# Multifractal pre-processing of AVHRR images to improve the determination of smoke plumes from large fires

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***Abstract*—In this study, we show how different spectral channels of NOAA-AVHRR acquired data can be used to produce a synthetized signal aimed at helping the characterization of plumes associated to fire events. The synthetized signal is computed using a reconstruction formula in the multifractal microcanonical formalism (herein referred to as MMF). The MMF is a recent development in the analysis of complex signals, well adapted to the study of turbulent acquired data, for instance geophysical fluids. It allows the computation, at each point of the signal's domain, of a singularity exponent, characteristic of the scale behaviour of the signal around that point; singularity exponents provide information about the strengths of the transitions inside a signal, and they are related to the multifractal hierarchy associated to structure functions in Fully Developped Turbulence (FDT). In the MMF, it is possible to reconstruct a turbulent signal from the manifold of most singular exponents. We make use of this property by computing *supergeometric structures* from a thermal infrared channel in NOAA-AVHRR acquired data, and we use the signal's gradient coming from other channels to reconstruct a signal in which plume pixels are easier to detect. This methodology is based on the turbulent properties of the plume accessible from the thermal infrared band; the algorithm is detailed and applied on a specific example, showing a new spatially-based method for helping the determination of plume pixels in NOAA-AVHRR data.**

## I. Introduction

The determination of natural or industrial fires and fire plumes from remotely sensed data is a well documented area of research [Cahoon *et al.*1999], [Chrysoulakis and Cartalis2003], [Chrysoulakis *et al.*2007], [Chu *et al.*1998], [Li *et al.*2001]. Most fire detection and plume determination algorithms are basically pixel-based: they use the grey-levels values of pixels corresponding to a satellite acquisition over an extended ground area; depending on the physical properties of the acquired radiations, they determine appropriate thresholds values and classify the pixels accordingly. Some of these methods may use spatial content information (see, for instance [Chrysoulakis *et al.*2007] but the majority of algorithms remains pixel-based.

In this paper we want to investigate specific spatial properties of the 2D signals acquired by NOAA-AVHRR over regions containing fire plumes. The goal is to find new spatial descriptors that can be incorporated into fire detection algorithm for better accuracy and less sensitivity to threshold values in the process of determining plume pixels. More precisely, we don't want to perform any type of classical texture analysis for plume pixels determination and enhancement; instead, we want to focus of some physical behaviour associated to atmospheric turbulence, and try to assess these properties from the NOAA-AVHRR signal. The key observation is that the turbulent behaviour of plumes corresponding to fire incidents should be accessible in the channels in which the acquired data correspond to the spatial distribution of a physical intensive variable like temperature. For that matter, we rely on signal processing multiscale analysis techniques powerful enough to capture the power-law behaviours found in turbulent phenomena [Arneodo *et al.*1995]. Many hours after an incident, plumes of different kinds ([Chrysoulakis and Cartalis2003], section 1) undergo various dispersion dynamics (for instance, in the case haze-like plumes, dispersion can be related to dominant winds over the area), and their spatial extension can become large. Consequently, we expect to find some of the plume turbulent behaviour in the NOAA-AVHRR acquisitions.

It is reasonnable to assume that the plumes recorded by the sensors are acquisitions of atmospheric fluids in the regime of fully developped turbulence (**FDT**). The acquired plumes can be dense plumes or haze-like plume, in either case we make the assumption that the plume belongs to the **FDT** regime. For such systems, it is now well known that there exists a fundamental connection between the multifractal hierarchy associated to turbulence and the spectrum of *singularity exponents* observed in the structure functions [Arneodo *et al.*1995]. We will make use of the microcanonical multifractal formalism **MMF** [Turiel and del Pozo2002] in preference to statistical formulations of the multifractal hierarchy. In the microcanonical multifractal formalism (**MMF**) and in the statistical formulations as well, *singularity exponents* play a fundamental role because of their importance in the description in the macroscopic features of a system [Arneodo *et al.*1995]. Moreover, from a physical point of view, the singularity exponents form the building block of many features associated to a multiscale description of an acquired geophysical fluid or aerosol. Satellite sensors have different spatial resolutions, consequently the determination of multiscale features may help the matching of turbulent structures between sensors of different resolutions.

