Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

A versatile tuneable curvelet-like directional filter with application to fracture detection in two-dimensional GPR data

Andreas Tzanis

Department of Geophysics and Geothermy, National and Kapodistrian University of Athens, Panepistimiopoli, Zografou 15784, Greece

A R T I C L E I N F O

Article history:
Received 28 January 2016
Received in revised form
4 May 2016
Accepted 5 July 2016

Keywords:
Ground Probing Radar
Image processing
Curvelet
Directional filter
Edge detection
Fracture detection

A B S T R A C T

The present work introduces a curvelet-like directional filter and discusses its application to edge detection in general images and fracture detection in GPR data. The filter is essentially a curvelet of adjustable anisotropy and orientation that can be tuned on any given (target) wavenumber; while retaining the properties of curvelets, it is not bound to the scaling rules of the Curvelet Frame but is individually steerable to any local trait of the data, hence it is dubbed "Curveletiform". Curveletiforms can be used in single- or multi-directional modes in a manner simple, computationally inexpensive and demonstrably efficient. GPR data generally contains straight or curved edge-like objects comprising reflections from planar interfaces and is notoriously susceptible to broadband noise. Fractures are an important class of interfaces as they determine the health state of rocks or man-made structures and are primary targets of GPR surveys in geotechnical, engineering and environmental applications. As demonstrated with examples, Curveletiforms can efficiently recover information of specific scale and geometry from straight or curved edges in general images. In GPR data they may distinguish reflections from small and large fractures, discriminate between groups of fractures, resolve fracture density and aid the assessment of damage in rocks and structures.

1. Introduction

The purpose of this presentation is to introduce an effective and efficient method of geometrical information retrieval from noisy images containing straight or curved objects (edges), with particular emphasis placed on the problem of recovering features associated with specific scales and geometry orientation. The technique will be mainly demonstrated with an application to fracture detection and rock health assessment in noisy Ground Probing RADAR (GPR) data, a problem that to all intents and purposes is equivalent to the problem of edge detection. The next paragraph of this introduction comprises a short exposition of the constitution of GPR data, so as to justify why advanced edge detection methods are suitable for GPR data analysis (conversely, why GPR data is suitable for testing such methods). The remaining main part will review methods developed for the retrieval/manipulation of geometrical information from digital images and how they have inspired the formulation of the proposed technique.

The GPR is an almost indispensable means of imaging near surface structures and enjoys a very diverse and broad range of applications. GPR data essentially comprise recordings of the amplitudes of transient waves propagating in the Earth (*wavefield*). A GPR section (or B-scan), provides a two-dimensional spatio-temporal image of the transient wavefield which contains different arrivals corresponding to different interactions with wave scatterers (inhomogeneities) in the subsurface. Accordingly, two-dimensional GPR images comprise wavefronts scattered or reflected from small targets and planar or bending interfaces such as geological bedding, miscellaneous structural boundaries, cracks, fractures and joints, empty or filled cavities associated with jointing or faulting and other conceivable structural configurations. The second group of targets, especially fractures, are usually not good reflectors and are spatially localized; in geological, geotechnical, civil engineering, mining and environmental protection applications their detection is frequently a primary objective as their presence and density is always associated with the level of damage sustained by native rocks or construction materials. Wavefronts from fractures are longitudinally smooth, transversely oscillatory and generally associated with the geometry of their originating reflectors: in short, they are genuine (curved) edges. At the same time, GPR data is notoriously susceptible to noise. A variety of natural and artificial objects can cause unwanted reflections and scattering, including extraneous or reflected airwaves, critically refracted airwaves and groundwaves. Anthropogenic noise is worse and includes interference from power lines and telecommunication devices. Finally, there's systemic noise,

---

E-mail address: atzanis@geol.uoa.gr

http://dx.doi.org/10.1016/j.sigpro.2016.07.009
0165-1684/© 2016 Elsevier B.V. All rights reserved.

Please cite this article as: A. Tzanis, A versatile tuneable curvelet-like directional filter with application to fracture detection in two-dimensional GPR data, Signal Processing (2016), http://dx.doi.org/10.1016/j.sigpro.2016.07.009

frequently manifested as ringing (antenna self-clutter). In many cases, the noise has definite geometrical characteristics which should be factored into any noise excision procedure. Raw GPR data usually require post-acquisition processing, as in their original form they provide only approximate target shapes and depths.

There are several methods to de-noise two dimensional data, focus on single or multiple scales and extract geometrical information. Almost all of them have been described in the excellent and comprehensive review of Jacques et al. [1]. The requirement to manipulate geometrical (orientation-dependent) information classifies suitable methods in two general categories: Directional Filters (or Directional Wavelets) and multi-directional Multi-Resolution Analysis (MRA).

Directional Filters (Directional Wavelets) are used in texture analysis, edge detection, image data compression, motion analysis, and image (signal) enhancement. They generally comprise anisotropic 2-D waveforms based on steerable semi-orthogonal or orthogonal wavelet arrays, whose frequency and/or wavenumber localization can be manipulated by changing their scale and orientation. These include Steerable Wavelets [2,3], Gabor wavelets [4–6] and B-Spline Wavelet Filters [7,8]. These methods may successfully process information at arbitrarily fine scales and single orientations but do not allow for a different number of directions at each scale. In order to obtain multidirectional representation of the data at each scale, it is necessary to apply the same filter rotated to different angles (under adaptive control if necessary) and combine the outputs, as in [2] for Steerable Wavelets and in [9] for Gabor Filters. Multidirectional applications of B-Spline Wavelet and Gabor Filters to the analysis of contaminated GPR data are given in [8,10] and have met with remarkable success. In any case, the angular selectivity of the most advanced directional filter designs depends on a number of shaping parameters, the coordination of which is generally application-specific and requires experience.

