1D, 2D, 3D wavelets methods for gamma-ray point source analysis

S. Ciprini, G. Tosti, F. Marcucci, C. Cecchi, G. Discepoli
E. Bonamente, S. Germani, D. Impiombato, P. Lubrano, M. Pepe

INFN PERUGIA (INFN Perugia & University of Perugia, Italy)

Abstract

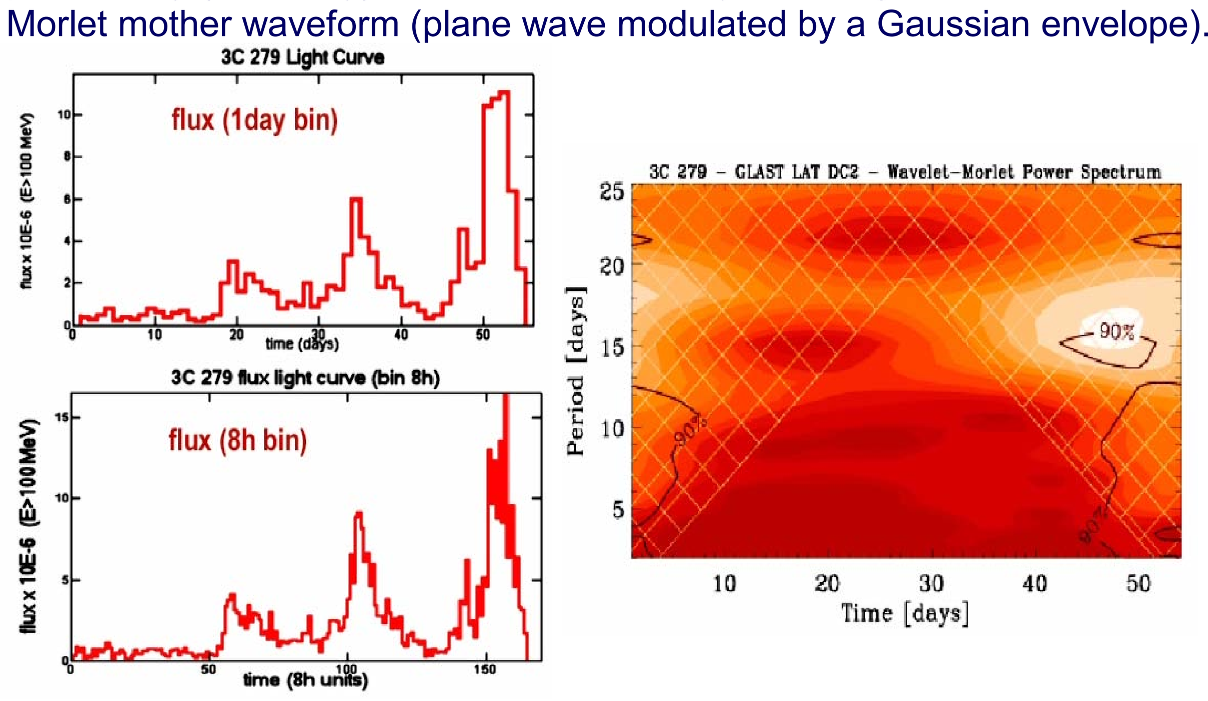
Wavelet transforms are commonly used to translate a 1D signal or a 2D/3D field into both space and scale/frequency, showing the information in a more useful shape. 1D wavelet transforms allow to characterize the variability behavior, which represents an useful piece of information in the astrophysical identification of gamma-ray sources. On the other hand the 2D/3D wavelet technique has turned out to be a valid alternative/partner of the classical (model-dependent) Likelihood analysis, permitting a rapid, efficient and blind detection of bright sources. Here are reported few examples of the application to EGRET observations and simulated data of GLAST.