## II. The microcanonical multifractal formalism

In this section review the key aspects of the **MMF**, and the reader is referred, among other references, to [Turiel and del Pozo2002] for a deeper exposition. Let $\mathbf{s}$ be the signal associated to a given acquisition. We consider that $\mathbf{s}$ is defined over a compact subset $\Omega \subset R^2$ (corresponding to the image acquisition plane) and takes real values. To introduce a variable with stationnary values, we consider the generalized gradient norm $\|\nabla \mathbf{s}\|$ instead of the signal values. We introduce the following density measure $\mu$:

$$\mathrm{d}\mu \;=\; \|\nabla \mathbf{s}\| \; \mathbf{dx} \tag{1}$$

i.e. a measure having density $\|\nabla \mathbf{s}\|$ w.r.t. to the Lebesgue measure $\mathbf{dx}$: for any measurable subset $\mathcal{A} \subset \Omega$, the measure $\mu(\mathcal{A})$ is defined as:

$$\mu(\mathcal{A}) \;=\; \int\!\!\int_{\mathcal{A}} \|\nabla \mathbf{s}\|(\mathbf{x}) \; \mathbf{dx} \tag{2}$$

The measure $\mu$ is *multifractal* if for any point $\mathbf{x} \in \Omega$ one has:

$$\mu\left(B_{\mathbf{r}}(\mathbf{x})\right) \;=\; \alpha(\mathbf{x}) \, \mathbf{r}^{h(\mathbf{x})+\mathbf{d}} \;+\; o\left(\mathbf{r}^{h(\mathbf{x})+\mathbf{d}}\right) \; (\mathbf{r} \rightarrow \mathbf{0}) \tag{3}$$

where $B_{\mathbf{r}}(\mathbf{x})$ stands for the ball of radius $\mathbf{r}$ centered at $\mathbf{x}$. Many geophysical signals of different types are of multifractal character [Turiel and Parga2000]. The shift $\mathbf{d} = 2$ (space dimension) is introduced to remove the contribution due to the integral, hence capturing the behaviour specific to the function $\|\nabla \mathbf{s}\|$. In equation (3), the coefficient $h(\mathbf{x})$, which is independant of the scale $\mathbf{r}$, is a *singularity exponent* at $\mathbf{x} \in \Omega$. It is the fundamental notion in the **MMF**. To compute it accurately, we make use of wavelet techniques on singularity analysis, as described in [Turiel and Parga2000].

### A. Geometric superstructures

The singular exponents computed in the framework of the **MMF** are good approximations of the power-law behaviour of thermodynamic observables in a geophysical turbulent flow. These exponents define a multifractal hierarchy of geometrical sets (the *geometric superstructures*) closely related to the corresponding multifractal hierarchy associated to structure functions in **FDT** [Turiel *et al.*2005b]. We assume that the spectrum of singularities is bounded, as experimentation shows. With these hypotheses, there is a lower bound $h_\infty = \inf\{h(x),\ x \in \Omega\}$ and a geometric superstructure, the Most Singular Manifold (**MSM**), can be defined as follows:

$$\mathcal{F}_\infty \;=\; \{\mathbf{x} \in \Omega \,|\, h(\mathbf{x}) \;=\; h_\infty\}. \tag{4}$$

The **MSM** is defined by the points featuring the sharpest transitions in the signal. In section II-B, it will be associated with the most informative content in the signal. These two notions are stongly interrelated. The **MSM** is made of isolated clusters of points or disconnected almost-linear features with Hausdorff dimension up to 1.

### B. Reconstructible systems

As the **MSM** is associated to sharpest continuous transitions, it is natural to derive a universal propagator that would permit the reconstruction of a whole signal from its values restricted to the **MSM** only. The reconstruction consists in propagating gradient values from the **MSM** to the whole image domain. The propagator and the associated reconstruction formula are defined by the following equation in the Fourier space [Turiel and del Pozo2002]:

$$\hat{\mathbf{s}}(\mathbf{f}) = \frac{\sqrt{-1}\mathbf{f} \cdot \widehat{\nabla|_{\mathcal{F}_\infty}\mathbf{s}(\mathbf{f})}}{\|\mathbf{f}\|^2} \tag{5}$$

with:

- $\mathbf{f} = (\mathbf{f}_x, \mathbf{f}_y)$ is the two-dimensionnal frequency vector.
- The hat symbol $\hat{\mathbf{s}}$ refers to the Fourier transform.
- $\nabla|_{\mathcal{F}_\infty}\mathbf{s}$ is the signal's gradient restricted to the **MSM**.
- The dot symbol $\cdot$ in formula (5) refers to vector dot product.

