Detection and reconstruction of coherent structures based on wavelet multiresolution analysis

M.J. Franca
Laboratoire d’Hydraulique Environnementale - École Polytechnique Fédérale de Lausanne, Switzerland
Present address: Instituto Superior Técnico – Technical University of Lisbon, Portugal, mfranca@civil.ist.utl.pt
U. Lemmin
Laboratoire d’Hydraulique Environnementale - École Polytechnique Fédérale de Lausanne, Switzerland

ABSTRACT: In turbulent river flows, coherent structures play a major role in transport and mixing processes. Coherent structures appear as non-stationary randomly distributed singularities in turbulent velocity signals. Wavelet analysis which characterizes signal variability both in time and space is well suited for the analysis of isolated phenomena such as coherent structures. With wavelet decomposition we may represent individual features of the instantaneous signal within a pre-determined scale. We developed a coherent structure detection technique based on wavelet multiresolution analysis, conditioned by event scale and amplitude. The samples are chosen using a correlation threshold condition. 3D reconstruction is made by composite averaging. We assess the relationship between coherent structures and other large- or small-scale flow features and the contribution of individual events to the turbulent flow structure such as velocity profile, Reynolds stress tensor and TKE budget. We apply our method to Acoustic Doppler Velocity Profiler measurements in a gravel-bed river.

1 INTRODUCTION

In geophysical flows, momentary variations of the velocity are related to such processes as the suspension of sediments and the dispersion of pollutants in the water. Coherent structures consist of macroscale “organized” phenomena, belonging to the productive range of the spectral space. In the inertial and the dissipative ranges, turbulence is essentially random and isotropic, composed of fine scale features such as small scale eddies. Coherent structures have a short life cycle. They cannot be identified with a time averaged analysis and require an investigation based on time and space correlation measurements or flow visualization techniques. In laminar and transitional flows, coherent structures occur periodically, whereas in turbulent flows they occur randomly in space and time. Hence, in addition to flow visualization techniques, conditional sampling and statistics techniques have to be used in the detection and characterization of coherent structures. Several authors applied conditional statistics to turbulence studies (Antonia & Atkinson 1973, Nakagawa & Nezu 1977 and Hurther & Lemmin 2000). Adrian et al. (2000) compared Reynolds decomposition, Galilean and LES techniques. In this study we will use Reynolds time-averaged decomposition.

Here we make use of conditional sampling techniques and the wavelet multilevel decomposition of single point instantaneous velocity measurements. Wavelet analysis is a suitable tool for the study of turbulence in geophysical flows. Foufoula-Georgiou & Kumar (1994) presented a compilation of papers dealing with the application of wavelet analysis in geophysics. Turner et al. (1994) examined scales and the location of flow structures related to temperature and flux data of atmospheric flow above a forest canopy. Yoshida & Nezu (2004) used wavelet analysis to study the importance of the bursting process near the free surface for gas transfer in open-channel flows.

We use velocity data obtained with the ADVP instrument in a river in order to develop a detection algorithm for coherent structures. This is based on wavelet multilevel decomposition of 3D instantaneous velocity profiles measured at one location over the whole water depth. A conditioned sample is created with scale, amplitude and cross-correlation threshold methods. Thereafter, the single-point detected structure is reconstructed three-dimensionally by a normalized composite average. We subsequently reconstruct the 3D flow structure over the whole water depth. The reconstructed structure and
its time distribution in the instantaneous velocity signal are discussed. The method is demonstrated for Quadrant II (QII) structures (ejections) but may be generalized to other quadrants. With the detection technique we were able to identify and analyze several sequential bursting packets of coherent structures. The influence of packet dynamics on the velocity profile, Reynolds stress tensor (RST) and TKE production are investigated.

The notation adopted for the Reynolds velocity decomposition is streamwise, \( u = \bar{u} + u' \); spanwise, \( v = \bar{v} + v' \); vertical, \( w = \bar{w} + w' \) (\( \bar{\cdot} \) time mean and \( ' \) instantaneous value). When referring to \( v = \bar{v} + v' \), \( v \) is velocity and the subscript \( i \) \{1, 2, 3\} is one of the 3D Cartesian coordinates \( \{x, y, z\} \).