Introduction

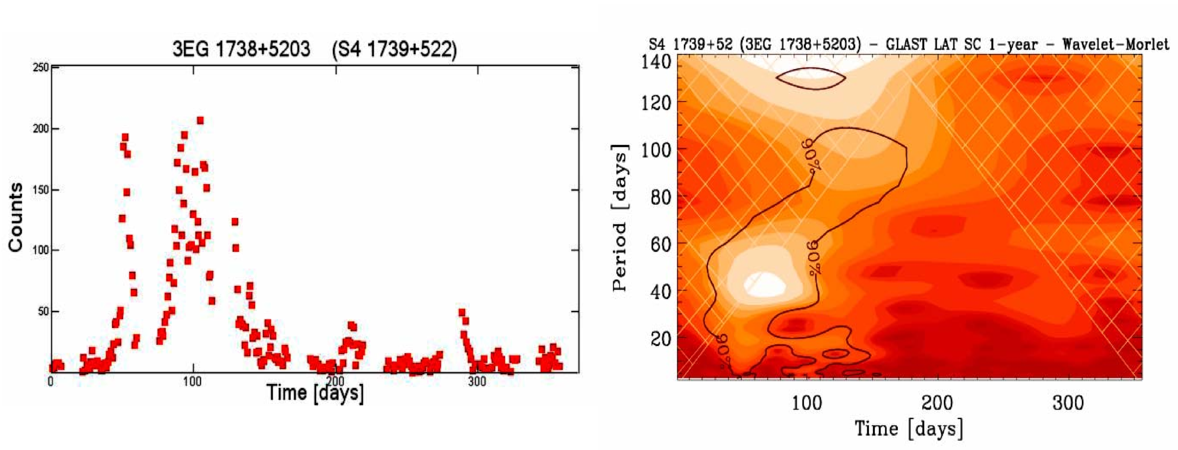
Wavelet transforms (WT) are commonly used to translate a 1D signal and 2D/3D array into both space and scale/frequency, showing the information in a more useful shape. WT make use of space-localized and oscillatory functions called wavelets, that are dilated and contracted before convoluting them in each part of the signal, providing a scale decomposition and analysis of local variations of power, and allowing an efficient decomposition, denoising, filtering and cleaning. Here are presented few examples of the application of the WT to light curves and gamma-ray maps from EGRET observations and full-instrument simulations of GLAST.
The large effective area (8500 cm^2 at 1 GeV) and wide field of view (2.4 sr) of the LAT instrument of GLAST (passband 30 MeV - 300 GeV), provide a 1-year sensitivity better than 25 times the 3EG catalog sensitivity, while the survey mode operation, gives a very uniform coverage of the sky. This means a rather continuous monitoring of variable sources on a wide range of time scales, and the expected detection of a few thousands of new gamma-ray point sources. Source detection, source identification, and variability analysis are therefore central problems for GLAST, and wavelets can play an useful role.

Light curve analysis with 1D wavelets

The continue wavelet transform (CWT) can be an useful tool to analyze coherent time structures, spectral features, and localized variations of power within a light curve. Light curves form the full instrument simulations of the LAT (Data-Challenge 2, DC2, 55-days of simulated observations, and now starting on Service Challenge, SC, 1-year simulations) are extracted using pythons scripts and the standard method of aperture photometry (DC2 only). These are then analyzed using the 1D WT with a Morlet mother waveform (plane wave modulated by a Gaussian envelope).



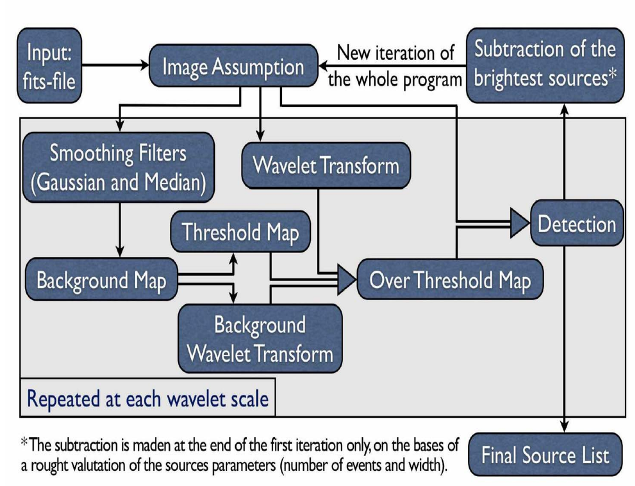
Full-LAT simulated DC2 (55-days) light curve of 3C 279, determined with a preliminary algorithm miming the standard method of aperture photometry by the count maps (integrated gamma-ray flux above 100 MeV in units of 10^-6 phot cm^-2 sec^-1). A possible 16/17 day characteristic time scale is found in this simulated light curve with structure function and periodogram techniques. This scale/period is well represented by the peak in the 1D wavelet scalogram (white filled spot on the right plot), even if edge effects (crosshatched region) can be important. Thick black contours are the 90% confidence levels of true signal features against white/red noise background spectrum.