The universal propagator, defined in Fourier space by

$$\hat{\mathbf{g}}(\mathbf{f}) = \frac{\sqrt{-1}\mathbf{f}}{\|\mathbf{f}\|^2}. \tag{6}$$

is a propagator corresponding to the power spectrum of a translational invariant signal, a well known requirement for natural images [Turiel and del Pozo2002]. Consequently, the reconstruction formula acts as a diffusion kernel propagation of gradient values from the **MSM**. If the **MSM** does encode the sharpest transitions, which correspond to the most informative content parts, the reconstruction formula should provide a good reconstruction of the original signal from its **MSM**. We will illustrate this in section III.

In NOAA-AVHRR acquisitions, five spectral channels are available: $c_1$ in the visible range ($\mu$m) (0.58-0.68), $c_2$ in the near infrared range ($\mu$m) (0.72-1.10), $c_3$ in the mid infrared range ($\mu$m) (3.55-3.93), $c_4$ in the thermal infrared range ($\mu$m) (10.5-11.3) and $c_5$ in the thermal infrared range ($\mu$m) (11.5-12.5). Since we are interested in the turbulent properties of the acquired signal, we use the thermal infrared bands of NOAA-AVHRR data to compute singular exponents and the **MSM** (NOAA channel $c_5$); this comes from the fact that in these bands, the acquired signal is an intensive variable, the temperature, reflecting the turbulent aspect of the acquisition. The reconstruction formula 5 consists in propagating gradient values from the **MSM**; consequently, the basic idea in this study consists in propagating gradients coming from some spectral bands, along the **MSM** computed in the band in which the turbulent properties of the signal are accessible. This idea is developped in the next subsection.

### *C. A modified reconstruction formula*

We use the assumption that the **MSM** computed in the thermal infrared band is directly related to the streamlines of the underlying fluid, so we take this set as the correct reference on the geophysical fluid flow dynamics. We will use the signal gradient of a function of channels $c_2$ and $c_3$ to enhance the discrimination between plumes and others bodies taking into acount temperature and reflectance information. Let $\varphi(c_2, c_3)$ be a function of the pixel's grey-level values acquired in spectral bands $c_2$ and $c_3$. We define a synthetized signal **p** by propagating $\varphi$'s gradient vectors from the **MSM** computed in channel $c_5$; that is, we use the reconstruction formula (5) in which the gradient information is replaced by $\varphi$'s gradient values $\nabla\varphi$:

$$\hat{\mathbf{p}}(\mathbf{f}) = \frac{\sqrt{-1}\mathbf{f} \cdot \widehat{\nabla|_{\mathcal{F}_\infty}\varphi}(\mathbf{f})}{\|\mathbf{f}\|^2} \tag{7}$$

which means that the gradient of $\varphi$ is diffused from the set of strongest transitions on the thermal infrared channel. The algorithm is then as follows:

(1) Compute the singular exponents of the acquired signal **s** using wavelet decomposition in the thermal infrared band $c_5$.
(2) Derive the **MSM** $\mathcal{F}_\infty$ from the singular exponents by selecting pixels whose exponents is in a given fixed interval centered around the lowest exponent.
(3) Compute the gradient values $\nabla\varphi$ and set to zero these values outside $\mathcal{F}_\infty$ to get the singular gradient values $\nabla|_{\mathcal{F}_\infty}\varphi$.
(4) Compute the synthetized signal $\hat{\mathbf{p}}(\mathbf{f})$ in Fourier space using equation (7).
(4) Determine the synthetized signal **p** in spatial coordinates by use of the inverse Fourier transform.

The resulting synthetized signal **p** is called a **multispectral reduced signal**. In the next section, we show the data used and some results.

## III. Experiments

To illustrate the concepts presented in this study, we use a NOAA-AVHRR image of a plume development caused by a fire on a large oil tanker near Genoa, Italy, that occurred on April, 13, 1991. The dataset consists in NOAA Level 1-b data with a dynamic range on 10 bits (1024 grey-level values), geometrically corrected and calibrated, with grey-level values converted into brightness temperatures values (infrared bands $c_3$, $c_4$ and $c_5$), and reflectance values ($c_1$ and $c_2$ bands). In the visible range, a plume reflectance is a function of the aerosol particle optical thickness (their size distribution) and of its liquid water content. In the thermal infrared range, a plume reflectance possesses a signature as it contains particles radiating as grey bodies. Fire in itself emits thermal radiation with a peak in the mid infrared region. Meteorological clouds have a strong reflectivity in the visible and near infrared bands. Water bodies strongly absorb radiations in the near infrared. Fire plumes' turbulent behaviour is mainly accessed in the thermal infrared bands of the electromagnetic spectrum, where the acquisition correspond to the spatial distribution of temperature.

