

# GeoPAT 2.0 user's manual

**Note:** This manual is work in progress

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# 1 Introduction

GeoPAT (Geospatial Pattern Analysis Toolbox) is a standalone suite of modules written in C and dedicated to analysis of large Earth Science datasets in their entirety using spatial and/or temporal patterns. Global scale, high resolution spatial datasets are available but are mostly used in small pieces for local studies. GeoPAT enables studying them in their entirety. GeoPATs core idea is to tessellate global spatial data into grid of square blocks of original cells (pixels). This transforms data from its original form (huge number of cells each having simple content) to a new form (much smaller number of supercells/blocks with complex content). Complex cell contains a pattern of original variable. GeoPAT provides means for succinct description of such patterns and for calculation of similarity between patterns. This enables spatial analysis such as clustering, segmentation, and search to be performed on the grid of complex cells (local patterns).

## 1.1 Basic concepts

- **Grid** is a topological structure applied to input data. Grid is a lattice of cells defined by its geographical position, spatial extent, number of cells, and cell size which defines grid resolution. Each cell in the grid contains a vector of values.
- **Pattern signatures** - compact numerical descriptors of patterns. We use histograms of patterns features as scene signatures.
- **Motifel** is an elementary unit of analysis - a square block of pixels representing local pattern. Motifel is represented by histogram of features (co-occurrence, decomposition). Distance between motifels is a distance between their histograms (for example using Jensen-Shannon Divergence).

## 2 GeoPAT 2.0 architecture

### 2.1 General description

The GeoPAT consists of twelve modules (Fig. 1). Five modules are designed for extracting pattern signatures from an original data grid, four modules for actual geoprocessing of the patterns and three utility modules.



Figure 1: Outline of the GeoPAT 2.0 architecture

The role of signature extraction modules (`gpat_gridhis`, `gpat_gridts`, `gpat_pointshis`, `gpat_pointststs`, `gpat_polygon`) is to calculate pattern signatures for scenes defined:

- **`gpat_gridhis`** - by a neighborhood of each cell in a grid (spatial pattern)
- **`gpat_gridts`** - by a neighborhood of each cell in a grid (spatiotemporal pattern)
- **`gpat_pointshis`** - in the neighborhoods of selected points (spatial pattern)
- **`gpat_pointststs`** - in the neighborhoods of selected points (spatiotemporal pattern)
- **`gpat_polygon`** - over irregular polygons

The role of geoprocessing modules (`gpat_search`, `gpat_compare`, `gpat_segment`, `gpat_distmtx`) is to perform:

- **`gpat_search`** - searching

- **gpat\_compare** - comparision
- **gpat\_segment** - segmentation (based on pattern data generated by the signature extraction modules)
- **gpat\_distmtx** - clustering

The role of utility modules (**gpat\_grd2txt**, **gpat\_globnorm**, **gpat\_segquality**) is to:

- **gpat\_grd2txt** - convert grid of signatures (grid-of-scenes) from a binary to text
- **gpat\_globnorm** - normalization of grid of signatures (grid-of-scenes) values
- **gpat\_segquality** - calculate the quality metrics (inhomogeneity and isolation) of a segmentation

## 2.2 GeoPAT Modules

### 2.2.1 Signature building

#### 2.2.1.1 gpat\_gridhis

Creates a binary grid of signatures from a categorical raster map(s).

Usage:

```
gpat_gridhis [-lh] -i <file_name> -o <file_name> [-s <signature_name>] [--level=<n>] [-z <n>]
              [-f <n>] [-n <normalization_name>] [-t <n>]

-i, --input=<file_name> name of input file (GeoTIFF)
-o, --output=<file_name> name of output file (GRID)
-s, --signature=<name> motifel's signature (use -l to list all signatures, default: 'cooc')
--level=<n> full decomposition level (default: 0, auto)
-z, --size=<n> motifel size in cells (default: 150)
-f, --shift=<n> shift of motifels (default: 100)
-n, --normalization=<name> signature normalization method (use -l to list all methods, default: 'pdf')
-l list all signatures and normalization methods
-t <n> number of threads (default: 1)
-h, --help print this help and exit
```

#### Options:

##### *input*

Defines a categorical raster layer(s) which will be used as a source for extracting pattern signature. Layers must be a categorical one. For the Cartesian product method ('prod') there can be more than one input map. Other methods use a one map only (the first one provided). In order to provide more than one input map, type multiple input options ("i map1.tif -i map2.tif" or "-input=map1.tif -input=map2.tif").

##### *output*

Output consists of two files: one of them is a dataset containing a grid of signatures in binary form, the other one is a header text file (the .hdr extension) containing a grid topology and an information about the input data parameters. Modifying the header is strongly discouraged as it may cause some calculations to fail. Structure of the header is as follows:

- dim – number of dimensions of each signature
- dims – size of each dimension
- type – type of data stored in the grid (integer, float, etc.)
- at0 – top left x
- at1 – w-e grid resolution
- at2 – rotation (0 if grid is north-up)
- at3 – top left y
- at4 – rotation (0 if grid is north-up)
- at5 – n-s grid resolution
- rows – number of rows in the grid
- cols – number of cols in the grid
- proj – projection in wkt style
- desc – command used to create the grid

#### *size*

Size of a motifel (local calculation window) expressed in the number of pixels. It defines the extent of a local pattern. It is the length of the side of square-shaped block of pixels (motifel). It must be at least 10 and cannot exceed the input map size.

#### *shift*

Parameter defines the shift between adjacent scenes along the grid in n-s and w-e directions. It describes the density of the output grid and defines a new topology of the grid. Formula  $\text{original\_resolution} \times \text{shift} = \text{new\_resolution}$  explains how resolution of the original map will be reduced. If shift is set to the same value as 'size', the input map will be simply divided into a grid of non-overlapping motifels. Setting shift to a value smaller than 'size' parameter will result in grid of overlapping motifels. Shift cannot be larger than 'size', and cannot be smaller than 5.

#### *signature*

Defines method of calculating signatures of motifels. GeoPAT offers the following methods:

- prod – Cartesian product of input category lists
- cooc – spatial cooccurrence of categories
- sdec – simple 2-level decomposition
- fdec – full decomposition
- lbp – histogram of local binary patterns
- lind – landscape indices vector
- linds – selected landscape indices vector

See Appendix B for the details.

#### *level*

This option is used only if 'full decomposition' (fdec) is used. It defines the highest level of decomposition. See Appendix B for the details.

#### *normalization*

Specifies normalization method used on the signatures. See Appendix C for the details.

#### *threads (-t)*

The module is parallel, therefore use more than one processing thread can be used in order to speed up calculations. This option specifies how many threads will be used. The default is 1.

### **Description:**

This module extracts a "grid-of-scenes" (grid of pattern signatures, grid of motifs). The output is a grid of the same spatial extent as the input raster map, but with a different cell size. Each cell in a new grid has only one attribute - the signature of its pattern. Pattern is calculated over a window centered on the cell and having a user-defined size. Resolution of the output grid equals to the resolution of the input raster map multiplied by the shift parameter. A signature of pattern for each scene is stored as a numerical vector in a binary form. The module outputs a header file (.hdr) containing a topology of a grid-of-scenes and a binary file containing signatures ordered by rows.

This module uses categorical raster data in GeoTIFF format as an input. It might be more than one map for the Cartesian product signature. Raster maps must be categorical and its size must be greater than the scene size specified by the user. Size defines the size of individual scene for which the histogram is calculated. Shift shows how scenes shift along the grid in n-s and w-e directions. Shift defines the resolution of the new grid. If window size is bigger than shift (recommended), motifs will overlap. If shift and size is equal, windows will not overlap. Shift cannot be greater than size.

The output grid may be an input to one of the following GeoPAT modules: *gpat\_search*, *gpat\_compare*, *gpat\_segment*, *gpat\_segquality*, *gpat\_grd2txt*, and *gpat\_globnorm*.



### 2.2.1.2 gpat\_gridts

Usage:

```
gpat_gridts [-nh] -i <file_name> [-i <file_name>]... -o <file_name> [-d <n>]

-i, --input=<file_name> name of input file(s) (GeoTIFF)
-o, --output=<file_name> name of output file (GRID)
-d, --dimension=<n> dimension of vector that describes time series element (default: 1)
-n, --normalize normalize each vector coordinate to [0.0, 1.0] (default: no)
-h, --help print this help and exit
```

*input*

*output*

*dimension*

*normalize*

**Description:**

### 2.2.1.3 gpat\_pointshis

Calculates numerical signatures of individual motifs within a raster map.