Multi-Resolution Analysis, e.g. [11,12], is the design method of most of the practically relevant discrete wavelet transforms and the justification of the fast wavelet transform. MRA allows an image – formally a space $L^2(\mathbb{R}^2)$ – to be decomposed into a sequence of nested sub-images (subspaces) arranged in order of increasing detail (decreasing scale), so as to satisfy certain self-similarity conditions in space, as well as completeness and regularity relations. This provides a means to manipulate localized (specific scale) events but leave the rest of the data generally unscathed. MRA has been applied to reflection seismic and GPR data, with most of the relevant studies focusing on noise suppression in a time-frequency sense. The pertinent literature is not abundant, but is progressively expanding, e.g. [13–18].

Wavelet-based MRA methods are not efficient in processing geometrical information. Just as Fourier methods are unsuitable for (or inadaptable to) problems involving aperiodic phenomena, which has led to the advent of the wavelet transform, wavelets are isotropic and may successfully operate only on phenomena that are generally isotropic, except for local irregularities (isolated singularities at exceptional points). Wavelets are less than ideal for phenomena occurring on curves or sheets (i.e. with singularities on curves), as for instance, edges in two-dimensional images or wavefronts in a seismic or GPR record. This problem has been addressed by advanced MRA-like algorithms collectively referred to as the "*X-let Transform*". These include *ridgelets* [19,20], *wedgelets* [21], *beamlets* [22], *bandlets* [23], *contourlets* [24], *wave atoms* [25], *surfacelets* [26] and others. It is also possible to combine *X*-lets with machine learning procedures for increased efficiency [e.g. 44,45]. At any rate, the *X*-lets vary substantially in scope, properties and efficiency so that even their general characteristics are beyond summarizing herein: a comprehensive review can be found in [1]. Additional effective and versatile methods are the second generation *Curvelet Transform* [27–31] and its spin-offs, the *Shearlet Transform* [32] and the *Riplet Transform* [33]. These are designed to associate scale with orientation, yield optimally sparse representations of the data and have optimal reconstruction properties (see below). These very desirable characteristics of the Curvelet Transform lineage have motivated research into its suitability for GPR data processing [34] and have partially inspired the present investigation which will concentrate on the most fundamental design: the Curvelet.

Curvelets trace their origin in Harmonic Analysis, where they were introduced as expansions for asymptotic solutions of wave equations [19,35]. In consequence, curvelets can be viewed as primitive and prototype waveforms – they are local in space or wavenumber and highly anisotropic as they obey the parabolic scaling principle, according to which their width is proportional to the square of their length. Their anisotropic shape endows them with the capacity to detect curved objects at different angles and scales because curvelets at a given scale and orientation can only locally match with curves (edges, wavefronts etc.) of the same scale and orientation. The 2nd generation Curvelet Transform [27–31], comprises a multiscale and multidirectional expansion that formulates an *optimally sparse* representation of objects with edges, in the sense that there is no other representation of the same order m that can yield a better approximation [30]. Optimal sparsity also leads to optimal image reconstruction in severely ill-posed problems [36] and renders Curvelets particularly suitable for reconstruction problems with corrupted and/or missing data [31,36].

The (Fast Discrete) Curvelet Transform was applied to the analysis of GPR data with notable success [34]. However, there is a small disadvantage in that the CT cannot be readily customized for specific high-precision applications because it is a *pyramidal decomposition* that partitions the Fourier plane into highly anisotropic and localized elements (curvelets), albeit in a rather inflexible manner, as detailed in the beginning of Section 2.1. At this point it suffices to state that in the CT formalism, if ρ and θ are the radial and azimuthal coordinates respectively, the Fourier plane is partitioned in concentric annuli (*coronae*) according to the rule $2^{j-1} \le \rho \le 2^{j+1}$, with each corona further partitioned into angular sectors according to the rule $\angle\theta \le 2^{-j/2}$ (*second dyadic decomposition*). This may affect operations in which "surgical" precision is desired. For example, objects whose Fourier-plane components straddle the boundaries of coronae and/or angular sectors may not be very effectively isolated because the predefined partitioning scheme will integrate information from a broader than necessary range of scales and angular spans. In addition, when the aspect ratio of the data matrix is high or low – e.g. too many columns with respect to rows as is often the case with GPR data – the angular partitioning becomes awkward and cumbersome, sometimes making impossible to analyse the data as a single matrix (image).

The above discussion indicates that a tuneable directional filter with all the nice and desirable properties of curvelets could be a useful addition to the arsenal of image processing, and GPR data processing in particular. The present work describes and applies a hybrid scheme in which the filter:

1. Retains the design characteristics and desirable microlocal properties of curvelets.
2. Is not bound to the scaling rules of the second dyadic decomposition but is automatically localizable and scalable (tuneable) around any pair of coordinates in the Fourier plane, hence any particular trait in the data.
3. Its design and construction is (almost) independent of shaping parameters so that it can be applied by users inexperienced in advanced filters and image processing schemes.

Please cite this article as: A. Tzanis, A versatile tuneable curvelet-like directional filter with application to fracture detection in two-dimensional GPR data, Signal Processing (2016), http://dx.doi.org/10.1016/j.sigpro.2016.07.009