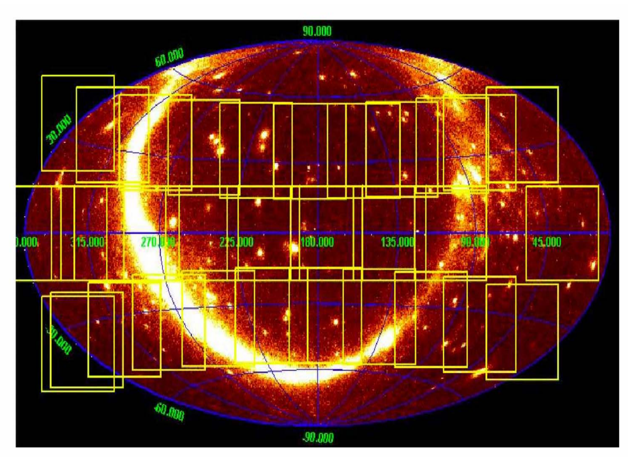
Full-LAT simulated SC (1 year) light curve in mere photon counts of S4 1739+52 (OT 566, 3EG 1736+5203, z=1.375) and the corresponding wavelet scalogram.

Detection of gamma-ray sources with 2D wavelets

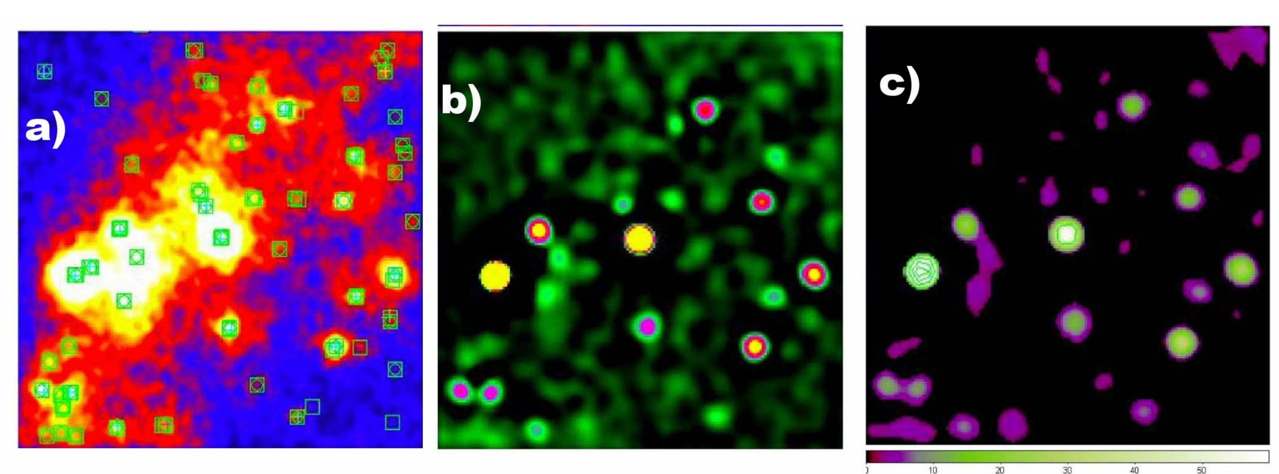
Source detection at gamma-ray energy bands is a tricky problem owed to the few photon counts collected. Statistics is intimately poor (Poissonian regime) and the S/R ratio of a typical source is low. Moreover high energy detectors show a large variation of the Point Spread Function (PSF) in energy, and a quite bad resolution compared with other lower frequencies (giving spreading, source overlap and harder source detection). On the other hand bright and extended sources (diffuse emission, some bright AGNs or SNR) obscures the closest and faint point-like sources, making harder their detection and characterization. The 2D wavelet called Mexican Hat (or Marr, i.e. the Laplacian of a Gaussian function) has the best features for the point-like source detection.
Our 2D WT algorithm (named PGWAVE) does not require ''a priori'' model of the source and could be profitably useful together with the standard, parametric, Likelihood techniques. This 2D tool was applied on the LAT DC2 simulated maps, dividing the gamma-ray sky in 34 areas, each one with a 30deg side and with a 0.25deg resolution. The final result is a catalogue with more than 800 sources (3sigma confidence). This result is satisfactory, compared with the DC2 official released catalogue. The method can generate additional information and files (like maps produced by the Gaussian, median, adaptive and wavelet filters, the threshold/over-threshold and significance maps).



