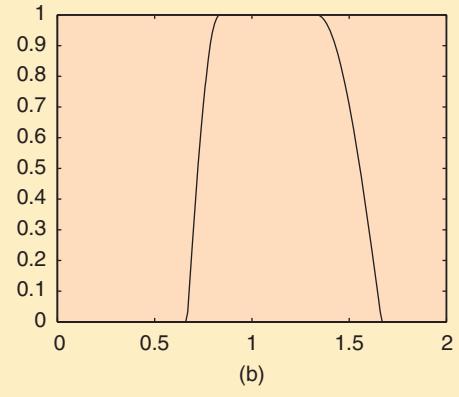
The above two functions $V(t)$ and $W(r)$ satisfy the conditions

$$\sum_{l=-\infty}^{\infty} V^2(\omega-l) = 1, \quad t \in \mathbb{R}, \quad (S1)$$

$$\sum_{j=-\infty}^{\infty} W^2(2^j r) = 1, \quad r > 0. \quad (S2)$$



(a)



(b)

[FIGS1] Plot of the (a) windows $V(\omega)$ and (b) $W(r)$.

In particular, the 2π periodic window functions $\tilde{V}_N(\omega)$ needed for curvelet construction, can now be obtained as 2π -periodization of $V(N\omega/2\pi)$.

$$\hat{\phi}_{-1}(\xi) := W_0(|\xi|) \quad \text{with} \quad W_0^2(r)^2 := 1 - \sum_{j=0}^{\infty} W(2^{-j}r)^2 \quad (5)$$

that is supported on the unit circle, and where we do not consider any rotation.

HOW MANY WEDGES SHOULD BE TAKEN IN ONE CIRCULAR RING?

As we have seen already in Figure 3 and postulated in the last subsection, for the curvelet construction, there are $N_j = 4 \cdot 2^{[j/2]}$ angles (or wedges) chosen in the circular ring (with radius $2^{j-1/2} \leq r \leq 2^{j+1/2}$) corresponding to the 2^{-j} th scale, see [11].

But looking at the above idea to ensure the admissibility condition for a tight frame, one is almost free to choose the number of wedges/angles in each scale. Principally, the construction works for all ratios of angles and scales. In fact this is an important point, where curvelets differ from other constructions.

- 1) If we take the number of wedges in a fixed way, independent of the scale, we essentially obtain steerable wavelets.

2) If the number of wedges increases like 1/scale (i.e., like 2^j), then we obtain tight frames of ridgelets.

3) If the number of wedges increases like $\sqrt{1/\text{scale}}$ (i.e., like $2^{j/2}$), the curvelet frame is obtained. This special anisotropic scaling law yields the typical curvelet elements whose properties are considered next.

WHAT PROPERTIES DO THE CURVELET ELEMENTS HAVE?

To obtain the complete curvelet family, we need to consider the rotations and the translations of the dilated basic curvelets $\phi_{j,0,0}$. We choose

- an equidistant sequence of rotation angles $\theta_{j,l}$
- the positions $b_k^{j,l} = b_{k_1,k_2}^{j,l} := R_{\theta_{j,l}}^{-1}((k_1/2^j)(k_2/2^{j/2}))^T$ with $k_1, k_2 \in \mathbb{Z}$, and where R_θ denotes the rotation matrix with angle θ .

Then the family of curvelet functions is given by

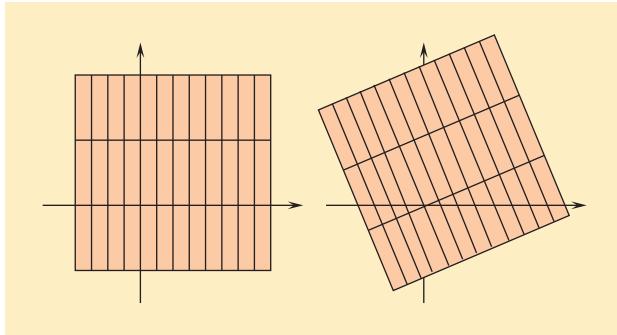
$$\phi_{j,k,l}(x) := \phi_{j,0,0}(R_{\theta_{j,l}}(x - b_k^{j,l})) \quad (6)$$

with indices $j \in \mathbb{N}_0$ and $k = (k_1, k_2)$, l as above.

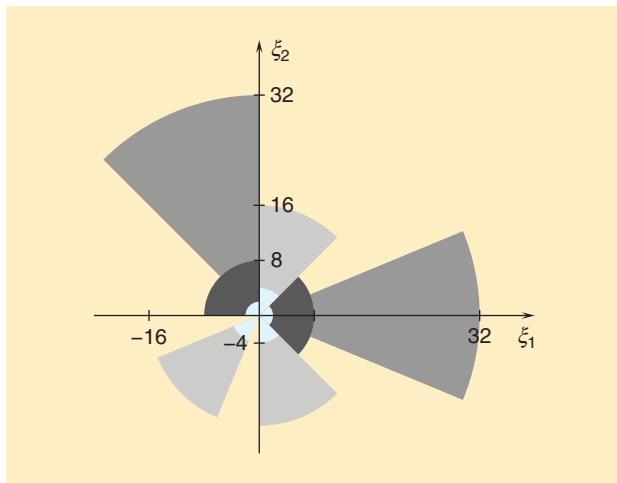
One should note that the positions $b_k^{j,l}$ are on different regular grids for each different rotation angle, and these grids have different spacing in the two directions being consistent with the parabolic scaling (i.e., with the ratio of angles and scales). This choice will lead to a discrete curvelet system that forms a tight frame, i.e., every function $f \in L^2(\mathbb{R}^2)$ will be representable by a curvelet series, and hence the discrete curvelet transform will be invertible.

For example, for $j = 0$ we consider the angles $\theta_{0,l} = \pi l / 2$, $l = 0, 1, 2, 3$ and the positions $\{b_k^{0,l}\}_{k \in \mathbb{Z}^2, l=0,1,2,3} = \mathbb{Z}^2$. For $j = 4$, the angles $\theta_{4,l} = \pi l / 8$, $l = 0, \dots, 15$ occur, and, depending on the angles $\theta_{4,b}$, eight different grids for translation are considered, where rectangles of size $1/16 \times 1/4$ are rotated by $\theta_{4,b}$, $b = 0, \dots, 7$, see Figure 5. In particular, the choice of positions yields a parabolic scaling of the grids with the relationship length $\approx 2^{-j/2}$ and width $\approx 2^{-j}$.

The underlying idea for the choice of the translation grids is as follows. Considering a band-limited function f , where \hat{f} has its support on a single wedge (e.g., in the scale 2^{-j} ; see Figure 6), one



[FIG5] Grid for $\theta_{4,0} = 0$ and for $\theta_{4,1} = \pi/8$.



[FIG6] Maximal supports of $\hat{\phi}_{2,k,0}$ and $\hat{\phi}_{2,k,5}$ (dark grey); $\hat{\phi}_{3,k,3}$, $\hat{\phi}_{3,k,6}$ and $\hat{\phi}_{3,k,13}$ (light grey); and of $\hat{\phi}_{4,k,0}$ and $\hat{\phi}_{4,k,11}$ (grey). The translation index $k \in \mathbb{Z}^2$ does not influence the support of the curvelet elements.

can determine a rotation angle and a translation to map this wedge into the center of the frequency plane, then find a rectangle of size $2^j \times 2^{j/2}$ to cover the wedge, and finally use the Shannon sampling theorem to fix the needed sampling rate for covering f . All sampling rates that are obtained in this way have to be taken, and thus one finds the needed positions as above.