Usage:

```
gpat_pointshis [-lah] -i <file_name> -o <file_name> [-s <signature_name>] [--level=<n>] [-z <n>]
  [-n <normalization_name>] [-x <double>] [-y <double>] [-d <string>] [--xy_file=<file_name>]

-i, --input=<file_name> name of input file (GeoTIFF)
-o, --output=<file_name> name of output file (TXT)
-s, --signature=<name> motif's signature (use -l to list all signatures, default: 'cooc')
--level=<n> full decomposition level (default: 0, auto)
-z, --size=<n> motif size in cells (default: 150)
-n, --normalization=<name> signature normalization method (use -l to list all methods, default: 'pdf')
-l list all signatures and normalization methods
-x <double> x coord
-y <double> y coord
-d, --description=<string> description of the location
--xy_file=<file_name> name of file with coordinates (TXT)
-a, --append append results to output file
-h, --help print this help and exit
```

**Options:**

*input*

Defines categorical raster map(s) in the GeoTIFF format, which will be used as a source for extracting pattern signature. For the Cartesian product method ('prod') there can be more than one input map. Other methods use one map only (the first one provided). In order

to provide more than one input map, type multiple input options ("-i map1.tif -i map2.tif" or "-input=map1.tif -input=map2.tif").

#### *output*

Name of output text file containing signatures. In the output file, each line corresponds to a single motifel's signature. Each signature is preceded by its header. A header always consists of: coordinates of the midpoint of motifel (scene), name, number of dimensions, and length of each dimension. Modifying the signature file is strongly discouraged as it may cause some calculations to fail.

#### *signature*

Defines method for calculating signatures of motifels. GeoPAT offers the following methods:

- prod – Cartesian product of input category lists
- cooc – spatial cooccurrence of categories
- sdec – simple 2-level decomposition
- fdec – full decomposition
- lbp – histogram of local binary patterns
- lind – landscape indices vector
- linds – selected landscape indices vector

See Appendix B for details.

#### *level*

This option is used only when 'full decomposition' (fdec) is used. It defines the highest level of decomposition. See Appendix B for the details.

#### *size*

Size of a motifel (scene) for which signature is calculated. Scene is a square centered at the coordinate pair location, while its extent is defined by size.

#### *normalization*

Specifies normalization method used on the signatures. See Appendix C for the details.

#### *x*

X coordinate of the midpoint of motifel for which signature will be calculated.

#### *y*

Y coordinate of the midpoint of motifel for which signature will be calculated.

#### *description*

Description of a motifel. It can be a name of location, description of pattern, or anything else. If not provided, the default description is "location".

*xy\_file*

Name of a text file with list of coordinates. This option is useful for calculating signatures for multiple motifels in a single run.

*append* (flag)

Append mode. Useful when using the coordinate pair mode and when scenes are processed one by one (see description below). If the append flag is used and the output file already exists, signatures will be appended at the end of file instead of overwriting it.

### Description:

This module extracts signatures for a scene (motifel) or collection of scenes defined over square-shaped windows. User provides coordinates of the center of each scene and the size of the scene. The module outputs a list of scene-labeled signatures. As an input the module uses categorical raster map in the GeoTIFF format (or a few maps if user calculates the Cartesian product of multiple maps), coordinates of the center of each scene and size of scenes. The coordinates must be in the input map's coordinate system. There are two ways of defining the scenes:

Definition by coordinate pair: This is the simplest mode designed for a batch or interactive processing. In this mode, scene is defined by a pair of its midpoint's coordinates (the *x* and *y* options) and scene size parameter (the *size* option). Only one scene can be processed at once. The *xy\_file* option is not used in this mode. If used with the append flag (-a), signatures can be calculated one by one and added to the same output file. Additionally, the *description* option lets user name a scene. This name will be stored in the output file.

Definition by text file: In this mode, scene midpoint's coordinates are defined in a external text file in which each line contains X,Y coordinates and, optionally, name/description using the following syntax: x\_coordinate,y\_coordinate,scene\_name. The name of a file with coordinates is provided using the *xy\_file* option. Extent of a scene is defined by the *size* parameter. The *x*, *y* and *description* options are not used in this mode. Example of the content of coordinates file:

```
1260500, 1277638, water
1289493, 1251381, urban
1304934, 1285000, crops
1316205, 1253206, pasture
1277700, 1261936
```

If a description is not provided (like in the example above), the program will assign a default name ("location") with id representing the number of line in the coordinate file.

The output signature text file can be used as an input to the following modules: *gpat\_search*, *gpat\_distmtx*.

#### 2.2.1.4 gpat\_pointsts

Usage:

```
gpat_pointsts [-ah] -i <file_name> -o <file_name> [-x <double>] [-y <double>] [-d <string>]
               [--xy_file=<file_name>]

-i, --input=<file_name> name of input file (GRID)
-o, --output=<file_name> name of output file (TXT)
-x <double> x coord
-y <double> y coord
-d, --description=<string> description of the location
--xy_file=<file_name> name of file with coordinates (TXT)
-a, --append append results to output file
-h, --help print this help and exit
```

*input*

*output*

*x coord (-x)*

*y coord (-y)*

*description*

*xy\_file*

*append*

**Description:**

### 2.2.1.5 gpat\_polygon

Calculates numerical signatures of irregular regions.

Usage:

```
gpat_polygon [-lh] -i <file_name> -e <file_name> -o <file_name> [-s <signature_name>] [-n
               <normalization_name>] [-t <n>]

-i, --input=<file_name> name of input file (GeoTIFF)
-e, --segments=<file_name> name of input file (GeoTIFF, int)
-o, --output=<file_name> name of output file (TXT)
-s, --signature=<name> signature method (use -l to list all methods, default: 'cooc')
-n, --normalization=<name> signature normalization method (use -l to list all methods, default: 'pdf')
-l list all signatures and normalization methods
-t <n> number of threads (default: 1)
-h, --help print this help and exit
```

**Options:**

*input*

Categorical raster map(s) in the GeoTIFF format, which will be used as a source for extracting pattern signature. For the Cartesian product method ('prod') there can be more than one input map. Other methods only use one map (the first one provided). In order to provide more than one input map, type multiple input options ("-i map1.tif -i map2.tif" or "-input=map1.tif -input=map2.tif").

#### *segments*

Categorical raster map in the GeoTIFF format which defines spatial division of area of interest into polygonal regions. In this map, regions should be defined as areas of unique ids. Layer must be a raster and its projection, extents and resolution should be identical to the main input map. This layer may be a result of the segmentation module *gpats\_segment* or any other categorical map (e.g. map of ids of watersheds).

#### *output*

Name of output text file containing signatures. In the output file each line corresponds to a region's signature. Each signature is preceded by its header. A header always consists of: the coordinates of the midpoint of region, name, number of dimensions, and length of each dimension. Modifying the signature file is strongly discouraged as it may cause some calculations to fail.

#### *signature*

Defines method for calculating signatures of motifs. GeoPAT offers the following methods:

- prod – Cartesian product of input category lists
- cooc – spatial cooccurrence of categories
- sdec – simple 2-level decomposition
- fdec – full decomposition
- lbp – histogram of local binary patterns
- lind – landscape indices vector
- linds – selected landscape indices vector

See Appendix B for the details.

#### *normalization*

Specifies normalization method used on the signatures. See Appendix C for the details.

#### *threads (-t)*

The module is parallel, therefore use more than one processing thread can be used in order to speed up calculations. This option specifies how many threads will be used. The default is 1.

## Description:

Module extracts signatures for a collection of irregular regions using the same methods as in the *gpat\_pointshis* and *gpat\_gridhis* modules. As an input, apart from categorical raster map from which signatures are calculated, user provides a categorical raster map which defines spatial division of area of interest into polygonal regions. The module outputs a list of polygon labeled-signatures stored in the form of a text file.

The output signature text file can be used as an input to the following modules: *gpat\_search*, *gpat\_distrib*.

## 2.2.2 Similarity measuring

### 2.2.2.1 gpat\_search

Produces similarity maps which show similarity value between query motifs (scenes) and every motif in the input grid.

#### Usage:

```
gpat_search [-dlh] -i <file_name> [-o <file_name>] -r <file_name> [-m <measure_name>]
            [--type=Byte/....] [-p <file_name>] [-n <n>] [-t <n>]

-i, --input=<file_name> name of input file (GRID)
-o, --output=<file_name> name of output file (TIFF)
-r, --reference=<file_name> reference data to calculate similarity (TXT)
-d, --description use description of the reference histogram(s) as name of output file(s)
-m, --measure=<measure_name> similarity measure (use -l to list all measures; default 'jsd')
-l, --list_measures list all measures
--type=Byte/.... output data type (default: Float64)
-p, --palette=<file_name> name of the file with colors definition (CSV)
-n, --no_data=<n> output NO DATA value (default: none)
-t <n> number of threads (default: 1)
-h, --help print this help and exit
```

#### input

Binary file containing grid of signatures (grid-of-scenes). Grid is mandatory. User has to provide a name of grid file (without the .hdr extension). Header file is read automatically. Grid is an output from either *gpat\_gridhis* or *gpat\_gridts* module. Header of the grid will define topology of the output layers. Do not modify header file.

#### output

Raster (GeoTIFF) file or files containing the map of similarity. The number of outputs depends on the number of scenes/polygons in the input reference file.

#### reference

Text file containing one or more signatures of either individual motifs (scenes) or irregular polygons. This option is mandatory. Input text file can be created using the *gpat\_pointshis*, *gpat\_pointsts* or *gpat\_polygons* module. The number of outputs depends on the number of scenes in the input scene file. At least one scene is required.