2 COHERENT STRUCTURE SAMPLING

2.1 Wavelet discrete transform and multiresolution analysis

Wavelet analysis is capable of localizing signal variability simultaneously both in time and scale (scale here refers to time duration) (Kantha & Clayson 2000). Contrary to Fourier based analysis, wavelet analysis can deal with non-stationary signals with randomly distributed singularities, such as the occurrence of coherent structures in turbulent velocity time series. In wavelet decomposition, the wavelet functions are scaled locally (dilation or contraction) in order to represent singularities. Thus, boundaries do not influence the local description of the signal. Fargé (1992) presented an introductory text on the use of wavelet transform in the study of turbulent signals. This paper is based on Fargé (1992), Fofoula-Georgiou & Kumar (1994), Kumar & Fofoula-Georgiou (1997) and Mallat (1999). Only 1D wavelet analysis is used.

In the continuous wavelet transform, the wavelet function \( \psi_{\lambda,t}(t) \) is parameterized by the real values of scale \( \lambda \) and time location \( t \), whereas in the discrete wavelet transform \( \psi_{m,n}(t) \) it is parameterized by the integers \( m \) and \( n \). As in Fourier analysis, we can apply a wavelet transform using appropriate wavelet functions and discrete scale and location parameters \( (m \) and \( n) \). The process consists of evaluating the signal locally (the wavelet covers all the time locations) in several modes, each corresponding to a defined scale. The scale is defined by the expansion of \( \lambda = \lambda_0^m \), where \( \lambda_0 \) is a fixed dilation step and \( m \) an integer. The time step to analyze the signal is a function of the chosen scale, \( t = n t_0 \lambda_0^m \). In this way, the time domain is covered by the discrete analysis.

A wavelet frame, which is characterized by the scale \( \lambda \) corresponds to each of the wavelets \( \psi_{m,n}(t) \). The partial reconstruction of the signal conditioned by the wavelet frame defined by \( m \) corresponds to one decomposition mode. Wavelet multiresolution consists of the decomposition of the original turbulence signal into one coarse set (the approximation) and several others with progressively smaller scale resolution (the details). Once the multilevel wavelet discretization of the signal is made, each level of the signal is reconstructed resulting in several low-resolution data series corresponding to each wavelet frame scale. A scale resolution higher than the scale of the last lower level of decomposition corresponds to the approximation. The signal may be successively reconstructed by adding the approximation \( (S) \) to the consecutive level details \( (D_2) \). Multiresolution analysis allows estimating the energy partition throughout the different scale frames associated with the decomposition modes. We may estimate the contribution of each wavelet frame to the streamwise flow energy by calculating the detail variance:

\[
D_{\lambda,u'}^2 = \frac{\sum_{n=1}^{N_{\text{time}}} D_{\lambda,u'}(n)}{N_{\text{time}}}
\]

where \( D_{\lambda,u'} \) = instantaneous detail of the instantaneous streamwise velocity associated with scale \( \lambda \); \( n = \) the integer defining the time step; and \( N_{\text{time}} = \) total number of time steps (the addition is made for the entire time domain).

We will now introduce a coherent structure detection technique and apply it to a single decomposition mode of the instantaneous 3D velocities measured at one level of the velocity profile. Subsequently the reconstruction of the velocity profile is made taking into account the detected events.

2.2 Wavelet-frame conditional quadrant analysis

The statistical distribution of coherent structures in the \( \{x,z\} \) plane may be analyzed by means of the threshold-based conditional sampling of instantaneous shear events \( \varepsilon' = u'w' \), combined with their quadrant location (Nakagawa and Nezu, 1977). The quadrant technique consists of analyzing the distribution of the instantaneous shear events \( \varepsilon' \) in the four quadrants of the \( \{x,z\} \) plane in order to detect coherent motions. For the positive detection of an event, a comparison of the relative amplitude of the instantaneous shear stress with a threshold value \( H \) is also required. Events for which the relative shear stress values \( (\varepsilon'/u'w') \) are lower than a threshold value \( H \) are called hole events. Using wavelet multi-
level decomposition of the instantaneous signals, we may condition the analysis of the coherent structures to a wavelet frame, by restricting the quadrant analysis to a chosen structure scale:

$$H_{c,k} = \frac{D_{\lambda,c}}{D_{\lambda,s} D_{\lambda,w}}$$

where $D_{\lambda,c}$ = time series of the instantaneous shear stress detail associated with scale $\lambda$, defined as $D_{\lambda,c} = D_{\lambda,w}^{-1} D_{\lambda,w}^{-1}$. $D_{\lambda,w}$ is the instantaneous detail of the instantaneous vertical velocity associated with scale $\lambda$.