SUPPORT IN FREQUENCY DOMAIN

In frequency domain, the curvelet function $\hat{\phi}_{j,k,l}$ is supported inside the polar wedge with radius $2^{j-1} \leq r \leq 2^{j+1}$ and angle $2^{-[j/2]} \pi (-1-l)/2 < \omega < 2^{-[j/2]} \pi (1-l)/2$. The support of $\hat{\phi}_{j,k,l}$ does not depend on the position $b_k^{j,l}$. For example, $\hat{\phi}_{2,k,l}(r, \omega)$ is supported inside the wedge with $2 \leq r \leq 8$ and $(-1-l)\pi/4 \leq \omega \leq (1-l)\pi/4$, $l = 0, \dots, 7$; see Figure 6. (Here we have used $\text{supp } \tilde{V}_{N_j} \subset [-2\pi/N_j, 2\pi/N_j]$ and $\text{supp } W \subset [1/2, 2]$.)

SUPPORT IN TIME DOMAIN AND OSCILLATION PROPERTIES

In time domain, things are more involved. Since $\hat{\phi}_{j,k,l}$ has compact support, the curvelet function $\phi_{j,k,l}$ cannot have compact support in time domain. From Fourier analysis, one knows that the decay of $\phi_{j,k,l}(x)$ for large $|x|$ depends on the smoothness of $\hat{\phi}_{j,k,l}$ in frequency domain. The smoother $\hat{\phi}_{j,k,l}$, the faster the decay.

By definition, $\hat{\phi}_{j,0,0}(\xi)$, $j \in \mathbb{N}_0$, is supported away from the vertical axis $\xi_1 = 0$ but near the horizontal axis $\xi_2 = 0$; see Figure 6. Hence, for large $j \in \mathbb{N}_0$ the function $\phi_{j,0,0}(x)$ is less oscillatory in x_2 -direction (with frequency about $2^{-j/2}$) and very oscillatory in x_1 -direction (containing frequencies of about 2^{j-1}). The essential support of the amplitude spectrum of $\phi_{j,0,0}$ is a rectangle of size $[-\pi 2^{j-1}, \pi 2^{j-1}] \times [-\pi 2^{j/2}, \pi 2^{j/2}]$, and the decay of $\phi_{j,0,0}$ away from this rectangle essentially depends on the smoothness of $\hat{\phi}$ respectively, the windows V and W . From (6), we simply observe that the essential support of $\phi_{j,k,l}$ is the rectangle rotated by the angle $\theta_{j,l}$ and translated by $R_{\theta_{j,l}} b_k^{j,l}$.

Remark

The concept “essential support” of a function f with good decay properties is used in literature without rigorous definition but with the following intuitive meaning: the essential support is a finite region that contains the most important features of the function. Outside this support, the graph of f consists mainly of asymptotic tails that can be neglected in certain considerations.

TIGHT FRAME PROPERTY

The system of curvelets

$$\{\phi_{-1,k,0} : k \in \mathbb{Z}^2\} \cup \{\phi_{j,k,l} : j \in \mathbb{N}_0, l = 0, \dots, 4 \cdot 2^{[j/2]} - 1, k = (k_1, k_2)^T \in \mathbb{Z}^2\}$$

satisfies a tight frame property. That means, every function $f \in L^2(\mathbb{R}^2)$ can be represented as a curvelet series

$$f = \sum_{j,k,l} \langle f, \phi_{j,k,l} \rangle \phi_{j,k,l} \quad (7)$$

and the Parseval identity

$$\sum_{j,k,l} |\langle f, \phi_{j,k,l} \rangle|^2 = \|f\|_{L^2(\mathbb{R}^2)}^2, \quad \forall f \in L^2(\mathbb{R}^2)$$

holds. For a proof, we refer to [11]. The terms $c_{j,k,l}(f) := \langle f, \phi_{j,k,l} \rangle$ are called curvelet coefficients. In particular, we obtain by Plancherel's Theorem for $j \geq 0$

$$\begin{aligned} c_{j,k,l}(f) &:= \int_{\mathbb{R}^2} f(x) \overline{\phi_{j,k,l}(x)} dx = \int_{\mathbb{R}^2} \hat{f}(\xi) \overline{\hat{\phi}_{j,k,l}(\xi)} d\xi \\ &= \int_{\mathbb{R}^2} \hat{f}(\xi) \hat{\phi}_{j,0,0}(\mathbf{R}_{\theta_{j,l}} \xi) e^{i\langle \mathbf{b}_k^{j,l}, \xi \rangle} d\xi. \end{aligned} \quad (8)$$

THE FAST CURVELET TRANSFORM

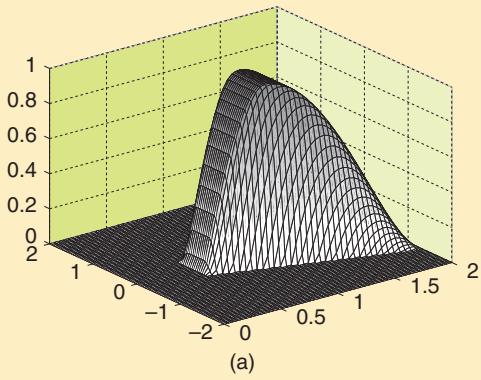
TRANSITION TO CARTESIAN ARRAYS

In practical implementations, one would like to have Cartesian arrays instead of the polar tiling of the frequency plane. Cartesian coronae are based on concentric squares (instead of circles) and shears (see Figure 7). Therefore, a construction of window functions on trapezoids instead of polar wedges is desirable. Hence, we need to adapt the discrete curvelet system as given in the section "What Properties Do the Curvelet Elements Have?" suitably. Let us remark that the frequency tiling into shears, as given in Figure 7, has been similarly used for the construction of contourlets [21] by a pyramidal directional filter bank. However, the tiling for the contourlet transform is slightly more flexible by allowing that the number of directions need not to be doubled at each second scale, see [21].

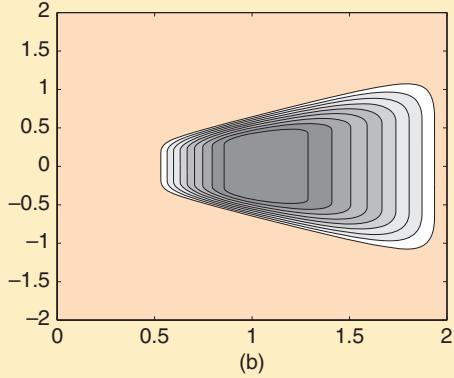
For the transition of the basic curvelet according to the new tiling, where rotation is replaced by shearing, we use the ansatz

$$\hat{\phi}_{j,0,0}(\xi) := 2^{-3j/4} W(2^{-j} \xi_1) V\left(\frac{2^{[j/2]} \xi_2}{\xi_1}\right)$$

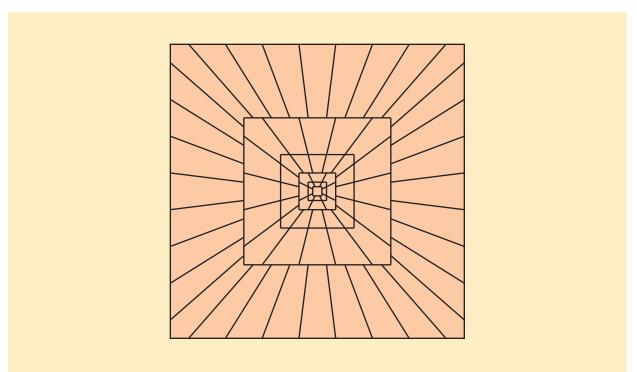
with the window function W as in the section "How to Transfer This Idea to the Curvelet Construction" and with a nonnegative window V with compact support in $[-2/3, 2/3]$; see "Window Functions." This adapted scaled basic curvelet $\hat{\phi}_{j,0,0}$ in Figure 8 is the Cartesian equivalent to $\hat{\phi}_{j,0,0}$ in (2) (see Figure 4).



