

Development of an Open Source toolbox for the analysis and visualization of remotely sensed time series

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Abstract

The GEONETCast data dissemination system delivers free multi-source raw satellite images and processed products to users worldwide. This data can be used to construct long time series that can be used to study dynamic phenomena. To explore these dynamics, using an animation with few controls is common practice. But animations easily lead to change blindness due to information overload, a problem that can be addressed in various ways. We present a combination of analytical and visual functionalities to better support visual exploration of animated time series. The aim is to reduce the problem of change blindness. Analytical pre-processing functions include slicing and tracking of objects of interest. Results of the slicing and the tracking are input to the visualization environment, which is further enriched by tools to make various time, attribute and area selections; options to visually enhance selections relative to the surroundings, visualization of the path of moving objects, and of multiple layers. The resulting toolbox is fully dedicated to visual exploration and analysis of dynamic phenomena. A case study demonstrates its use. Some of the visualization functions are tested with users, and test results already led to some improvements. Factors influencing the performance of the toolbox are described, and directions of future research.

Keywords: multi-source time series, geovisual analytics, tracking, animated visualization, change blindness, ILWIS.

1. Introduction

Using satellite sensors is often the only way to quickly obtain data with a large spatial coverage and a high temporal frequency. Currently, several satellite image providers have distribution networks that offer images at low cost or even for free. For example, images originating from a number of satellites, both geostationary and polar orbiting, are distributed to end users through the GEONETCast data dissemination system. These images are freely available for educational and research purposes (<http://www.earthobservations.org/geonetcast.shtml>).

The GEONETCast images are suitable for a wide variety of applications such as meteorology, climate monitoring, estimation of land and sea surface temperature, crop monitoring, calculation of various vegetation indices, fire detection and many more. In a typical set up, the user of the GEONETCast data dissemination system can receive up to 10 GB of satellite

images per day, resulting in long time series that users can explore to study dynamic phenomena.

The purpose of such an exploration is to find patterns, trends and relationships in order to detect, monitor and predict the behaviour of the phenomena under investigation at different spatio-temporal scales. Currently, satellite time series are mainly explored by animating image sequences, but functionalities are mostly confined to media player controls (play for-/backward, pause, stop, etc.). This is very limited functionality for time series, e.g.: subsets (in time, space, attribute values) cannot be extracted easily, and comparisons with a related data set or in time are difficult to make. Another problem is that although animated satellite images mimic real world dynamics, users are easily overwhelmed by rapid sequences of changing pixel values (Monmonier 1992; Harrower 2002) and relevant ones may pass unnoticed: a phenomenon generally known as 'change blindness' (Rensink, O'Regan, and Clark 1997; Simons and Chabris 1999)

A main reason is that the encoding and comparison process needed to detect change is not successful due to the limited capacity and short duration of working memory, where information is processed (Kosslyn and Osherson 1995). For example, part of the motion signals (local and temporal variation in appearance created by changes in a visual scene that have no meaning yet) are not encoded because there are too many, causing a 'cognitive traffic jam' (Harrower 2007) for working memory. On the other hand, changes may also be too slow, below the threshold for perception, and signals can be missed due to saccades made in the search for patterns or to legends (Rensink, O'Regan, and Clark 1997). Attention might also be fully engaged in detecting changes that are related to a specific task and other, even big changes go unnoticed: a phenomenon called inattention blindness (Mack and Rock 1998). To consciously perceive changing objects, focussed attention is needed to interpret motion signals and perceive objects that have some constancy over time (Simons and Ambinder 2005). But attention is limited, it can only concentrate on a few moving objects at any time, and it can be distracted (e.g. by too many motion signals or a different task, as explained; Rensink 2002). In short, change blindness is influenced by a mixture of bottom-up and top-down processes. Bottom-up processes are driven by visual information entering the brains, and top-down processes originate in the brains, and are attention or task driven (Ware 2008).

Given the problems sketched above, visual exploration of animated times series is a rather subjective and difficult process. Users who are interested in the evolution of phenomena have to identify relevant features and concentrate to visually sieve and track the often highly dynamic features to discover their behaviour. To this end, they need to employ a cognitive management mechanism to selectively process information that is relevant for the task at hand (Geerinck and others 2009).