2.3 Wavelet-frame threshold and cross-correlation conditional sampling

We discussed how to sample coherent structures according to their scale, quadrant location and shear amplitude. Now we define a time window around the detected structures in a determined wavelet frame centred at the location of the instantaneous shear event detected as relevant ($t_\varepsilon$). Its range ($t_\varepsilon \pm \Delta t_\varepsilon$) is defined by the following window parameter $\xi$:

$$\Delta t_\varepsilon = \frac{\xi}{2} \lambda$$

The choice for the event reconstruction may be refined with an analysis based on the cross-correlation between individual data windows. A correlation coefficient threshold $H_\rho$ below which the windowed instantaneous velocity data are rejected is defined as:

$$\rho_i|_{\xi} = \frac{C_{\xi,\lambda,v_i|\xi}}{\sigma_{\xi,\lambda} \sigma_{\xi,v_i}}$$

if $\rho_i|_{\xi} < H_\rho$, $v_i|_{\xi}$ is rejected

where $\rho_i|_{\xi}$ = correlation coefficient between a windowed instantaneous velocity ($v_i|_{\xi}$) and the composite average within the window ($\bar{v}_i|_{\xi}$); $C_{\xi,\lambda,v_i|\xi}$ = covariance between $\bar{v}_i|_{\xi}$ and $v_i|_{\xi}$; and $\sigma_{\xi,\lambda}$ and $\sigma_{\xi,v_i}$ = standard deviations of $\bar{v}_i|_{\xi}$ and $v_i|_{\xi}$, respectively. Appropriate normalization is made for the representation of the identified shear events. The time variable is normalized by the scale corresponding to the wavelet frame used as a basis to identify the structures ($t^+$). The velocities are normalized by the event amplitude within the time window:

$$v_i^+ = \frac{v_i|_{\xi}}{\max(v_i|_{\xi}) - \min(v_i|_{\xi})}$$

2.4 Method

Using the wavelet multilevel decomposition of the signal, a conditional sampling technique is presented that allows detecting and windowing similar coherent motion in a given velocity signal. The main steps of the procedure are:

1) Wavelet discrete transform of the turbulent velocity signal: multilevel decomposition of the signal into several wavelet-frames.
2) Multiresolution decomposition: reconstruction of each wavelet-frame resulting in several low-resolution data series corresponding to different time scales.
3) Scale conditional sampling of the decomposed signal with a chosen reference scale ($\lambda$).
4) Quadrant analysis and threshold-based ($H_{c,k}$) sampling of instantaneous shear events conditioned by the chosen scale ($\lambda$).
5) Windowing and composite averaging of the detected structures with a defined window parameter ($\xi$).
6) Correlation coefficient threshold ($H_\rho$) resampling: refinement of the windowed events based on the coherence of different instantaneous events detected within the defined window.
7) Normalization and composite averaging of the windowed events: time normalized by the scale $\lambda$, and velocities normalized by the event amplitude (Eq. 5: $u^+$, $v^+$ and $w^+$ respectively for streamwise, spanwise and vertical components).

3 RIVER MEASUREMENTS

This research is based on a timeseries of instantaneous velocity profiles measured in the Swiss river Venoge (canton of Vaud) during the summer of 2004, under stationary shallow water flow conditions. The measuring position was located about 90 m upstream of the Moulin de Lussery. The hydraulic characteristics of the river and of the measured profile are shown in Table 1.