(a)



[FIG8] (a) Basic curvelet $\hat{\phi}_{0,0,0}$ and (b) its support adapted to the Cartesian arrays in frequency domain.



[FIG7] Discrete curvelet tiling with parabolic pseudopolar support in the frequency plane.

Observe that the support of $V_j(\xi) := V(2^{[j/2]} \xi_2/\xi_1)$ is now inside the cone $K_1 := \{(\xi_1, \xi_2): \xi_1 > 0, \xi_2 \in [-2\xi_1/3, 2\xi_1/3]\}$. Hence the adapted basic curvelet $\hat{\phi}_{j,0,0}$ determines the frequencies in the trapezoid

$$\left\{ (\xi_1, \xi_2): 2^{j-1} \leq \xi_1 \leq 2^{j+1}, -2^{-[j/2]} \cdot \frac{2}{3} \leq \xi_2/\xi_1 \leq 2^{-[j/2]} \cdot \frac{2}{3} \right\}.$$

To replace rotation of curvelet elements by shearing in the new grid, we need to consider the eastern, western, northern, and southern cone separately (see Figure 9 for the eastern cone). Let us only consider the shearing in the eastern cone $K = \{(\xi_1, \xi_2)^T: \xi_1 > 0, -\xi_1 < \xi_2 \leq \xi_1\}$, for the other cones, suitable curvelet elements are then obtained by rotation by $\pm \pi/2$ radians and reflection.

Instead of equidistant angles, we define a set of equispaced slopes in the eastern cone

$$\tan \theta_{j,l} := l 2^{-[j/2]}, \quad l = -2^{[j/2]} + 1, \dots, 2^{[j/2]} - 1.$$

Observe that the angles $\theta_{j,l}$, which range between $-\pi/4$ and $\pi/4$, are not equispaced here, while the slopes are.

Now, let the curvelet-like functions be given by

$$\tilde{\phi}_{j,k,l}(x) := \tilde{\phi}_{j,0,0}(\mathbf{S}_{\theta_{j,l}}^T(x - \tilde{\mathbf{b}}_k^{j,l})), \quad (9)$$

being the Cartesian counterpart of $\phi_{j,k,l}$ in (6), with the shear matrix

$$S_\theta = \begin{pmatrix} 1 & 0 \\ -\tan\theta & 1 \end{pmatrix},$$

and where $\tilde{\mathbf{b}}_k^{j,l} := S_{\theta,j,l}^{-T}(k_1 2^{-j}, k_2 2^{-|j/2|}) =: S_{\theta,j,l}^{-T} \mathbf{k}_j$ denotes the position of $\tilde{\phi}_{j,k,l}$ in space domain. Let us have a closer look at the functions $\tilde{\phi}_{j,k,l}$. The Fourier transform gives by $S_{\theta,j,l}^{-1} \xi = (\xi_1, \xi_1 \tan\theta_{j,l} + \xi_2)^T$

$$\begin{aligned} \hat{\phi}_{j,k,l}(\xi) &= e^{-i(\tilde{\mathbf{b}}_k^{j,l}, \xi)} \hat{\phi}_{j,0,0}(S_{\theta,j,l}^{-1} \xi) \\ &= e^{-i(\tilde{\mathbf{b}}_k^{j,l}, \xi)} 2^{-3j/4} W(2^{j/2} \xi_1) V(2^{j/2} \xi_2 / \xi_1 + l). \end{aligned}$$

Hence, $\hat{\phi}_{j,k,l}$ is compactly supported on sheared trapezoids.

Let us for example examine $\hat{\phi}_{4,k,l}$. For $j = 4$, we consider the angles $\tan\theta_{4,l} = l/4$, $l = -3, \dots, 3$. The support of $\hat{\phi}_{4,k,l}$ is symmetric with respect to the ξ_1 axis, and for $j = 4$ we have

$$\text{supp } \hat{\phi}_{4,k,0} = \left\{ (\xi_1, \xi_2)^T : 8 \leq \xi_1 \leq 32, -\frac{1}{6} \leq \frac{\xi_1}{\xi_2} \leq \frac{1}{6} \right\}.$$

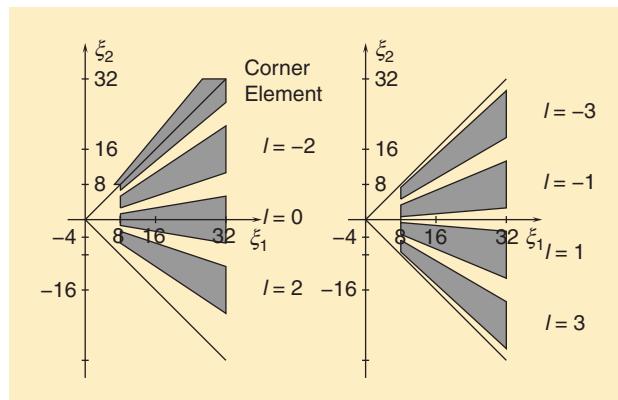
The supports of $\hat{\phi}_{4,k,l}$ with $l = -3, \dots, 3$ in the eastern cone are now sheared versions of this trapezoid (see Figure 9).

The set of curvelets $\hat{\phi}_{j,k,l}$ in (9) needs to be completed by symmetry and by rotation by $\pm\pi/2$ radians to obtain the whole family. Moreover, as we can also see in Figure 9, we need suitable “corner elements” connecting the four cones (north, west, south, and east). In [7], it is suggested to take a corner element as the sum of two half-part sheared curvelet functions of neighboring cones as indicated in Figure 9 (on the left).

Finally, the coarse curvelet elements for low frequencies are needed, and we take here

$$\tilde{\phi}_{-1,k,0}(\mathbf{x}) := \tilde{\phi}_{-1}(\mathbf{x} - \mathbf{k}), \quad \mathbf{k} \in \mathbb{Z}^2,$$

where $\hat{\phi}_{-1}(\xi) := W_0(\xi_1)W_0(\xi_2)$ [with W_0 in (5)] has its support in $[-1, 1]^2$. For this construction of curvelet-like elements one can show the frequency tiling property



[FIG9] Supports of the functions $\hat{\phi}_{4,k,l}$ for $l = -3, \dots, 3$, and one corner element.

$$\hat{\phi}_{-1}(\xi) + \sum_{j=0}^{\infty} \sum_{l=-2^{j/2}}^{2^{j/2}} 2^{3j/4} \hat{\phi}_{j,0,l}(\xi) = 1$$

for all ξ in the eastern cone $K = \{\xi = (\xi_1, \xi_2)^T : \xi_1 > 0, \xi_2 \in [-\xi_1, \xi_1]\}$, where we have taken also the two corner elements in the sum. Similarly, this assertion is true for the rotated functions in the other three cones.