Block diagram of the 2D algorithm.

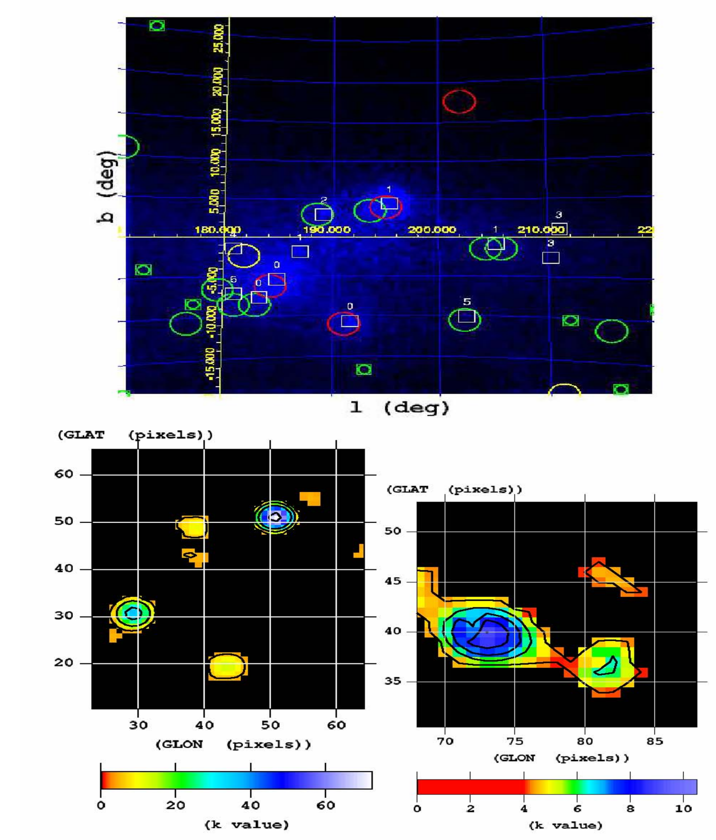


Subdivision of the LAT DC2 gamma-ray sky in 34 regions.



a) LAT DC2 simulated map of the Crab region with the superimposed sources found by our 2D wavelet (PG-WAVE) algorithm (box-circle), the DC2 source catalog (cross) and Third Egret (3EG) catalog (box).
b) Wavelet-transformed map of the same region at the scale a = 0.5 deg.
c) The k-significance of the same region (k being the confidence level chosen for the threshold map at a given scale).