<table>
<thead>
<tr>
<th>$Q$ (m$^3$/s)</th>
<th>$S$ (%)</th>
<th>$h$ (m)</th>
<th>$U$ (m/s)</th>
<th>$Re$</th>
<th>$Fr$</th>
<th>$u^*$ (m/s)</th>
<th>$D_{50}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.76</td>
<td>0.33</td>
<td>0.17</td>
<td>0.60</td>
<td>6.4</td>
<td>0.29</td>
<td>0.040</td>
<td>68</td>
</tr>
</tbody>
</table>
where $Q = \text{river discharge}; S = \text{river slope}; h = \text{water depth}; U = \text{depth-averaged streamwise mean velocity}; Re = \text{Reynolds number}; Fr = \text{Froude number}; u^* = \text{shear velocity estimated using the eddy-correlation method} (\text{Monin and Yaglom 1971}); D_{50} = \text{bottom grain size diameter for which 50\% of the grain diameters are smaller}$. The riverbed material grain distribution was sampled according to the Wolman (1954) method. The riverbed is hydraulically rough, with coarse gravel and randomly spaced macro-roughness elements scaling with as much as half the water depth ($0.5h$). We used the deployable ADVP developed at the LHE-EPFL, which allows measuring 3D quasi-instantaneous velocity profiles over the entire depth of the flow in rivers (Rolland & Lemmin 1997). Data were sampled for 211 s at a frequency of 26 Hz. We implemented a dealiasing method which corrects the instantaneous Doppler frequencies measured by the four receivers (Franca & Lemmin 2006). The vertical resolution of the measurements is around 0.5 cm. Figure 1 shows the mean velocity ($U$) profile. The coherent structure analysis was applied to a point which is located in the boundary layer of the logarithmic velocity profile, 1.4 cm above the riverbed (Fig. 1).

4 RESULTS

4.1 Detection and single point 3D reconstruction

Coherent structures were sampled according to the method described in Section 2. In Table 1 we indicate the parameters used for the application of the analysis.

<table>
<thead>
<tr>
<th>N</th>
<th>Wavelet type</th>
<th>$\lambda$</th>
<th>Shear event</th>
<th>$H_{\epsilon\lambda}$</th>
<th>$\xi$</th>
<th>$H_{\rho}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Daubechies D4</td>
<td>0.43</td>
<td>Ejection</td>
<td>5</td>
<td>2.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

where N is the number of decomposition levels. The chosen scale ($\lambda = 0.43 \text{ s}$) corresponds to the most energetic scale in the timeseries. The length of the most energetic coherent structures corresponds to a macro scale with an order of magnitude situated between a characteristic bed grain dimension ($\approx D_{50}$) and the water depth ($h$). Its value is around $\lambda = 0.43 - 0.86 \text{ s}$ (in length scale, $\Lambda \approx 0.10$ to 0.20 m). An N = 8 level wavelet decomposition with the Daubechies type D4 function (Daubechies 1988) is sufficient to describe the energy partition throughout the different structure scales present in the flow. At this scale, negative shear events situated in QII and QIV are predominant. Restricting our analysis to coherent structures belonging to QII and to a threshold level of $H_{\epsilon\lambda = 0.43} = 5$, 46 shear events are detected. A high degree of scattering around the mean value is found in the individual windowed data series. By windowing the detected events with a window-parameter $\xi = 2.2$, and a refinement using a correlation coefficient threshold of $H_{\rho} = 0.5$, this number is reduced to 20 events. Under these conditions we reconstructed a composite 3D normalized coherent structure at a single-point using the three components of the instantaneous signal.

The windowed composite average ($\tilde{v}_{\xi = 2.2}$) are presented (Figure 2) in the data time series of the corresponding instantaneous streamwise, vertical and spanwise velocity components ($v_{\xi = 2.2}$). In Figure 3 the reconstructed coherent structures from the composite-averaged three velocity components are shown within the selected window.
Figure 3. Reconstruction of the detected coherent structure normalized by the local variables. The three velocity components are plotted as a function of time. Symbols ○ and □ represent the beginning and the end of the sweep-ejection cycle (point 1 and 5 in the figure), and ◊ the beginning of the detected ejection (point 3). Labels are explained in the text.

Coherence exists between the sampled events in the three Cartesian components. Before and after the occurrence of the detected ejection \( (t_\varepsilon = 0 \text{ s}) \), lower amplitude sweeps occur \( (u^+ \text{ and } w^+) \) fields. This is a characteristic of the bursting phenomenon. Some in-phase movement is seen in the spanwise velocity data.