THE ALGORITHM

We find the Cartesian counterpart of the coefficients in (8) by

$$\begin{aligned} \hat{\phi}_{j,k,l}(f) &= \langle f, \tilde{\phi}_{j,k,l} \rangle = \int_{\mathbb{R}^2} \hat{f}(\xi) \hat{\phi}_{j,0,0}(S_{\theta,j,l}^{-1} \xi) e^{i(\tilde{\mathbf{b}}_k^{j,l}, \xi)} d\xi \\ &= \int_{\mathbb{R}^2} \hat{f}(S_{\theta,j,l} \xi) \hat{\phi}_{j,0,0}(\xi) e^{i(\mathbf{k}_j, \xi)} d\xi \end{aligned} \quad (10)$$

with $\mathbf{k}_j = (k_1 2^{-j}, k_2 2^{-|j/2|})^T$, $(k_1, k_2)^T \in \mathbb{Z}^2$.

The forward and the inverse fast discrete curvelet transform as presented in [7] have a computational cost of $\mathcal{O}(N^2 \log N)$ for an $(N \times N)$ image, see e.g., CurveLab (<http://curvelab.org>) with a collection of MATLAB and C++ programs. The redundancy of that curvelet transform implementation is about 2.8 when wavelets are chosen at the finest scale, and 7.2 otherwise (see e.g., [7]); see the “Forward Algorithm,” which uses formula (10).

For the inverse curvelet transform, one applies the algorithm in each step in reversed order. Observe that in the second step, a suitable approximation scheme has to be applied in the forward transform and in the inverse transform.

THREE-DIMENSIONAL CURVELET TRANSFORM

For three-dimensional (3-D) data, a generalization to 3-D multiscale geometric methods is of great interest. So far, only a few papers have been concerned with applications of the 3-D

[FORWARD ALGORITHM]

1) Compute the Fourier transform of f by means of a 2-D FFT.

Let f be given by its samples $f((n_1/N, n_2/N))$, $n_1, n_2 = 0, \dots, N-1$, where N is of the form $N = 2^J$, $J \in \mathbb{N}$. Suppose, that f can be approximated by a linear combination of bivariate hat functions. Let $\tilde{s}(x) = s(x_1)s(x_2)$ with $s(x_1) := (1 - |x_1|) \chi_{[-1, 1]}(x_1)$ and

$$f(x) = \sum_{n_1=0}^{N-1} \sum_{n_2=0}^{N-1} f\left(\frac{n_1}{N}, \frac{n_2}{N}\right) \tilde{s}(Nx_1 - n_1, Nx_2 - n_2).$$

With $\hat{s}(\xi) = (\text{sinc } \xi_1/2)^2 (\text{sinc } \xi_2/2)^2$ it follows that

$$\hat{f}(\xi) = \sum_{n_1=0}^{N-1} \sum_{n_2=0}^{N-1} f\left(\frac{n_1}{N}, \frac{n_2}{N}\right) e^{-i(n_1 \xi_1 + n_2 \xi_2)/N} \hat{s}\left(\frac{\xi}{N}\right),$$

and the 2-D FFT of length N gives us the samples $\hat{f}(2\pi n_1, 2\pi n_2)$, $n_1, n_2 = -N/2, \dots, (N/2)-1$.

2) Compute $\hat{f}(S_{\theta,j,l} \xi)$ by interpolation.

Fix the scales to be considered, say $j_0 \leq j \leq J$. The support of $\hat{\phi}_{j,0,0}$ is contained in the rectangle $R_j = [2^{j-1}, 2^{j+1}] \times [-2^{j/2}, 2^{j/2}]$. For each pair (j, l) compute now $\hat{f}(2\pi n_1, 2\pi n_2 - 2\pi n_1 \tan\theta_{j,l})$ for $2\pi(n_1, n_2) \in R_j$.

3) Compute the product $\hat{f}(S_{\theta,j,l} \xi) \hat{\phi}_{j,0,0}(\xi)$.

For each pair (j, l) compute the product $\hat{f}(2\pi n_1, 2\pi n_2 - 2\pi n_1 \tan\theta_{j,l}) \hat{\phi}_{j,0,0}(2\pi n_1, 2\pi n_2)$.

4) Apply the inverse 2-D FFT to obtain the discrete coefficients $\tilde{c}_{j,k,l}^D(f)$ that are an approximation of the coefficients in (10).

curvelet transform to 3-D turbulence [2], [47] and 3-D seismic processing [52].

The idea of the 3-D curvelet transform on Cartesian arrays can be carried out analogously as done in the section “Transition to Cartesian Arrays” for the 2-D case. This time, one considers curvelet functions being supported on sheared truncated pyramids instead of sheared trapezoids. The 3-D curvelet functions then depend on four indices instead of three; the scale, the position and two angles; and for the shearing process, one can introduce 3-D shear matrices.

A fast algorithm can be derived similarly as in the section “The Algorithm” for the 2-D case. The computational complexity of the 3-D discrete curvelet transform based on FFT algorithms is $\mathcal{O}(n^3 \log n)$ flops for $n \times n \times n$ data [7]. For further details, we refer to [7] and [68].

RECENT APPLICATIONS

In this section, we shall review applications of the curvelets in image processing, seismic exploration, fluid mechanics, solving of PDEs, and compressed sensing, to show their potential as an alternative to wavelet transforms in some scenarios.

IMAGE PROCESSING

In 2002, the first-generation curvelet transform was applied for the first time to image denoising by Starck et al. [60], and by Candès and Guo [13]. The applications of the first-generation curvelets were extended to image contrast enhancement [62] and astronomical image representation [61] in 2003, and to fusion of satellite images [17] in 2005. After the effective second-generation curvelet transform [12] had been proposed in 2004, the applications of curvelets increased quickly in many fields involving image/video presentation, denoising, and classification. For instance, Ma et al. applied the second-generation curvelets for motion estimation and video tracking of geophysical flows [45] and deblurring [43]. Ma and Plonka presented two different models for image denoising by combining the discrete curvelet transform with nonlinear diffusion schemes. In the first model [49], a curvelet shrinkage is applied to the noisy data, and the result is further processed by a projected total variation diffusion to suppress pseudo-Gibbs artifacts. In the second model [56], a nonlinear reaction-diffusion equation is applied, where curvelet shrinkage is used for regularization of the diffusion process. Starck et al. [63], [3] applied curvelets for morphological component analysis. Recently, B. Zhang et al. [69] used curvelets for Poisson noise removal in comparison with wavelets and ridgelets. In [70], C. Zhang et al. successfully applied the multiscale curvelet transform to multipurpose watermarking for content authentication and copyright verification. Jiang et al. [36] considered structure and texture image in painting with the help of an iterative curvelet thresholding method. Tessens et al. [66] proposed a new context adaptive image denoising by modeling of curvelet domain statistics. By performing an intersubband statistical analysis of curvelet coefficients, one can distinguish between two classes of coefficients: those that represent useful image content, and those dominated by noise. Using a prior model based on

marginal statistics, an appropriate local spatial activity indicator for curvelets has been developed that is found to be very useful for image denoising, see [66]. Geback et al. [30] applied the curvelets for edge detection in microscopy images.

Interestingly, the pure discrete curvelet transform is less suitable for image compression and for image denoising. The reason may be the redundancy of the curvelet frame. Most successful approaches related with the discrete curvelet transform are hybrid methods, where curvelets are combined with another technique for image processing. These methods usually can exploit the ability of the curvelet transform to represent curve-like features.