*description*

*measure*

Defines method for calculating distance between motifs. GeoPAT offers the following measures:

- jsd – Jensen Shannon Divergence
- euc – Euclidean distance
- eucn – Normalized euclidean distance
- eucp – Normalized euclidean distance (periodic)
- wh – Wave-Hedges distance
- cos – Cosine distance
- jac – Jaccard distance
- roz – Rozicka distance
- rozp – Rozicka distance (extended)
- hass – Hassanat distance
- tsEUC – time series - euclidean distance
- tsEUCP – periodic time series - euclidean distance
- tsDTW – time series - Dynamic Time Warping distance
- tsDTWP – time series - Periodic Dynamic Time Warping distance
- tsDTWPa – time series - Synchronized Dynamic Time Warping distance

See Appendix D for the details.

*list\_measures*

Lists all the available measures.

*type*

Data type of the output raster (GeoTIFF) file. Types of Byte, UInt16, Int16, UInt32, Int32, Float32, Float64, CInt16, CInt32, CFloat32 and CFloat64 are supported.

*palette*

*no\_data*

Specify NO DATA value of the output raster (GeoTIFF) file.

*threads (-t)*

The module is parallel, therefore use more than one processing thread can be used in order to speed up calculations. This option specifies how many threads will be used. The default is 1.

### **Description:**

Searching task is dedicated to perform a query-by-pattern-similarity (QBPS). Searching procedure compares query/queries with the database in the scene-by-scene fashion and creates a layer(s) having the same topology as a grid-of-scenes but containing values of similarity between a query/queries and each scene in a grid-of-scenes. The results of QBPS can be visualized as a similarity map. Searching task is accomplished using `gpat_search` module. An input is a query scene (or a list of query scenes) is an output of `gpat_pointshis` or `gpat_polygon` modules and a grid-of-scenes (database to be queried) outputted by the `gpat_gridhis` module. Signature histogram of each query and signatures of histograms in a grid-of-scenes must be calculated using the same method (e.g. crossproduct must be used in both cases). The number of output map depends on the number of provided query scenes. Each output map gets its name from the name of query scene preceded by a prefix.

### **2.2.2.2 gpat\_compare**

Usage:

```
gpat_compare [-lh] -i <file_name> -i <file_name> -o <file_name> [--type=Byte/....] [-p
<file_name>] [-n <n>] [-m <measure_name>] [-t <n>]

-i, --input=<file_name> name of input files (GRID)
-o, --output=<file_name> name of output file with similarity (TIFF)
--type=Byte/.... output data type (default: Float64)
-p, --palette=<file_name> name of the file with colors definition (CSV)
-n, --no_data=<n> output NO DATA value (default: none)
-m, --measure=<measure_name> similarity measure (use -l to list all measures; default 'jsd')
-l, --list_measures list all measures
-t <n> number of threads (default: 1)
-h, --help print this help and exit
```

*input*

Two binary files containing grid of signatures (grid-of-scenes). User has to provide names of grid files (without the .hdr extension). Grid is an output from either `gpat_gridhis` or `gpat_gridts` module. Headers of the grids will define topology of the output layers. Do not modify header files.

*output*

Raster (GeoTIFF) file containing the map of similarity between two input grid of signatures.

*type*



Data type of the output raster (GeoTIFF) file. Types of Byte, UInt16, Int16, UInt32, Int32, Float32, Float64, CInt16, CInt32, CFloat32 and CFloat64 are supported.

*palette*

*no\_data*

Specify NO DATA value of the output raster (GeoTIFF) file.

*measure*

Defines method for calculating distance between motifs. GeoPAT offers the following measures:

- jsd – Jensen Shannon Divergence
- euc – Euclidean distance
- eucn – Normalized euclidean distance
- eucp – Normalized euclidean distance (periodic)
- wh – Wave-Hedges distance
- cos – Cosine distance
- jac – Jaccard distance
- roz – Rozicka distance
- rozp – Rozicka distance (extended)
- hass – Hassanat distance
- tsEUC – time series - euclidean distance
- tsEUCP – periodic time series - euclidean distance
- tsDTW – time series - Dynamic Time Warping distance
- tsDTWP – time series - Periodic Dynamic Time Warping distance
- tsDTWPa – time series - Synchronized Dynamic Time Warping distance

See Appendix D for the details.

*list\_measures*

Lists all the available measures.

*threads (-t)*

The module is parallel, therefore use more than one processing thread can be used in order to speed up calculations. This option specifies how many threads will be used. The default is 1.

### **Description:**

This module compares two grids-of-scenes (grid of histograms) in a scene-by-scene fashion. Both grids must be calculated using the same shift parameter and the same method. The output of `gpat_compare` is a raster having the same topology as the input grids. Each cell in the output file contains the value of similarity between corresponding pairs of scenes where one scene is coming from the first grid and the other scene is coming from the second grid. The module is useful for comparing data of the same area created at two different times. It is also useful for estimating the uncertainty of the results.

### **2.2.2.3 gpat\_segment**

Usage:

```
gpat_segment [-lcgaqh] -i <file_name> -o <file_name> [-v <file_name>] [--size=<n>] [-m
  <measure_name>] [--lthreshold=<double>] [--uthreshold=<double>] [--swap=<double>]
  [--minarea=<n>] [--maxhist=<n>] [-t <n>]

-i, --input=<file_name> name of input files (GRID)
-o, --output=<file_name> name of output file with segments (TIFF)
-v, --vector=<file_name> name of output vector file with segments (SHP)
--size=<n> output resolution modifier (default: 1)
-m, --measure=<name> similarity measure (use -l to list all measures; default: jsd)
-l, --list_measures list all measures
--lthreshold=<double> minimum distance threshold to build areas (default: 0.1)
--uthreshold=<double> maximum distance threshold to build areas (default: 0.3)
--swap=<double> improve segmentation by swapping unmatched areas. -1 to skip (default: 0.001)
--minarea=<n> minimum number of motifs in individual segment (default: 0)
--maxhist=<n> create similarity/distance matrix for maxhist histograms; leave 0 to use all (default:
  200)
-c, --complete use complete linkage (default is average)
-g, --no_growing skip growing phase
-a, --no_hierarchical skip hierarchical phase
-q, --quad quad mode (rook topology)
-t <n> number of threads (default: 1)
-h, --help print help and exit
```

#### *input*

Binary file containing grid of signatures (grid-of-scenes). Grid is mandatory. User has to provide a name of grid file (without the .hdr extension). Header file is read automatically. Grid is an output from either `gpat_gridhis` or `gpat_gridts` module. Header of the grid will define topology of the output layers. Do not modify header file.

#### *output*

Categorical raster map in the GeoTIFF format which defines spatial division of area of interest into polygonal regions (segments). In this map, regions (segments) are defined as

areas of unique ids.

*vector*

Vector (shapefile) map of segmentation. This data is automatically created by vectorization of the output file.

*size*

*measure*

Defines method for calculating distance between motifs. GeoPAT offers the following measures:

- jsd – Jensen Shannon Divergence
- euc – Euclidean distance
- eucn – Normalized euclidean distance
- eucp – Normalized euclidean distance (periodic)
- wh – Wave-Hedges distance
- cos – Cosine distance
- jac – Jaccard distance
- roz – Rozicka distance
- rozp – Rozicka distance (extended)
- hass – Hassanat distance
- tsEUC – time series - euclidean distance
- tsEUCP – periodic time series - euclidean distance
- tsDTW – time series - Dynamic Time Warping distance
- tsDTWP – time series - Periodic Dynamic Time Warping distance
- tsDTWPa – time series - Synchronized Dynamic Time Warping distance

See Appendix D for the details.

*list\_measures*

Lists all the available measures.

*lthreshold*

The purpose of *lthreshold* is to control (to some degree) sizes of the segments. It takes values between 0 and 1.

*uthreshold*

The purpose of *uthreshold* is to prevent the growth of inhomogeneous segments. It takes values between 0 and 1.

*swap*

Because the segment growing is a greedy process there is a chance that some motifs located at segments boundaries show more affinity to motifs across the boundary than to motifs in its own segment. The swap parameter is used to alleviate this problem. It adjusts the boundaries between the segments. For each border motif its linkage to the parent segment,  $D_{par}$ , as well as its linkage to the segment across the boundary,  $D_{neigh}$  is calculated. If the difference between  $D_{par}$  and  $D_{neigh}$  is positive (the linkage to the segment across the boundary is smaller than the linkage to parent segment) the motif is marked for possible reassignment (resulting in an adjustment to the boundary). The boundary between segments is adjusted only when the swap value is larger than the difference between  $D_{par}$  and  $D_{neigh}$ . 0 forces repetition till all unmatched segments will be swapped (note: this could distinctly increase the calculation time).

*minarea*

Minimum number of cells in an individual segment not subject to removal process. The removal process is turned off if the minarea value equals to 0.

*maxhist*

Calculating linkage between two segments could be computationally expensive if the segments contain large numbers of motifs. When the number of motifs in the segment exceeds the maxhist value, so-called leveraging is used to speed up the calculation. This means that only a maxhist number of motifs, randomly selected from the segment, are used to calculate the linkage. 0 switches off the leveraging.