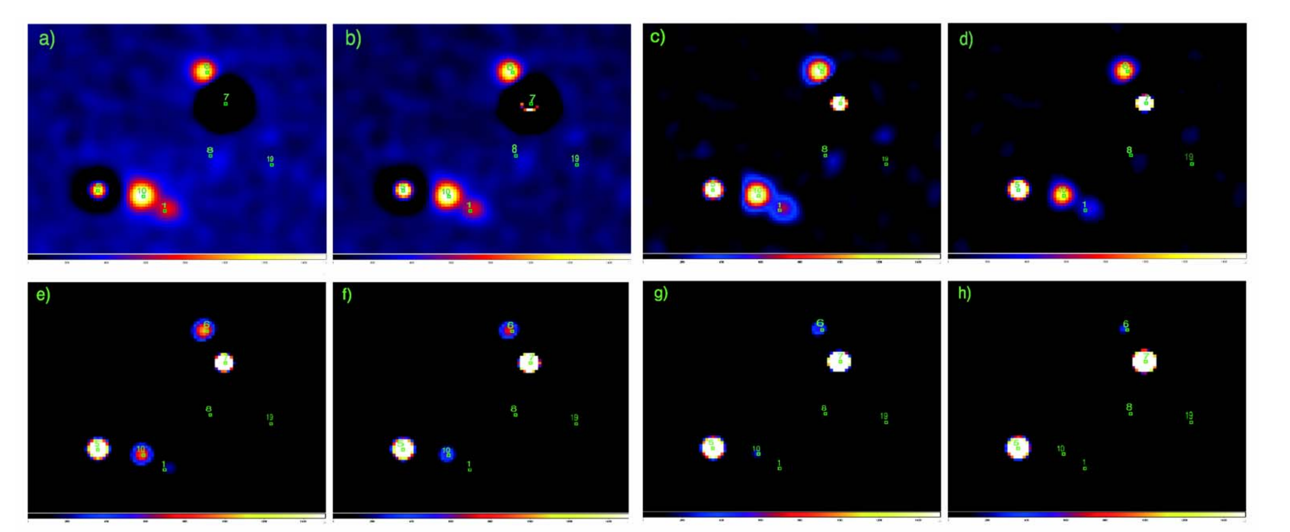
The 2D WT method was tested and applied also to real data available from the EGRET mission. The test was done using standard counts-maps of the first 4 combined observation cycles, selecting 4 typical pointed regions (Vela, Cygnus, 3C 279 and Anti Center). The fitting and subtraction procedures are more difficult because of the bin size in the maps (0.5deg), the background, and low statistics in EGRET data. Almost half of detected sources match with the 3EG catalog (identified and unidentified sources) while the rest are far from EGRET catalog sources.



2D wavelet application to the EGRET map of the Galactic anti-center region.
Top: sources detected through our algorithm (white boxes), 3EG sources (red circles), 3EG unidentified sources (green circles).
Bottom: map of k-significance for sources detected on the same region: zoom on the central part of the map (left) and on the galactic plane (right).

Detection of gamma-ray sources with 3D wavelets

The 2D WT can be extended adding the energy or time as third dimension, to obtain "cubes" holding, respectively, the spectral energy development or count/intensity temporal behavior of a sky region. The 3D WT algorithm, was applied as a first test in the DC2 LAT area around 3C 279, working with the energy (logarithmic binning), like third dimension. At lowest energy (below 100MeV) the background noise is very strong and prevents any significant detection. At higher energies the method identify easily the sources, and shed light on different energy spectra (some sources present at lower energies can disappear at higher energies, while other sources become brighter). Such method might also define the position of the detected sources with a finer precision, respect to the 2D version in some cases (as the PSF improves in spatial resolution at higher energies).



3D wavelet source detection in the field of 3C 279 (detail). Each image represents a map extracted in a defined energy band. Energy in the panels rises from 100MeV (panel a) to 200 GeV (panel h).

Summary

- 1D WT method can be useful to analyze and characterize variability of the gamma-ray sources, and it thus represents also an useful tool in the identification process of new detected sources.
- 2D WT algorithm allows a fast, efficient and blind source detection without any complex model or parameterization of sources. It can be useful for a first quick look of transients, flares and bright signals, and produced already a source catalogue from the full-LAT simulations.
- 2D WT provides a first and fast source location, that can be used as input for the subsequent likelihood analysis, devoted to a better physical description.
- 2D WT might be used also for extended structures, searching for over-threshold contribution at larger scales, and detecting real sources on the galactic plane, where working is definitely harder.
- The application to the poor resolution, and low photon count, images of EGRET reduced the detection potentiality of such 2D algorithm.
- 3D WT method is able to analyze cubes and showing variable behaviors on time or the source energy spectrum. In some cases it might provide a finer determination in the source position, with respect to the 2D version, because it handles different energy bands.