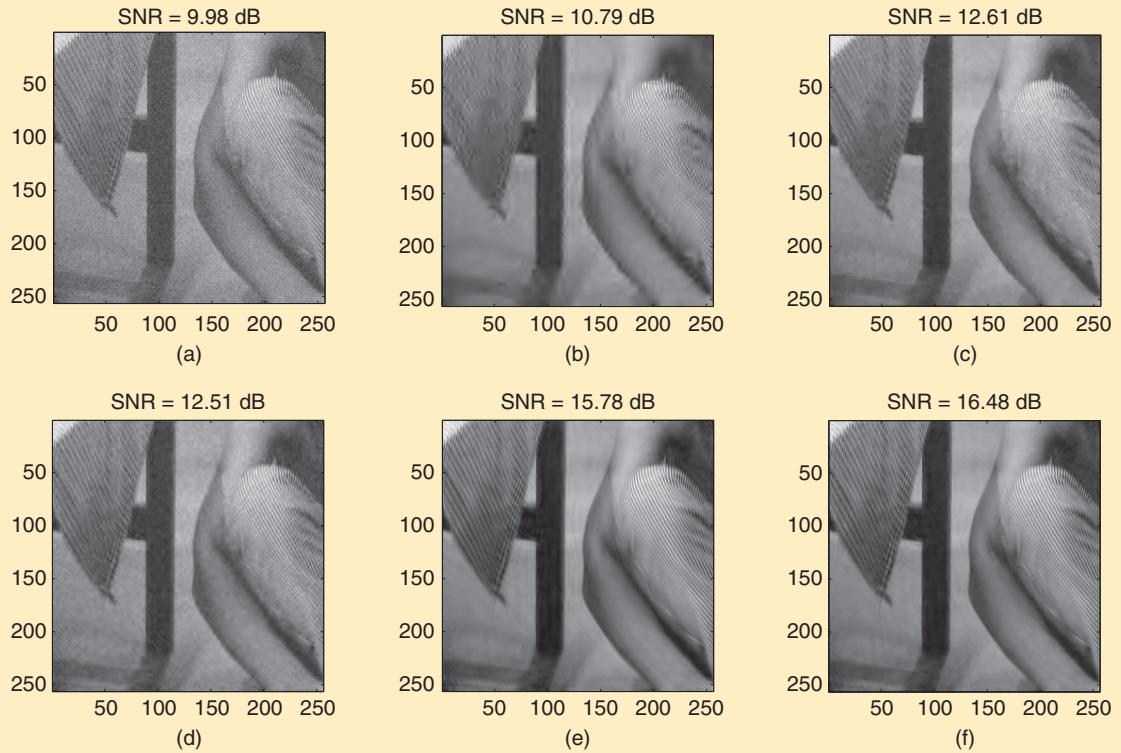
Let us give one example of image denoising [49], where curvelet shrinkage is combined with nonlinear anisotropic diffusion. Figure 10(a) shows a part of noisy Barbara image. Figure 10(b)–(f) present the denoising results by using tensor-product Daubechies’s DB4 wavelets, TV diffusion, contourlets, curvelets, and TV-combined curvelet transform [49], respectively. The curvelet-based methods preserve the edges and textures well.

SEISMIC EXPLORATION

Seismic data records the amplitudes of transient/reflecting waves during receiving time. The amplitude function of time is called seismic trace. A seismic data or profile is the collection of these traces. All the traces together provide a spatio-temporal sampling of the reflected wave field containing different arrivals that respond to different interactions of the incident wave field with inhomogeneities in Earth’s subsurface. Common denominators among these arrivals are wave fronts (as shown in Figure 11(a) for a real seismic profile), which display anisotropic line-like features, as edges and textures in images. They basically show behaviors of C^2 -continuous curves. The main characteristic of the wave fronts is their relative smoothness in the direction along the fronts and their oscillatory behavior in the normal direction. A crucial problem in seismic processing is to preserve the smoothness along the wave fronts when one aims to remove noise. From a geophysical point of view, curvelets can be seen as local plane waves. They are optimal to sparsely represent the local seismic events and can be effectively used for wave front-preserving seismic processing. Therefore, the curvelet decomposition is an appropriate tool for seismic data processing.

Figure 11 shows a denoising of a real seismic data set by curvelets, in comparison to wavelets. Five decomposing levels are used in both transforms. Figure 12 shows the comparison of subband reconstruction in the first three levels; from coarse scale to fine scale. It can be seen clearly that the curvelets perform much better than wavelets to preserve the wave fronts/textures in multiscale decomposition and denoising. We also observe that the curvelet transform can achieve an almost complete data reconstruction if used without any thresholding for coefficients (reconstructed signal-to-noise ratio (SNR) = 310.47 and error = 2.9770e-010).

So far, curvelets have been applied successfully in seismic processing. Hennenfent and Herrmann [32] suggested a nonuniformly sampled curvelet transform for seismic denoising. Neelamani et al. [52] proposed a 3-D curvelet-based effective approach to attenuate random and coherent noise in a 3-D data



[FIG10] Image denoising: (a) noisy image, (b) wavelet denoising, (c) TV-diffusion denoising, (d) contourlet denoising, (e) curvelet denoising, and (f) TV-combined curvelet denoising.

set from a carbonate environment. Comparisons of wavelets, contourlets, curvelets, and their combination for denoising of random noise have been also investigated in [58]. Douma and de Hoop [25] presented a leading-order seismic imaging by curvelets. They show that using curvelets as building blocks of seismic data, the Kirchhoff diffraction stack can (to leading order in angular frequency, horizontal wave number, and migrated location) be rewritten as a map migration of coordinates of the curvelets in the data, combined with an amplitude correction. This map migration uses the local slopes provided by the curvelet decomposition of the data. Chauris and Nguyen [16] considered seismic demigration/migration in the curvelet domain. The migration consists of three steps: decomposition of the input seismic data (e.g., common offset sections) using the curvelet transform; independent migration of the curvelet coefficients; and inverse curvelet

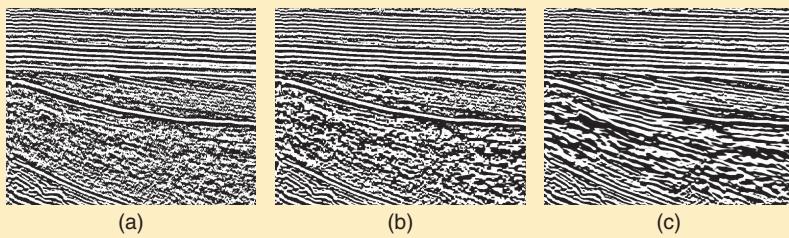
transform to obtain the final depth migrated image. Currently, they concentrate on a ray-based type of prestack depth-migration (i.e., common-offset Kirchhoff depth migration) with respect to heterogeneous velocity models. It turns out that curvelets are almost invariant under the migration operations. The final objective is to be able to derive a formulation and build an efficient algorithm for the full waveform inversion in the curvelet domain.

In addition, curvelet-based primary-multiple separation [35], extrapolation [41], and seismic data recovery [34], [33], [65] have been also proposed by Herrmann et al.

TURBULENCE ANALYSIS IN FLUID MECHANICS

Turbulence has been a source of fascination for centuries because most fluid flows occurring in nature, as well as in engineering applications, are turbulent. Fluid turbulence is a paradigm of multiscale phenomena, where the coherent structures evolve in an incoherent random background. Turbulence is difficult to approximate and analyze mathematically or to calculate numerically because of its range of spatial and temporal scales. The geometrical representation of flow structures might seem to be restricted to a well-defined set of curves along which the data are singular.