*complete*

As the default, the average linkage (Unweighted Pair Group Method with Arithmetic Mean) is used for calculation of a dissimilarity between two segments. This option changes the measure of dissimilarity between two segments to the complete linkage.

*no\_growing*

Skips growing phase of the segmentation.

*no\_hierarchical*

Skips hierarchical phase of the segmentation.

*quad*

As the default, the 6-connected brick wall topology is used, where square motifs are laid in alternative layers with each layer shifted a half motif length with respect to the previous one like in masonry. This option sets quad mode, which means that the rectangular grid topology with 4-connectivity will be used.

*threads (-t)*

The module is parallel, therefore use more than one processing thread can be used in order to speed up calculations. This option specifies how many threads will be used. The default is 1.

#### **Description:**

This module segments a grid-of-scenes into regions of uniform patterns in the same fashion as traditional segmentation algorithms segment image (or other rasters) into segments of uniform color and texture. The difference is that `gpat_segment` segments a grid-of-scenes rather than an ordinary grid, and uses scene signature as attribute rather than color or image texture to decide how to delineate the segments. The module uses a variant of the region growing algorithm. The segmentation provided by the `gpat_segment` module is typically used as an intermediate step in regionalization of the dataset. The goal of regionalization is to generalize and thus simplify spatial representation of data so it is more meaningful and easier to analyze. Examples of regionalization include delineation of landscape types or delineation of physiographic units. Regionalization is achieved by clustering segments output by `gpat_segment` into a number of distinct pattern type classes. An output of the `gpat_distmtx` module could be used as a distance matrix for clustering in an external software.

#### **2.2.2.4 gpat\_distmtx**

Usage:

```
gpat_distmtx [-lsh] -i <file_name> -o <file_name> [-m <measure_name>]

-i, --input=<file_name> name of input file with signatures (TXT)
-o, --output=<file_name> name of output file (CSV) with similarity matrix
-m, --measure=<name> similarity measure (use -l to list all measures; default 'jsd')
-l, --list_measures list all measures
-s, --similarity_output is a similarity matrix
-h, --help print this help and exit
```

*input*

*output*

*measure*

Defines method for calculating distance between motifs. GeoPAT offers the following measures:

- jsd – Jensen Shannon Divergence
- euc – Euclidean distance
- eucn – Normalized euclidean distance
- eucp – Normalized euclidean distance (periodic)

- wh – Wave-Hedges distance
- cos – Cosine distance
- jac – Jaccard distance
- roz – Rozicka distance
- rozp – Rozicka distance (extended)
- hass – Hassanat distance
- tsEUC – time series - euclidean distance
- tsEUCP – periodic time series - euclidean distance
- tsDTW – time series - Dynamic Time Warping distance
- tsDTWP – time series - Periodic Dynamic Time Warping distance
- tsDTWPa – time series - Synchronized Dynamic Time Warping distance

See Appendix D for the details.

#### *list\_measures*

Lists all the available measures.

#### *similarity*

##### **Description:**

This module computes a distance matrix between a collection of scenes. It uses signatures output by `gpat_pointshis`, `gpat_pointsts`, or `gpat_polygon` and selected distance measure. The resultant distance matrix is usually used as an input for scene clustering, which could results in discovering structures in the data. Clustering itself is not implemented in GeoPAT 2.0; we recommend using clustering algorithms implemented in R. An example of `gpat_distmtx` usage would be the clustering of a collection of cities on the basis of the patterns of land cover classes within their boundaries.

## **2.2.3 Tools**

### **2.2.3.1 gpat\_grd2txt**

Usage:

```
gpat_grd2txt [-h] -i <file_name> -o <file_name>

-i, --input=<file_name> name of input file (GRID)
-o, --output=<file_name> name of output file (TXT)
-h, --help print this help and exit
```

#### *input*

Binary file containing grid of signatures (grid-of-scenes). Grid is mandatory. User has to provide a name of grid file (without the .hdr extension). Header file is read automatically. Grid is an output from either *gpat\_gridhis* or *gpat\_gridts* module. Header of the grid will define topology of the output layers. Do not modify header file.

*output*

**Description:**

### 2.2.3.2 gpat\_globnorm

Usage:

```
gpat_globnorm [-lh] -i <file_name> -o <file_name> [-m <method_name>] [-t <n>]

-i, --input=<file_name> name of input file (GRID)
-o, --output=<file_name> name of output file (GRID)
-m, --method=<method_name> normalization method (use -l to list all methods, default: '01')
-l, --list_methods list all methods
-t <n> number of threads (default: 1)
-h, --help print this help and exit
```

*input*

Binary file containing grid of signatures (grid-of-scenes). Grid is mandatory. User has to provide a name of grid file (without the .hdr extension). Header file is read automatically. Grid is an output from either *gpat\_gridhis* or *gpat\_gridts* module. Header of the grid will define topology of the output layers. Do not modify header file.

*output*

Normalized binary file containing grid of signatures (grid-of-scenes) and the header text file (the .hdr extension) containing a grid topology and an information about the input data parameters.

*method*

Specifies normalization method used on the signatures.

- 01 – normalize coordinates to [0,1]
- N01 – normalize coordinates to N(0,1)
- ind01 – normalize coordinates to [0,1] for 72 landscape indices

See Appendix C for the details.

*list\_methods*

Lists all the available normalization methods.

*threads (-t)*

The module is parallel, therefore use more than one processing thread can be used in order to speed up calculations. This option specifies how many threads will be used. The default is 1.

#### **Description:**

### **2.2.3.3 gpat\_segquality**

Usage:

```
gpat_segquality [-lcqwh] -i <file_name> -s <file name> [-g <file_name>] [-o <file_name>] [-m
<measure_name>] [--maxhist=<n>] [-t <n>]

-i, --input=<file_name> name of input file (GRID)
-s, --segments=<file name> name of input segmentation map (TIFF)
-g, --inhomogeneity=<file_name> name of output file with segment inhomogeneity (TIF
F)
-o, --isolation=<file_name> name of output file with segment isolation (TIFF)
-m, --measure=<name> similarity measure (use -l to list all measures; default: jsd)
-l, --list_measures list all measures
--maxhist=<n> create similarity/distance matrix for maxhist histograms; leave 0 to use all (default:
200)
-c, --complete use complete linkage (default is average)
-q, --quad quad mode (rook topology)
-w, --no_weight switch off edge-based weighting in isolation
-t <n> number of threads (default: 1)
-h, --help print help and exit
```

#### *input*

Binary file containing grid of signatures (grid-of-scenes). Grid is mandatory. User has to provide a name of grid file (without the .hdr extension). Header file is read automatically. Grid is an output from either *gpat\_gridhis* or *gpat\_gridts* module. Header of the grid will define topology of the output layers. Do not modify header file.

#### *segments*

Categorical raster map in the GeoTIFF format which defines spatial division of area of interest into polygonal regions. In this map, regions should be defined as areas of unique ids. Layer must be a raster and its projection, extents and resolution should be identical to the main input map. This layer may be a result of the segmentation module *gpat segment* or any other categorical map (e.g. map of ids of watersheds).

#### *inhomogeneity*

The name of a raster (GeoTIFF) file containing the values of segment's inhomogeneity. Inhomogeneity is a property of a single segment; it measures the degree of mutual dissimilarity between all motifs within the segment. Inhomogeneity has a range between 0 and 1, smaller values are better.

#### *isolation*



The name of a raster (GeoTIFF) file containing the values of segment's isolation. It is calculated as the average dissimilarity between the focus segment and all of its immediate neighbors. It measures how much the segments stand out from its surroundings. Isolation has a range between 0 and 1, larger values are better

#### *measure*

Defines method for calculating distance between motifs. GeoPAT offers the following measures:

- jsd – Jensen Shannon Divergence
- euc – Euclidean distance
- eucn – Normalized euclidean distance
- eucp – Normalized euclidean distance (periodic)
- wh – Wave-Hedges distance
- cos – Cosine distance
- jac – Jaccard distance
- roz – Rozicka distance
- rozp – Rozicka distance (extended)
- hass – Hassanat distance
- tsEUC – time series - euclidean distance
- tsEUCP – periodic time series - euclidean distance
- tsDTW – time series - Dynamic Time Warping distance
- tsDTWP – time series - Periodic Dynamic Time Warping distance
- tsDTWPa – time series - Synchronized Dynamic Time Warping distance

See Appendix D for the details.

#### *list\_measures*

Lists all the available measures.

#### *maxhist*

Calculating linkage between two segments could be computationally expensive if the segments contain large numbers of motifs. When the number of motifs in the segment exceeds the maxhist value, so-called leveraging is used to speed up the calculation. This means that only maxhist motifs, randomly selected from the segment, are used to calculate the linkage.

*complete*

As the default, the average linkage (Unweighted Pair Group Method with Arithmetic Mean) is used for calculation of a dissimilarity between two segments. This option changes the measure of dissimilarity between two segments to the complete linkage.

*quad*

As the default, the 6-connected brick wall topology is used, where square motifs are laid in alternative layers with each layer shifted a half motif length with respect to the previous one like in masonry. This option sets quad mode, which means that the rectangular grid topology with 4-connectivity will be used.