We denote by $r_i$ the pixels' grey-level values of channel $c_i$ in the NOAA-AVHRR acquisition dataset ($1 \le i \le 5$). Among the simplest functions that makes use of the $c_2$ and $c_3$ spectral bands, we simply take the sum: $\varphi(c_2, c_3) = r_2 + r_3$ with the following conventions: first the values $r_2$ and $r_3$ are normalized between 0 and 1, and the result is clamped to 1 if $r_2 + r_3 > 1$. For the Genoa incident, we present the data in figure 1, displaying channels $c_1$ (visible) and $c_5$ (thermal infrared) of the acquisition. The singularity exponents and the resulting **MSM** are shown in figure 2. Figure 3 illustrates the result of the reconstruction process, performed on channel $c_5$. The **multispectral reduced signal** is displayed figure 4. Almost all clouds are eliminated, and the plume only remains, displaying strong contrast changes due to the aerosol's radiative and reflective properties encoded by spectral bands $c_2$ and $c_3$.

## IV. Dicussion and conclusion

The experiments conducted on the Genoa incident provide particularly good results. This comes from the relatively important size of the plume in this case. Experimentations conducted on other industrial incidents may sometimes produce less satisfactory results: the plume is always present, along with other bodies. Such poor results are particularly noticeable for small plumes, in which the turbulent behaviour is not easily assessed due to the spatial resolution of the NOAA-AVHRR sensor. The search for an "optimal" reconstruction function $\varphi$, that would produce satisfactory results in all cases, is a subject of research. The method presented in this paper is based on the **MMF** and consequently is an attempt at characterizing plume pixels from spatial content associated to turbulence in the data. Presently, our method can be considered as a preprocessing step to help the process of pixel-based plume determination, in the sense that it can be given as an input data to more classical pixel-based plume detection methods, like the one presented in [Chrysoulakis *et al.*2007].

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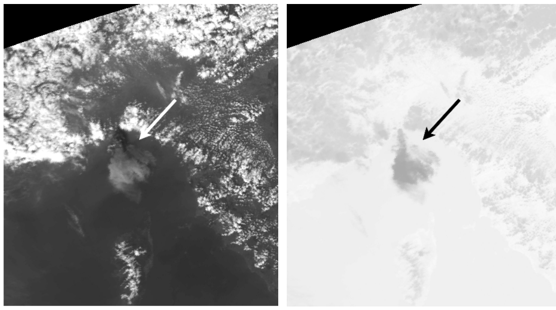

Fig. 1. NOAA-AVHRR acquisitions of the Genoa event of April 13, 1991, channels $c_1$ (visible, top) and $c_5$ (thermal infrared, bottom). The plume generated by the fire incident is denoted by an arrow.

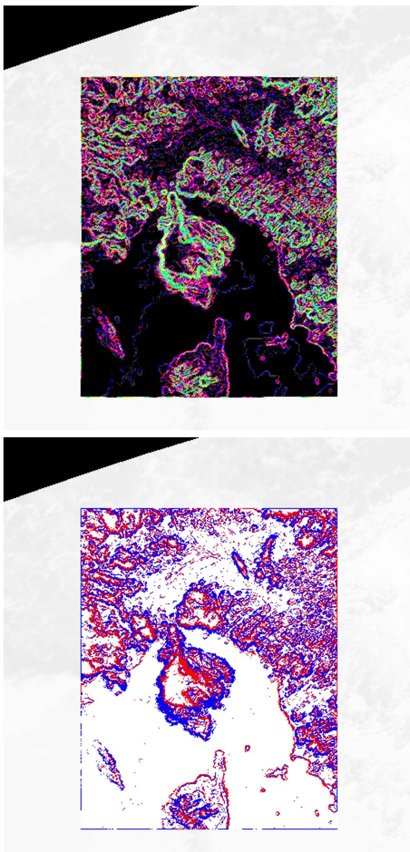

Fig. 2. Top: singularity exponents, computed on a selected rectangular area around the incident in the Genoa acquisition, channel $c_5$ in the NOAA-AVHRR dataset. Bottom: the oriented **MSM**, made of most singular points.

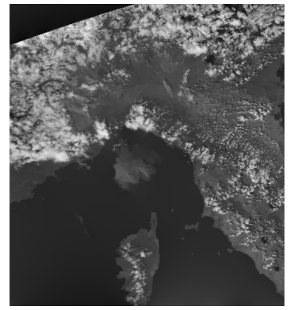

Fig. 3. Result of the reconstruction process, channel $c_5$, consisting of diffusing the gradient from the **MSM**. The image has been normalized.

Fig. 4. Resulting multispectral reduced signal computed on a selected area of the original dataset. The plume only remains (with land pixels).

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