As a consequence, the efficient compression of a flow field with minimum loss of



[FIG11] Comparison of seismic denoising: (a) original data, (b) wavelet denoising, and (c) curvelet denoising.

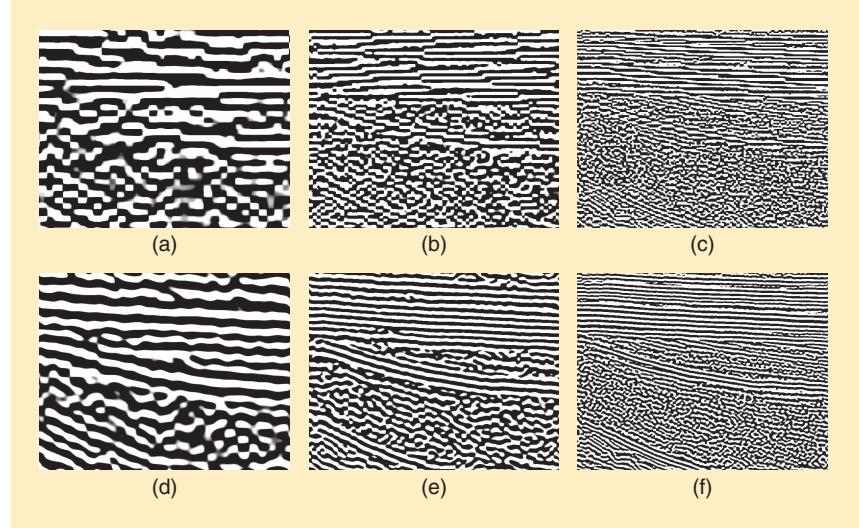
the geometric flow structures is a crucial problem in the simulation of turbulence. The development of appropriate tools to study vortex breakdown, vortex reconnection, and turbulent entrainment at laminar-turbulent interfaces, is imperative to enhance our understanding of turbulence. Such tools must capture the vortical structure and dynamics accurately to unravel the physical mechanisms underlying these phenomena.

Recently, the curvelets have been applied to study the nonlocal geometry of eddy structures and the extraction of the coherent vortex field in turbulent flows [2], [47], [48]. Curvelets start to influence the field of turbulence analysis and have the potential to upstage the wavelet representation of turbulent flows addressed in [26] and [27]. The multiscale geometric property, implemented by means of curvelets, provides the framework for studying the evolution of the structures associated to the main ranges of scales defined in Fourier space, while keeping the localization in physical space that enables a geometrical study of such structures. Such a geometrical characterization can provide a better understanding of cascade mechanics and dissipation-range dynamics. Moreover, curvelets have the potential to contribute to the development of structure-based models of turbulence fine scales, subgrid-scale models for large-eddy simulation, and simulation methods based on prior wavelet transforms [2].

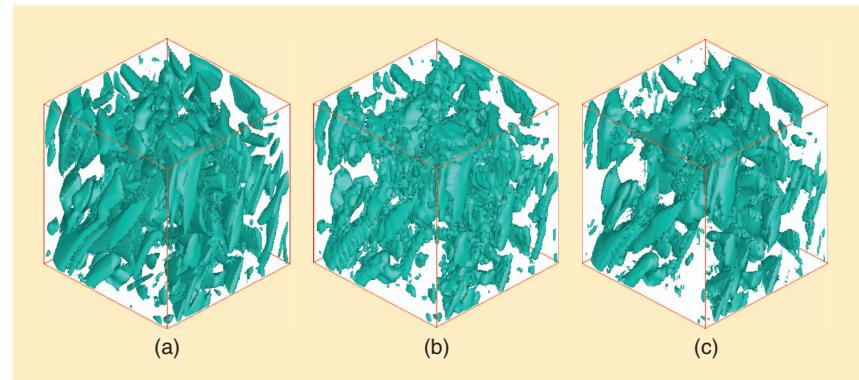
Figure 13 gives an example of the extraction of coherent fields from turbulent flows. The curvelet method preserves the edges and structures better than wavelet methods. The results of multiscale turbulence analysis depend on the threshold or shrinkage. The question of how to find the optimal threshold to separate coherent fields and incoherent random fields still remains open.

SOLVING OF PDEs

Candès and Demanet [5], [6] have shown that curvelets essentially provide optimally sparse representations of Fourier integral operators. While the wavelet transform is optimal for solving elliptical PDEs, the motivation to use the curvelet transform is that for a wide class of linear hyperbolic differential equations, the curvelet representation of the solution operator is both optimally sparse and well organized. Sparsity means that the matrix entries decay nearly exponentially fast, and they are well organized in the sense that very few nonnegligible entries occur near a few shifted diagonals. Wave fronts



[FIG12] Comparisons of subband reconstruction in the first three levels from coarse scale to fine scale by (a)–(c) wavelet transform and (d)–(f) curvelet transform.



[FIG13] Extraction of coherent fields from turbulent flows: (a) original flow, (b) coherent components by wavelets, and (c) curvelets.

of solutions can be also sparsely represented in curvelet domain [6]. Some updated results for hyperbolic evolution equations with limited smoothness have been obtained by Andersson et al. [1]. The key idea of the existing methods is first to decompose the initial fields by the curvelet transform, and then to compute the rigid motions of the significant curvelet coefficients along Hamiltonian ray flows at each scale. Finally, one needs to reconstruct the evolution coefficients at all scales by an inverse curvelet transform and obtains an approximate wave field $u(x, t)$ at a given time t . The theory is quite elegant but still far away from practical applications. The papers cited above show the potential of curvelets for solving of PDEs from the point of view of mathematical analysis and raise the hope to achieve fast algorithms for the solution of hyperbolic PDEs using curvelets.

Let us consider a wave equation with the associated Cauchy initial value problem

$$\frac{\partial^2 u}{\partial t^2}(x, t) = v^2 \Delta u(x, t) \quad u(x, 0) = u_0(x), \quad \frac{\partial u}{\partial t}(x, 0) = u_1(x). \quad (11)$$

For simplicity, assume that v is a constant wave speed, and $\Delta u(x, t) = \partial^2/x_1^2 u(x, t) + (\partial^2)/(x_2^2)u(x, t)$ denotes the usual Laplace operator. Its solution can be written as $u(x, t) = F(x, t)u_0(x) + G(x, t)u_1(x)$, with suitable solution operators $F(x, t)$ and $G(x, t)$ (involving Green's functions) that can be sparsely represented in curvelet domain.