*no\_weight*

*threads (-t)*

The module is parallel, therefore use more than one processing thread can be used in order to speed up calculations. This option specifies how many threads will be used. The default is 1.

**Description:**

This module computes inhomogeneity and isolation of grid of signatures (grid-of-scenes for each segment (region)). It uses signatures output by `gpat_gridhis` and selected distance measure. The resultant raster files could be also used to calculate the quality of a segmentation or regionalization. Quality is equal to  $1 - (\text{inhomogeneity/isolation})$ . It has a range between 0 and 1 and larger numbers are better.

### 3 Basic workflow paths with examples

In this section, the basic GeoPAT procedures are presented. These are:

- **Search** - search for areas similar to a query
- **Change detection** - comparison of local patterns between two maps
- **Segmentation** - division of a map into regions of cohesive patterns
- **Clustering** - grouping patterns that are similar to each other

The procedures are explained using the workflow schemes and examples. All of the examples how to process categorical data are shown on a  $42 \times 69$  km ( $1400 \times 2300$  px) part of the National Land Cover Dataset (NLCD) covering area around the city of Augusta, GA (Figure 2). This area is characterized by high diversity of land cover categories and patterns. Thus it is perfect for various pattern analyzes.

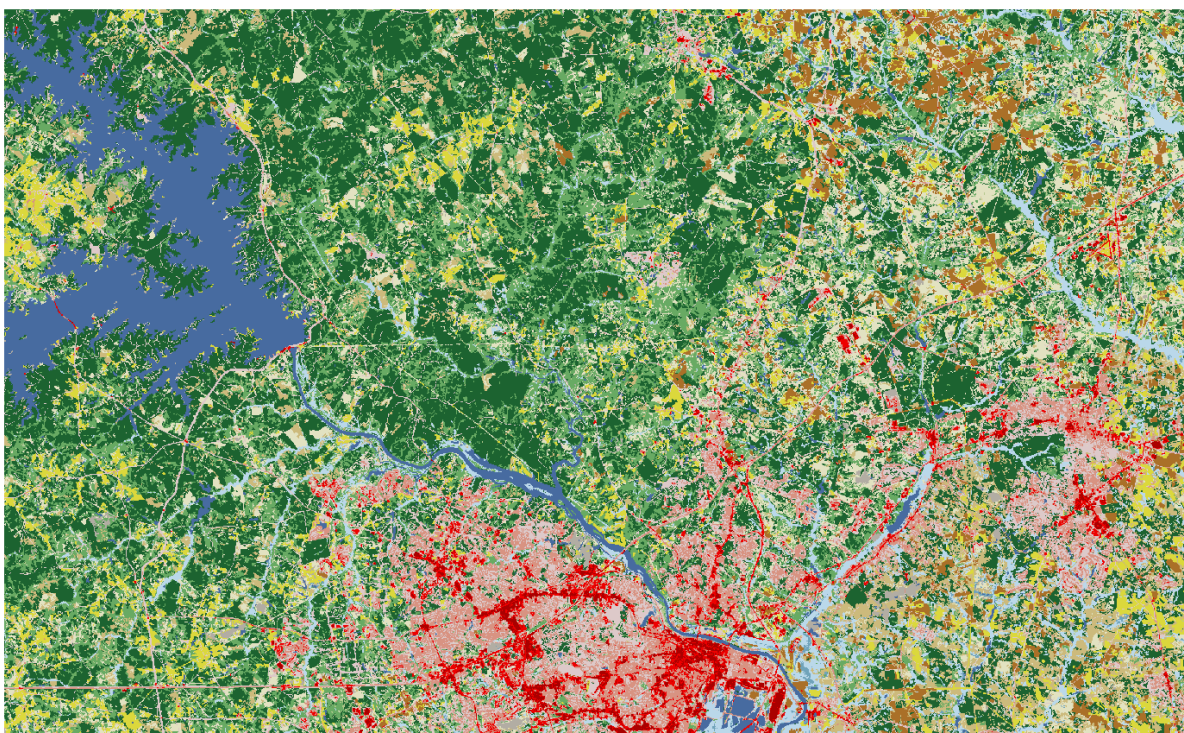


Figure 2: Part of NLCD, covering area around Augusta, GA used in the examples

#### 3.1 Search

Search functionality enables user to produce maps of similarity. These maps show the level of similarity between a specified motif (query) and a grid of motifs. The input is one or more GeoTIFF raster maps (depending on a data and signature type; see appendix B for

more information), and XY coordinates of one or more points in space. The result is one or more GeoTIFF raster maps which have the same extent as the grid of motifs specified by user. The number of resulting maps is the same as the number of points provided. The workflows for categorical and time series maps differ.

### 3.1.1 Search on categorical maps

Figure 3 presents general workflow path for producing similarity maps using a categorical raster data.

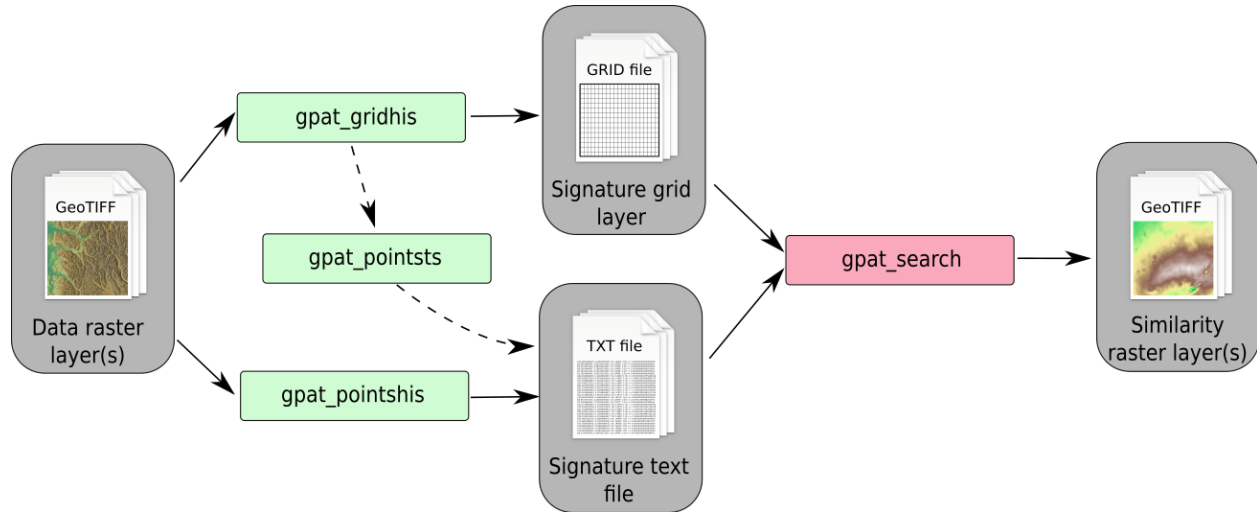


Figure 3: Workflow path for search on categorical maps

The first step is to prepare signature files for both, query motifs and grid of motifs, using two separate modules, *gpat\_pointshis* and *gpat\_gridhis* respectively. The second step is to use these signature files as inputs to *gpat\_search* module in order to produce similarity maps.

#### Example:

```

gpat_gridhis -i Augusta2011.tif -o grid -s cooc -z 50 -f 50 -n pdf
gpat_pointshis -i Augusta2011.tif -o query_signatures.txt -s cooc -z 50 -n pdf
--xy_file=coordinates.txt
gpat_search -i grid -r query_signatures.txt
  
```

do not have to have the same size (but is recommended)

### 3.1.2 Search on time series

TODO

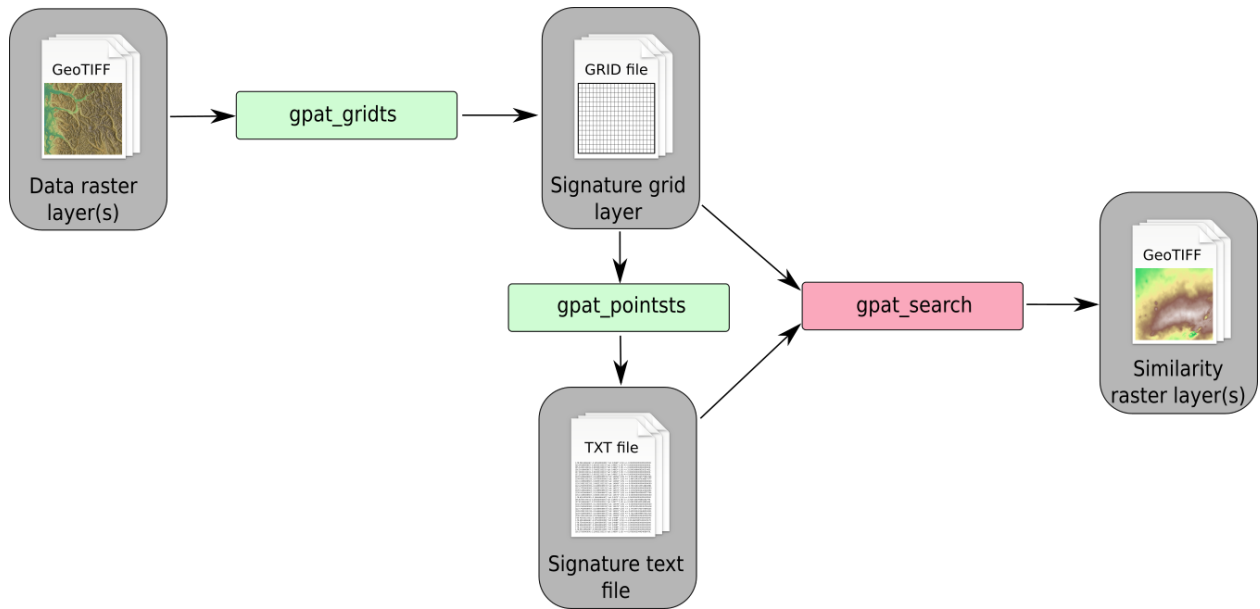


Figure 4: Workflow path for search on time series.

```
gpat_pointsts -i grid -o query-signatures.txt --xy_file=coordinates.txt
```