The existence of sweeps before and after the detected ejection is a coherent event in all selected structures. Thus, the detection process allows isolating a combined sweep-ejection cycle. In the 3D reconstructed coherent structure, the three velocity components present a statistical coherent structure, mainly in the \( \{x-z\} \) direction. Six key moments are identified in the process. In chronological order, they are:

1) When all three instantaneous velocity components have low amplitudes;
2) Local maximum amplitude of the \( u' \) signal in the first sweep (S1);
3) Before the beginning of the detected ejection when all three instantaneous velocity components again have low amplitudes;
4) High amplitude ejection located in the center of the frame (E1);
5) End of the detected ejection, the three instantaneous velocity components once again have low amplitudes;
6) Local maximum of the \( u' \) signal amplitude in the second sweep (S2).

Moments 1, 3 and 5 may be called “stop” points, since all three velocity components simultaneously have low amplitudes and roughly the same value. The spanwise component evolution is in-phase with the vertical component and out-of-phase with the streamwise component, suggesting an interaction between the three components.

4.2 Reconstruction of the velocity profile

Having reconstructed one sweep-ejection cycle three-dimensionally in a single point, it is now possible to analyze the remaining water column. The same framing and composite averaging method is applied to the profile, using the time position detected from the single point analysis (the single point analyzed is considered as the detection point for the velocity profile). In Figure 4 the composite averages of the velocity components are represented for the six key moments of the detected cycle indicated in Figure 3.

The momentary deformation of the velocity profile due to the sweeps and ejections is evident. The streamwise velocity profile acquires its time mean value immediately before and after the events at the so-called “stop” points. The plots of the instantaneous streamwise velocity profiles clearly show the position of the sweep-ejection-sweep cycle detected. The existence of complementary shear events suggest a certain packet behaviour. We are thus in the presence of a bursting packet composed of a sequence of sweeps, S1 and S2 and an ejection, E1.

4.3 Effect of the passage of the bursting packet on the turbulence intensities

In this section we analyse the effect of the passage of the bursting packet on the distribution of turbulent intensities (TIs), composite-averaged within the predefined frame. The TIs or normal components of the Reynolds stress tensor (RST) correspond to the variance of the three velocity components \( \overline{(v^+)^2} \). The composite-variance calculated within the predefined frame is denoted by \( \overline{v_i^2} \). The normal stresses define the turbulent energy content of the flow. Since they
are production features of the flow, coherent structures are expected to enhance the turbulent energy during their passage. The total mean and composite-averaged (within the frame) TI profiles is presented in Figure 5. The composite-averaged values are denoted by the symbol ~. Both are normalized by the peak values of the mean distribution.

The peak values of the TIs are $\bar{u'}^2 = 0.0061 \text{ m}^2\text{s}^{-2}$, $\bar{v'}^2 = 0.0015 \text{ m}^2\text{s}^{-2}$ and $\bar{w'}^2 = 0.0010 \text{ m}^2\text{s}^{-2}$. As expected, the TIs are enhanced by the bursting packet sequence. Compared with the total time mean, the spanwise TI (Fig. 5b) presents a peak enhancement of about 25 times. This suggests that compared to the background fluctuating field, the component in this direction is particularly strong during these events. The ratio of the peak enhancements for the streamwise (Fig. 5a) and spanwise composite (Fig. 5b) TI is $\bar{v'}^2 / \bar{u'}^2 \approx 0.77$. On the average the turbulence structure of the flow is determined by the streamwise velocity component. However, strong short-term processes, such as the sequential bursting packet discussed here, are 3D with an important spanwise component. The determination of streamwise friction velocities by a 2D analysis will thus distort the estimate of the instantaneous bottom drag and provide erroneous information on sediment/mass suspension and transport across the boundary layer.

These results support the observations by Franca (2005) which indicated that 2D friction velocity concepts may not be suitable to determine bottom stress for sediment transport calculations in shallow rough bed rivers. The vertical TI profile (Fig. 5c) is 1 to 2 times greater than the total time average value. The increase is due to the additional vertical momentum introduced into the flow by the packet process. Reynolds shear stress distributions (not shown here) confirm that the strongest transport/suspension processes may occur along both the streamwise and spanwise direction, in agreement with the above observed effect on the friction velocity.