Curvelet-based finite difference schemes for seismic wave equations have been studied in [64]. The goal is to construct a fast adaptive scheme for numerical modeling of wave propagation. Similarly as with prior wavelet-based finite difference schemes, one crucial problem is to explore how the differential operator Δ (or ∂_{x_i}) can be computed by the curvelet transform in an efficient way. The 2-D wave field u can be transformed into curvelet domain by $u(x_1, x_2, t) = \sum_{\mu} c_{\mu}(t) \phi_{\mu}(x_1, x_2)$. Here, we have used the tight frame property (7) with the short notation $\mu = (j, k, l)$, and $c_{\mu}(t)$ denotes the μ th curvelet coefficient of u at time t . A possible way to compute the curvelet coefficients of Δu is

$$\begin{aligned} c_{\mu}^{\Delta} := c_{\mu}(\Delta u) &:= \int \Delta u(x, t) \overline{\phi_{\mu}(x)} dx = \int \Delta u(\xi, t) \overline{\phi_{\mu}(\xi)} d\xi \\ &= \int (-\xi_1^2 - \xi_2^2) \hat{u}(\xi, t) \overline{\phi_{\mu}(\xi)} d\xi. \end{aligned}$$

Using the definition of the curvelet coefficients in (10), we obtain with $S_{\theta_{j,l}} \xi = (\xi_1, -\xi_1 \tan \theta_{j,l} + \xi_2)^T$

$$\begin{aligned} c_{\mu}^{\Delta} &= \int [- (1 + \tan^2 \theta_{j,l}) \xi_1^2 - \xi_2^2 + 2(\tan \theta_{j,l}) \xi_1 \xi_2] \\ &\quad \times \hat{u}(S_{\theta_{j,l}} \xi) \hat{\phi}_{j,0,0}(\xi) e^{i k_j \cdot \xi} d\xi \\ &= 4^j (1 + \tan^2 \theta_{j,l}) \frac{\partial^2 c_{\mu}}{\partial k_1^2} + 4^{[j/2]} \frac{\partial^2 c_{\mu}}{\partial k_2^2} - 2^{j+1} 2^{[j/2]} \tan \theta_{j,l} \frac{\partial^2 c_{\mu}}{\partial k_1 \partial k_2}. \end{aligned}$$

Here we recall that $k = (k_1, k_2)^T \in \mathbb{Z}^2$ and $k_j = (k_1/2^j, k_2/2^{[j/2]})^T$. That means, we can obtain the curvelet coefficients of Δu by

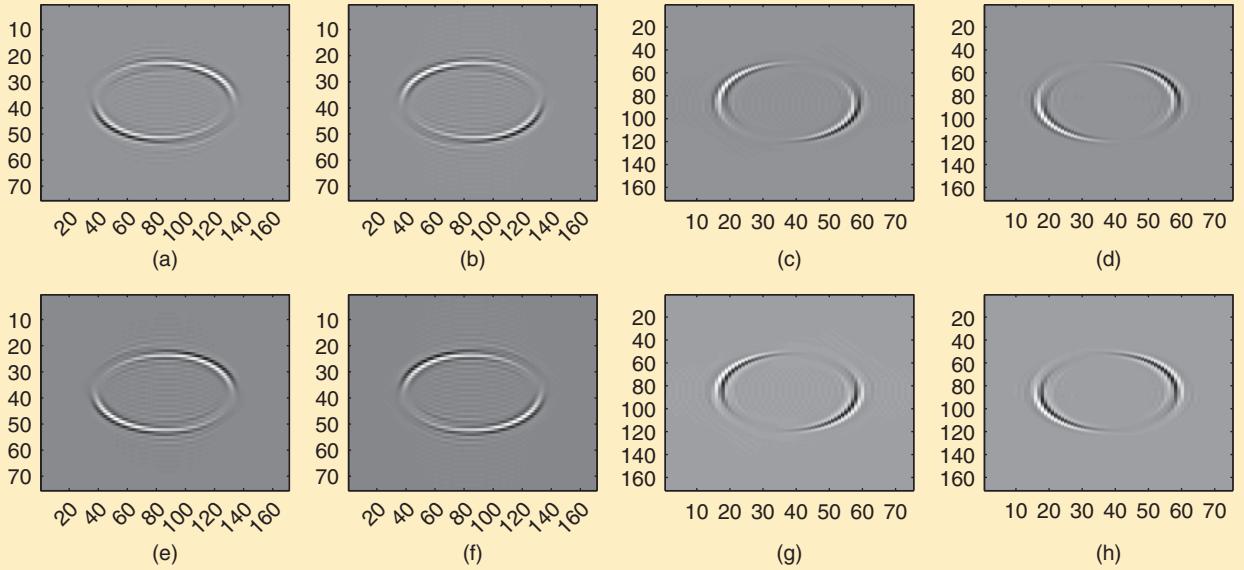
using the coefficients of the instant wave field u . Thus, we can rewrite the wave equation in coefficient domain by

$$\begin{aligned} \frac{\partial^2 c_{\mu}}{\partial t^2} &= v^2 \left(4^j (1 + \tan^2 \theta_{j,l}) \frac{\partial^2 c_{\mu}}{\partial k_1^2} + 4^{[j/2]} \frac{\partial^2 c_{\mu}}{\partial k_2^2} \right. \\ &\quad \left. - 2^{j+1} 2^{[j/2]} \tan \theta_{j,l} \frac{\partial^2 c_{\mu}}{\partial k_1 \partial k_2} \right). \end{aligned} \quad (12)$$

Figure 14 shows an example of curvelet coefficients of an instant wave field at the coarsest curvelet detail scale, by implementing the computation in curvelet domain as given in (12). For details of this approach we refer to [64]. Using suitable thresholding, one can implement a fast adaptive computation for the wave propagation. Unfortunately, due to the redundancy of the current discrete curvelet algorithm, the curvelets have not performed at the level that we expected. The matrices are not as sparse as the estimates promise. The efficient numerical treatment of PDEs using curvelets is still a challenging problem.

COMPRESSED SENSING

Finally, we mention a new direction of applications of the curvelet transform to the so-called compressed sensing or compressive sampling (CS), an inverse problem with highly incomplete measurements. CS [14], [15], [22] is a novel sampling paradigm that carries imaging and compression simultaneously. The CS theory says that a compressible unknown signal can be recovered by a small number of random measurements using sparsity-promoting nonlinear recovery algorithms. The number of necessary measurements is considerably smaller than the number of needed traditional measurements that satisfy the Shannon/Nyquist sampling theorem, where the sampling rate has to be at least twice as large as the maximum frequency of the signal. The CS-based data acquisition depends on its sparsity



[FIG14] Curvelet coefficients of an instant wave field at the coarsest curvelet detail scale. (a)–(h) denotes eight different directional subbands in this curvelet scale.

rather than its bandwidth. CS might have an important impact for designing of measurement devices in various engineering fields such as medical magnetic resonance (MRI) imaging and remote sensing, especially for cases involving incomplete and inaccurate measurements limited by physical constraints, or very expensive data acquisition.

Mathematically, we handle the fundamental problem of recovering a signal $x \in \mathbb{R}^N$ from a small set of measurements $y \in \mathbb{R}^K$. Let $A \in \mathbb{R}^{K \times N}$ be the so-called CS measurement matrix, where $K \ll N$, i.e., there are much fewer rows in the matrix than columns. The measurements can be described as [14]

$$y = Ax + \epsilon. \quad (13)$$

Here ϵ denotes possible measurement errors or noise. It seems to be hopeless to solve this ill-posed underdetermined linear system since the number of equations is much smaller than the number of unknown variables. However, if the x is compressible by a transform, as e.g., $x = T^{-1}c$, where T denotes the discrete curvelet transform, and the sequence of discrete curvelet coefficients $c = (c_\mu)$ is sparse, then we have $y = AT^{-1}c + \epsilon = \tilde{A}c + \epsilon$. If the measurement matrix A is not correlated with T , the sparse sequence of curvelet coefficients c can be recovered by a sparsity-constraint l_1 -minimization [14]

$$\min_c \|y - \tilde{A}c\|_{l_2} + \lambda \|c\|_{l_1}.$$

The second term is a regularization term that represents the a priori information of sparsity. To solve the minimization, an iterative curvelet thresholding (ICT) can be used, based on the Landweber descent method (see, e.g., [33])

$$c_{p+1} = S_\tau(c_p + \tilde{A}^T(y - \tilde{A}c_p)),$$

until $\|c_{p+1} - c_p\| < \varepsilon$, for a given error ε . Here the (soft) threshold function S_τ , given by