## 3.2 Change detection

TODO

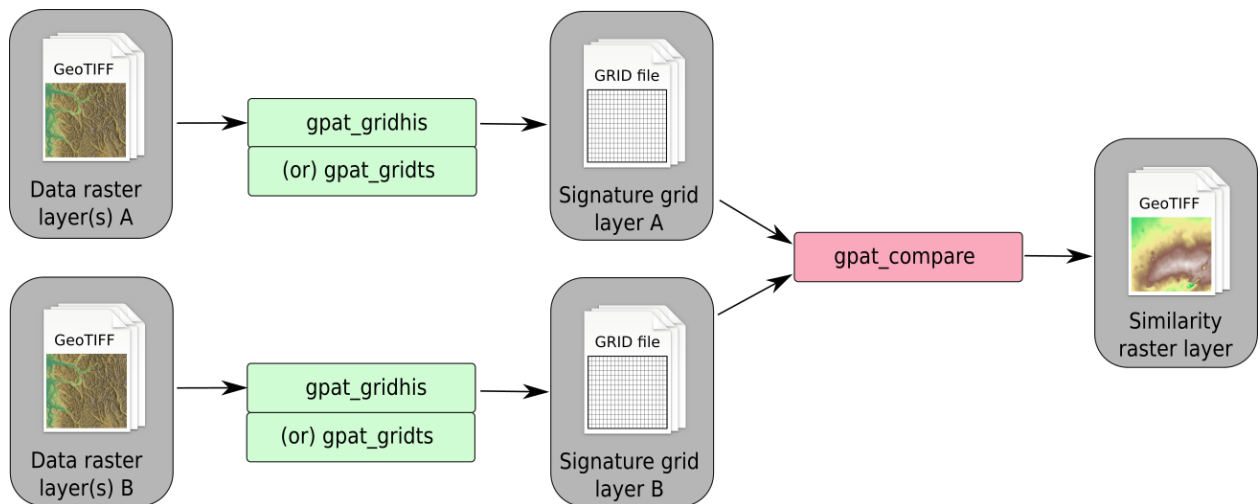


Figure 5: Workflow path for change detection.

## 3.3 Segmentation

TODO

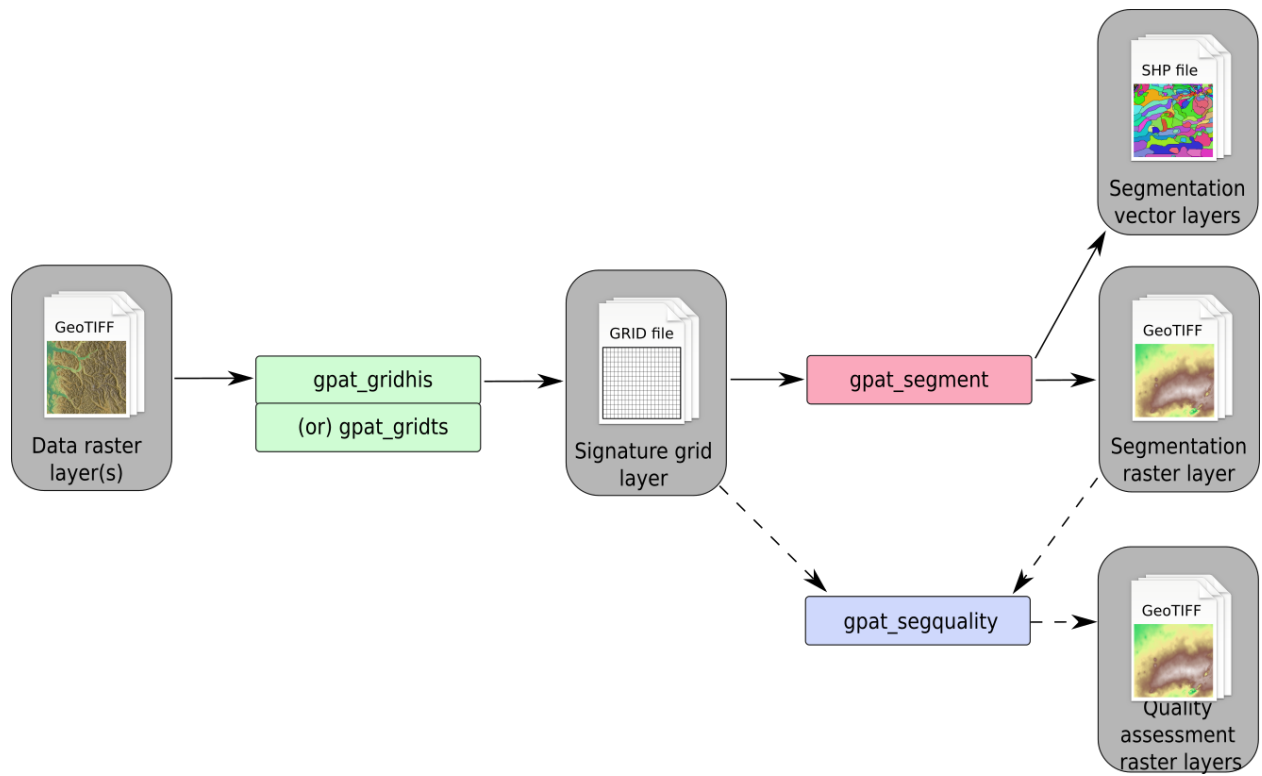


Figure 6: Workflow path for segmentation.

### 3.4 Clustering

TODO

### 3.4.1 Clustering of individual motifels

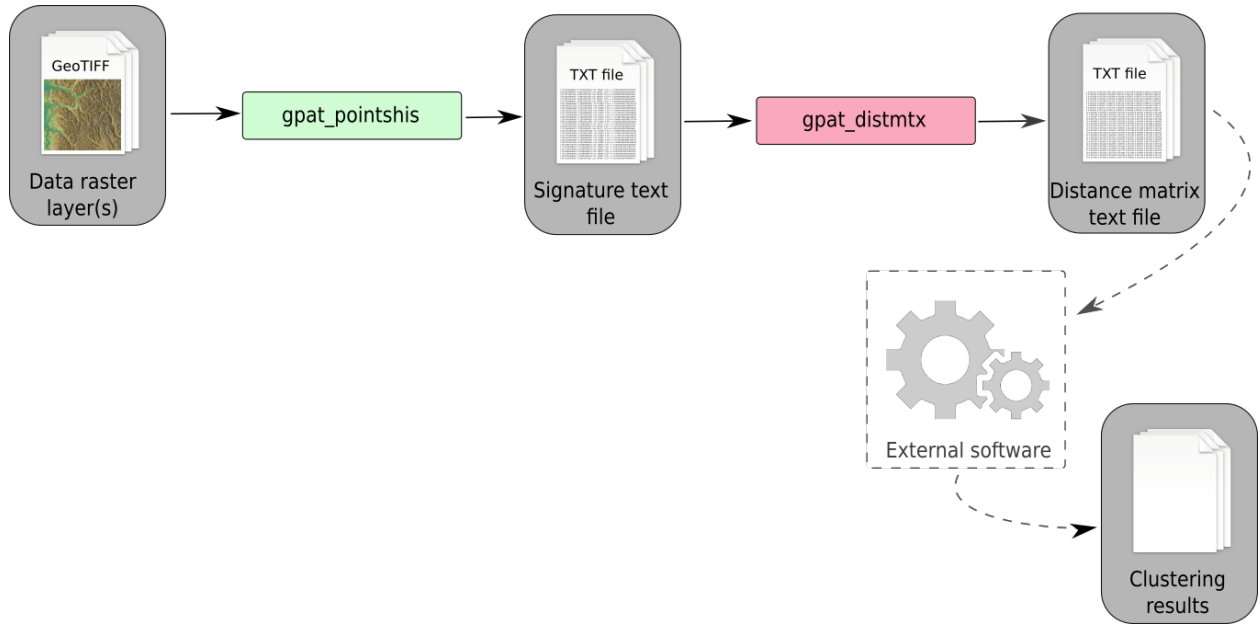


Figure 7: Workflow path for clustering of motifels.