4.4 Effect of the passage of the bursting packet on the instantaneous TKE budget

The turbulent kinetic energy (TKE) transport equation, also known as the TKE budget, represents the dynamic equilibrium of the energy terms due to the turbulent motion of the flow. For an incompressible flow of an isothermal fluid, the TKE equation is (Schlichting 1968):

$$\frac{\overline{Dk}}{Dt} = P + D - \varepsilon$$

where $\overline{k}$ is the temporal mean of the turbulent kinetic energy (TKE: $\overline{k'} = \overline{u'^2 + v'^2 + w'^2}$); $P$ is the production rate or generation of TKE by the interaction of Reynolds stress and mean shear; $D$ is the diffusive term; and $\varepsilon$ is the dissipation rate. The diffusive term $D$ is negligible for high Reynolds number flows.

Background small-scale turbulence present throughout the flow produces dissipation, but production results from individual large-scale events such as the coherent structures described here. The instantaneous production term of TKE, $P'$, is defined by

$$P' = -\bar{v'} \bar{v'j} \frac{\partial \bar{v'}}{\partial x_j}$$

ADVP measurements do not allow direct access to the instantaneous spanwise gradients ($\partial / \partial y$). In order to estimate instantaneous production, we assume that $\frac{\partial u}{\partial y} \approx \frac{\partial v}{\partial x}$, $\frac{\partial w}{\partial y} \approx \frac{\partial v}{\partial z}$, and $\frac{\partial v}{\partial y} \approx \frac{\partial w}{\partial z}$. The streamwise gradients are determined using Taylor’s frozen hypothesis. Figure 6 shows the composite-averaged production $\bar{P}$ profile normalized by the peak of the mean distribution. The maximum increase in the production rate due to the bursting packet is about two times the mean production peak. Despite their short duration, coherent structure packets are highly productive.
5 CONCLUSIONS

Using ADVP measurements in a shallow river, we developed a method for identifying and reconstructing coherent structures based on a wavelet multiresolution analysis. Coherent structures were detected by analyzing the turbulent velocity signal at one level located in the boundary layer. The reconstruction in time and 3D space was carried out using instantaneous velocity profile measurements. The reconstructed signal provided a visualization of a sequential bursting packet of coherent motion.

The time reconstruction and the phase plots between the three Cartesian components of the reconstruction allowed the following observations:

- The three velocity components present statistical coherent motion.
- A sweep (QIV) was detected before an ejection, with equivalent amplitude and time duration; the compositely reconstructed coherent motion may be a signature of a bursting process.
- A second but weaker sweep (QIV) is observed after the detected ejection.
- Between the sweeps and ejections we observed what may be called “stop” points where all the three components of the instantaneous velocity have low-activity periods simultaneously.
- In summary, the sequence of the movement inside the frame may be characterized by six consecutive key moments: 1) “stop” point; 2) first sweep (S1); 3) “stop” point; 4) ejection, located in the center of the frame (E1); 5) “stop” point; 6) second sweep (S2) (see Figure 3).

We reconstructed the detected coherent motion in the profile, compositely time-averaging the 3D velocity in the water depth. The momentary deformation of the velocity profiles is obvious in the vertical and the streamwise component. The ejection E1 covers a certain scale domain in the water column. An enhancement of the streamwise velocity is limited to the lower layer, whereas the vertical component is affected until \( z/h \approx 0.50 \). The spanwise velocity profiles are not conclusive. Nevertheless, strong variations of this component occur before the onset of sweeps, suggesting a certain relationship with the shear events in the \( \{x-z\} \) plane. Lateral momentum transfer seems to exist between adjacent ejections and sweeps.

We also analyzed the impact of the passage of the coherent structures packet on the turbulence distribution in the flow, mainly on the RST and on the TKE production. We compared the total time-averaged quantities with frame averages.

The spanwise turbulence intensities are enhanced during the passage of a packet, momentarily equaling the streamwise intensities. Transport and suspension processes, characterized by single or short events, may thus occur in both horizontal directions. The observed packet is highly energetic, and it produces twice the mean peak production during a relatively short period of time.

Based on the present measurements, further systematic research will be conducted in the 3D measuring grid, in order to develop an overall concept of the influence of bursting events on transport and mixing processes in rivers. These extremely energetic events are rare but of great importance in the processes described here. Therefore new approaches are needed in geophysical modeling in order to take their contribution into account.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support by the Swiss National Science Foundation (2000-063818) and the Portuguese Science and Technology Foundation (BD 6727/2001). We are most grateful to Gene Terray for introducing us to wavelet analysis.
REFERENCES