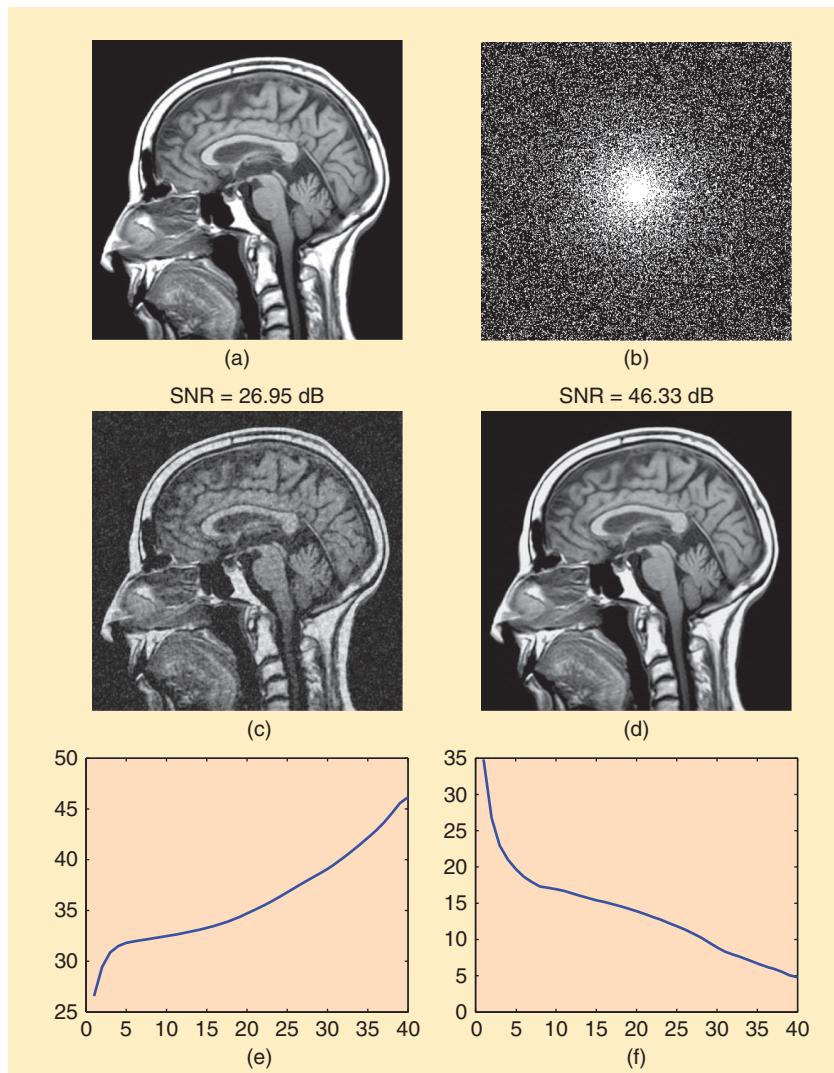
$$S_\tau(x) = \begin{cases} x - \tau, & x \geq \tau, \\ x + \tau, & x \leq -\tau, \\ 0, & |x| < \tau, \end{cases}$$

is taken component wisely, i.e., for a sequence $a = (a_\mu)$ we have $S_\tau(a) = (S_\tau a_\mu)$.

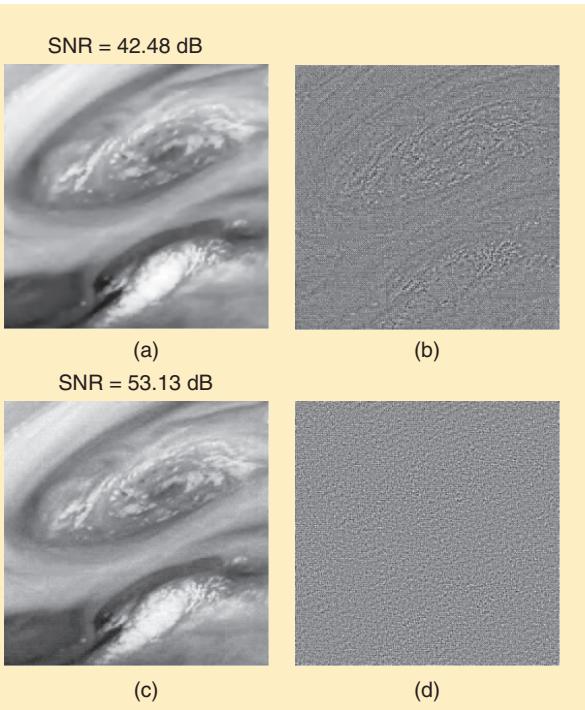
Figure 15 shows an example of compressed sensing with 25% Fourier measurements. Here the operator A is

obtained by a random subsampling of the Fourier matrix. Figure 15(b) shows the 25% samples in Fourier domain, Figure 15(c) is the recovering result by zero-filling reconstruction, and Figure 15(d) is the result found by ICT. Figure 15(e) and (f) denotes the changes of the SNR and errors of the recovered images as the number of iterations increases. The unknown MRI image can be obtained by using highly incomplete measurements, which can reduce the online measurement time and thus lessen the pain of a patient.

The motivation of applying the curvelet thresholding method is that most natural images are compressible by the curvelet transform. Currently, a few researchers have applied the ICT method to compressed sensing in seismic data recovery [33], [34], [65], and remote sensing [44], [46]. Variant ICT methods (see e.g., [57]) have been also proposed for compressed sensing.



[FIG15] Compressed sensing in Fourier domain for medical imaging: (a) original MRI image, (b) pseudorandom Fourier sampling, (c) recovery by zero-filling reconstruction, (d) recovery by ICT, (e) SNR (in dB) of the recovered image versus the number of iterations for the ICT, and (f) recovery error versus the number of iterations for the ICT.



[FIG16] Compressed sensing in remote sensing: (a) recovery by iterative wavelet thresholding, (b) recovery error by the wavelet method, (c) recovery by ICT, and (d) recovery error by the curvelet method.

Figure 16 shows an example for the curvelet-based compressed sensing in remote sensing [44], [46]. It can be seen that the curvelet method is superior to the wavelet method to recover the edges.

FUTURE WORK

The multiresolution geometric analysis technique with curvelets as basis functions is verified as being effective in many fields. However, there are some challenging problems for future work.

- 1) The computational cost of the curvelet transform is higher than that of wavelets, especially in terms of 3-D problems. However, the theory and application of the 3-D curvelets are burgeoning areas of research, and it is possible that more efficient curvelet-like transforms will be developed in the near future. Currently, a fast message passing interface-based parallel implementation can somewhat reduce the cost [68]. How to build a fast orthogonal curvelet transform is still open.
- 2) The issue of how to explore suitable thresholding functions that incorporate and exploit the special characteristics of the curvelet transform is very important for curvelet applications involving edge detection, denoising, and numerical simulation.

ACKNOWLEDGMENTS

Jianwei Ma was supported by the NSFC under grants (40704019), CACS Innovation Fund (20094030085), TBRF

(JC2007030), and PetroChina Innovation Fund (060511-1-1). Gerlind Plonka was supported by the German Research Foundation within the projects PL 170/11-2 and PL 170/13-1. This support is gratefully acknowledged.

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