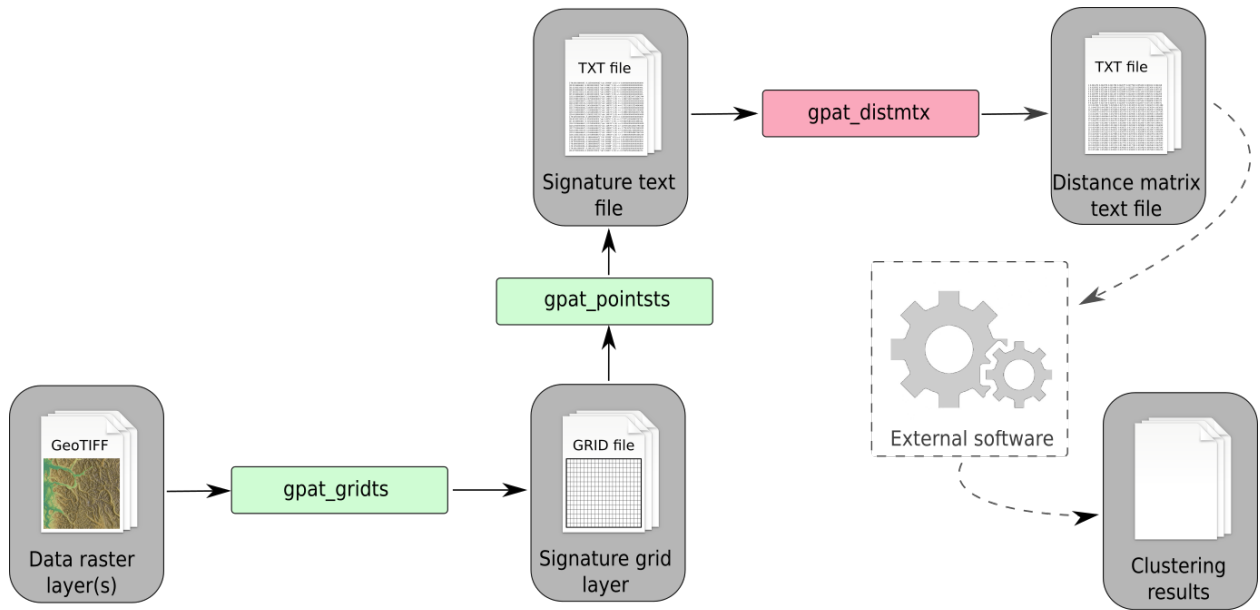


Figure 8: Workflow path for clustering of time series motifels.

### 3.4.2 Clustering of grid of motifs

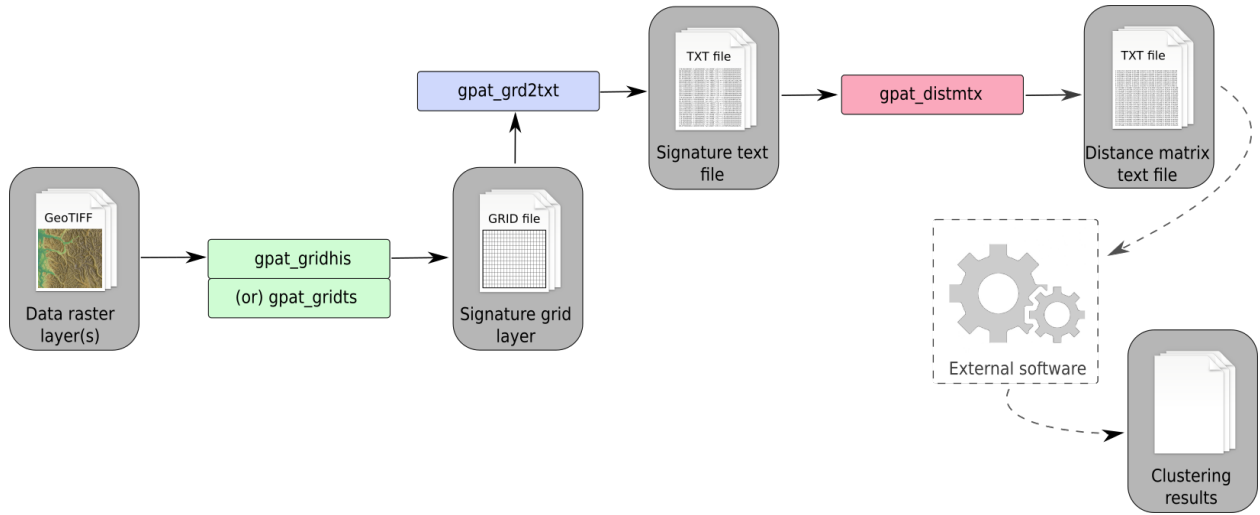


Figure 9: Workflow path for clustering of grid of motifs.

### 3.4.3 Clustering of segments/predefined irregular regions

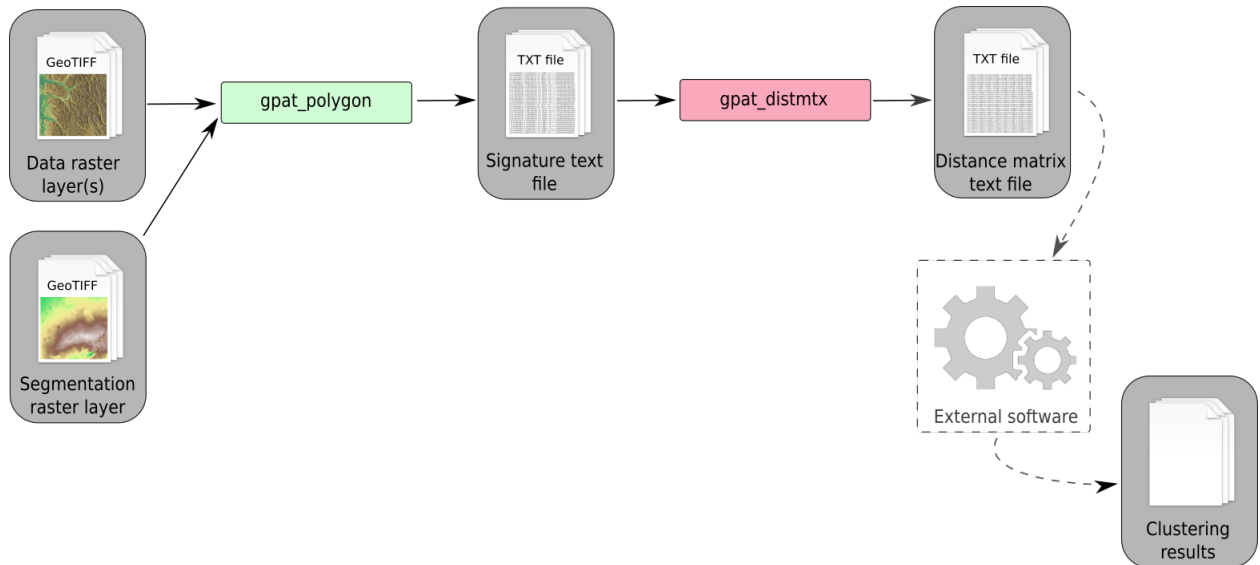


Figure 10: Workflow path for clustering of segments (regions).



# Appendices

## A GeoPAT 2.0 installation

### A.1 System requirements

The Windows installer and Linux binaries provides all necessary components. To build GeoPAT 2.0 from the source code, the user needs to install the GDAL library and compile and install the ezGDAL and SML libraries.

### A.2 Windows installer

The Windows installer works under 64 bit versions of Windows 7, 8.1, and 10. The installer provides four components:

- GDAL library package
- ezGDAL and SML libraries
- GeoPAT 2.0 software
- Microsoft Visual C 13 runtime libraries (optional)

To start the installation process user has to run GPAT20setup.exe. The setup program should be run in "Run as administrator" mode. If an antivirus software is running on the computer, user should turn it off temporary for the time of GeoPAT installation. The installer will create the directory for GDAL and GeoPAT and copy all necessary files. Optionally, GPAT20setup.exe will start the Microsoft Visual C runtime libraries installer. When installation is completed, the user can find "SIL GeoPAT 2.0" in the Windows start menu with two files - "GeoPAT console" and "Uninstall GeoPAT".

The installer for Windows x64 is available at:

```
http://sil.uc.edu/cms/data/uploads/software_data/GPAT20setup.exe
```

### A.3 Fedora 25 binary installation

To install the binary version of GeoPAT 2.0, user has to copy contents of the gpat20 directory from gpat20.tar.gz file to the /usr/local directory. The GeoPAT 2.0 binaries require the GDAL package to be installed on the computer. The user can install this package using dnf package manager on a Fedora system.

```
dnf install gdal
```

The additional requirement is a proper configuration of the libraries paths. The Fedora system should look for libraries in /usr/local/lib. Therefore, it could be necessary to create the local.conf file containing the following text: "/usr/local/lib". The new file has to be placed in the /etc/ld.so.conf.d directory.

The Fedora 25 x64 binaries are available at:

```
http://sil.uc.edu/cms/data/uploads/software_data/gpat20.tar.gz
```

## A.4 Building from source code

The building from source code procedure is presented using the Fedora 25 Linux distribution. This procedure could differ between Linux distributions, therefore the user should modify it to their system.

To build GeoPAT 2.0 from the source, the user has to do the four following steps:

1. Install the development version of GDAL
2. Build and install the ezGDAL library
3. Build and install the SML library
4. Build and install the GeoPAT 2.0 software

The dnf package manager can be used in a Fedora system to install the development version of GDAL:

```
dnf install gdal-devel
```

To install the ezGDAL library the user has to download the ezGDAL source code and unpack it. The source code of ezGDAL is available at:

```
http://pawel.netzel.pl/data/uploads/software/libezgdal.src.tar.gz
```

Next, the user has to compile the code by calling the following command in an unpacked source code directory:

```
make
```

And install it using:

```
make install
```

By default, the library is placed in the /usr/local/lib directory and the include file is placed in /usr/local/include. The user can change the destination directory by adding the PREFIX parameter.

```
make PREFIX=/my/destination/directory
```

When PREFIX is provided, the library is placed in /my/destination/directory/lib and the include file is placed in /my/destination/directory/include.

The installation procedure of the SML library is similar. The source code of SML is available at:

```
http://pawel.netzel.pl/data/uploads/software/libsmml.src.tar.gz
```

After an extraction of the source code of SML, the user should call:

```
make  
make install
```

The command "make install" should be called using the sudo command or in the root user context. After finishing libraries installation procedure the user has to ensure that PREFIX/lib is on the library search path.

The last step of the installation procedure is a compilation of the GeoPAT 2.0 source code. The source code of GeoPAT 2.0 is available at:

```
http://sil.uc.edu/cms/data/uploads/software\_data/gpat2.0src.tar.gz
```

GeoPAT 2.0 depends on the GDAL, SML, and ezGDAL libraries. Therefore, after the installation of the above libraries, the user has to unpack, compile and install the GeoPAT 2.0. The installation procedure is similar to the installation procedures of the ezGDAL and SML libraries.

```
make  
make install
```

The "make" and "make install" commands should be run in the main GeoPAT 2.0 source code directory. PREFIX parameter works in the same way.

## B Numerical signatures available in GeoPAT

A signature is a numerical description of a motif

### B.1 Cartesian product

This method calculates signature as a  $k$ -dimensional histogram using  $k$  primitive features assigned to each cell. Examples of such features include cell class, the size of the clump to which the cell belongs, the shape of the clump and its spatial orientation. Because all features must be categorical (so the histogram can be formed), numerical features need to be categorized. For example, clump sizes need to be categorized into size categories from the smallest to the largest. The number of bins in the crossproduct histogram is  $N_1 \times N_2 \times \dots \times N_k$ , where  $N_i$  is the number of categories of  $i$ -th feature. Crossproduct signature is designed to be effective in encapsulating spatial structures with clear geometric quality (having relatively low complexity); an example of a dataset with such a structure is the land cover raster.

### B.2 Class co-occurrence histogram

This method uses a color co-occurrence histogram, a variant of the Gray-Level Co-occurrence Matrix (GLCM) originally introduced by to characterize texture in grayscale images. In GeoPAT, color is replaced by cell class and a single cell separation of one pixel is used to calculate a co-occurrence histogram. This results in a single primitive feature - a pair of classes assigned to two neighboring cells; eight-connectivity is assumed for establishing the existence of a neighborhood relationship between the two cells. Thus, eight features are calculated for each cell, but their total number is halved as the same feature is generated twice by the pairs of neighboring cells. For a scene with  $k$  cell classes, the co-occurrence histogram has  $(k^2 + k)/2$  bins,  $k$  of them correspond to same-class pairs, which measure the composition of the classes in the scene, and  $(k^2 - k)/2$  bins correspond to different-class pairs, which measure the configuration of the classes in the scene. The co-occurrence signature is designed to be effective in encapsulating spatial structures exhibiting high complexity patterns like the ones resulting from a geomorphons-based classification of a DEM.

### B.3 Decomposition histogram

This signature method is used to describe a scene using a set of sub-scenes having a hierarchy of sizes. For the decomposition method to work best the scene should be a square having a linear size of  $2^D$  cells. The scene with  $k$  cell classes is scanned without overlap by a series of square moving windows with sizes  $w = 2^i$  cells where  $i = 2, \dots, D$  are the decomposition levels. The size of the maximum scanning window,  $2^D$ , is the size of the scene. At the smallest decomposition level  $i = 2$  a scene is scanned by a window having a size of  $4 \times 4 = 16$  cells. At each scanning position the percentages,  $p_1, \dots, p_k$ , of the window's area occupied by cells having classes  $1, \dots, k$ , respectively are recorded and a window area is assigned a list of  $k$  tags (one for each class) representing those percentages. These tags are classified into one of three categories, 1 if the percentage is below  $\frac{1}{4}$ , 2 if it is between  $\frac{1}{4}$  and  $\frac{1}{2}$ , and 3 if it is above  $\frac{1}{2}$ . Tallying all tags results in a histogram with  $3 \times k$  bins (three bins for each

class). The decomposition signature is designed to be effective for patterns of all levels of complexity, however, we have not yet accumulated sufficient experience working with this signature to offer definitive advice on the types of datasets to which it can be best applied.

## **B.4 Local binary pattern histogram**

## **B.5 Landscape indices vector**

# **C Normalization methods available in GeoPAT**

## **C.1 01**

Normalize to  $[0,1]$

## **C.2 pdf**

Normalize to pdf

## **C.3 N01**

Normalize to  $N(0,1)$

## **C.4 ind01**

Normalize to  $[0,1]$  for 72 landscape indices

## D Dissimilarity measures available in GeoPAT

Distance, which assesses the degree of dissimilarity between two scenes, is the opposite of similarity. When the value of distance function is equal to zero identical histograms are indicated, and thus scenes have identical or very similar patterns, whereas large values of the distance function indicate very different histograms and scenes having significantly different patterns. Note that all histogram distance measures are heuristic and no single measure will work well with all signatures.

### D.1 Jensen Shannon Divergence

This measure expresses the informational distance between two histograms  $P$  and  $Q$  by calculating a deviation between the Shannon entropy of the mixture of the two histograms  $(P + Q)/2$  (the second term in eq.(1) below) and the mean of their individual entropies (the first term in eq.(1)). The value of the Jensen-Shannon divergence is given by the following formula,

$$d_{JSD} = \sqrt{\sum_{i=1}^d \left[ \frac{P_i \log_2 P_i + Q_i \log_2 Q_i}{2} - \left( \frac{P_i + Q_i}{2} \right) \log_2 \left( \frac{P_i + Q_i}{2} \right) \right]} \quad (1)$$

where  $d$  is the number of bins (the same for both histograms) and  $P_i$  and  $Q_i$  are the values of  $i$ th bin in the two histograms. We have found Jensen-Shannon divergence works well (yields dissimilarity values in agreement with human visual perception) for comparison of land cover patterns as encapsulated by crossproduct signatures.

### D.2 Euclidean distance

### D.3 Normalized euclidean distance

### D.4 Normalized euclidean distance (periodic)

### D.5 Wave-Hedges distance

This measure is designed to work with co-occurrence signature histograms that tend to be dominated by bins corresponding to adjacent cells having the same class. The value of the Wave Hedges distance is given by the following formula,

$$d_{WH} = \sum_{i=0}^d e_i \frac{|P_i - Q_i|}{\max(P_i, Q_i)} \quad (2)$$

where  $d$  is the maximum number of possible bins and  $e_i = 1$  if  $\max(P_i, Q_i) > 0$  or  $e_i = 0$  otherwise. In other words, only pattern features present in at least one of the two scenes contribute to the value of the distance. In Wave Hedges distance formula all present features contribute to the overall value of distance with the same weights regardless of feature abundance in the scenes. In the case of the co-occurrence histogram this means that composition-related features and configuration-related features contribute equally to the distance value despite the heavy dominance of composition-related features in histograms stemming from all

realistic scenes. This makes the Wave Hedges distance particularly suitable for comparison of terrain scenes as encapsulated by co-occurrence signatures.

## **D.6 Cosine distance**

## **D.7 Jaccard distance**

This measure is an extension of the Jaccard similarity coefficient , originally developed to assess a similarity between two sets, but used here for assessing the dissimilarity between two histograms. The value of the Jaccard distance is given by the following formula,

$$d_J = 1 - \frac{\sum_{i=1}^d P_i Q_i}{\sum_{i=1}^d P_i^2 + \sum_{i=1}^d Q_i^2 - \sum_{i=1}^d P_i Q_i} \quad (3)$$

We have found that the Jaccard distance works well for comparison of land cover patterns as encapsulated by decomposition signatures.

## **D.8 Rozicka distance**

## **D.9 Rozicka distance (extended)**

## **D.10 Euclidean distance - time series**

## **D.11 Dynamic Time Warping distance - time series**

## **D.12 Periodic Dynamic Time Warping distance - time series**

## **D.13 Synchronized Dynamic Time Warping distance - time series**