There is, therefore, a need to better support visual exploration of animated time series. Our aim is to influence top-down and bottom-up encoding mechanisms in visual perception, i.e.: to facilitate focusing of attention and selective perceptual processing of information that is relevant for the task at hand through effective graphical representations (Geerinck and others 2009). This paper approaches the problem by providing analytical support to the visual exploration process and additional functionalities and improvements to the

visualization. More precisely, it presents a dedicated geovisual-analytics and open-source toolbox to support interactive exploration of satellite time series.

The rest of the paper is organized as follows: section 2 presents the main characteristics of the toolbox and its implementation as open-source software. Section 3 describes a case study, namely the tracking of precipitation in relation to vegetation dynamics in Ethiopia with details on the specific functionality required for this case. In section 4, we describe the evaluation of selected functions and some aspects related to the overall performance of the toolbox. Finally, section 5 summarizes our main findings and describes our future work to further expand and evaluate the toolbox.

2. The toolbox

2.1 Functionality

Ware (2008) states that bottom-up and top-down perception processes can be improved by implementation of appropriate visual aids. In accordance with this and with our aim to facilitate visual information processing, we focus on employing methods that support the perceptual transformation of sequences of changing pixel values (visual primitives) into a higher level structure or pattern: a 'figure' that stand out of the 'ground'. The figure/ground concept is developed by Gestalt psychologists. MacEachren (1995) provides an overview of the Gestalt 'laws' of perceptual grouping and their relevance for the representation of geodata.

Because users of time-series data are primarily interested in the evolution of phenomena, 'figure' perception can be improved in several ways. A common method to explore the evolution of features of interests in raster data is by applying classification methods and/or using spectral indices (i.e. combination of two or more spectral bands). If the analyst works with a classification or a spectral index, then a query and/or the slicing of the values is sufficient to identify and visually track features of interest along the time series.

'Figure' perception can also be supported by an analytical process that detects image features that have some constancy, and binds them into easily perceivable objects, that are represented as polygons in the animation. It helps users to focus attention and is a crucial first step in understanding how objects evolve (Samtaney and others 1994). A number of detection and tracking algorithms exist and application depends, amongst others, on the dynamic characteristics and size of the phenomenon under study, and the sampling frequency of observations. We have implemented a method that is suitable for tracking precipitation (see section 3.1).

To further support users to focus attention on particular changes, there are options to select an area of interest (by zooming), attribute values of interest (through attribute slicing) and moments or periods of time (through time selection). However, to visually explore highly dynamic phenomena, things happening around the selection may provide a useful context, and users may want to quickly switch between 'figure' (area and/or attribute values of interest) and 'ground' (the surrounding context). Therefore, we also support the display of area and attribute selections in a user-defined, subdued context.

Different cue-based techniques (like colour-based highlighting, depth of field highlighting, transparency and contouring) are considered for the implementation since they generally employ human perception to separate a 'figure' (the selection) from the 'ground' (the context; Kosara, Miksch, and Hauser 2002; Robinson 2006). Colour highlighting can be applied in our toolbox to a selected range of attribute values, a class, in the whole display area. Depth of field highlighting and contouring are not considered suitable because they either change or partly obscure the context. The transparency technique has been implemented, a selected area and/or attribute values of interest appear enhanced relative to the more transparent unselected context, which is simultaneously displayed, giving a subdued impression. It is a way to create brightness contrast, a strong salient property in a visual scene, important to direct attention (Cavanagh 1993). The technique can be efficiently implemented by a layering technique, and transparency level and colours can be managed according to a user's preferences.

The evolution of a dynamic phenomenon often needs to be compared with related data (e.g. vegetation and precipitation). The toolbox supports the use of multiple layers, for example to overlay an animation with tracked objects or sliced selections on a land use map, a DEM, or even another time series, of a related phenomenon.

Finally, to reduce the effect of change blindness due to rapid sequences of motion signals that hinder encoding and comparison of changes in working memory, control over the display speed of the animation should be added. Some other functions that are case-specific will be described in section 3, and section 5 will address future research in additional options to support visual exploration.

2.2 Implementation

Some of the functions mentioned in this paper (like animated display of selected moments or time intervals only; attribute slicing and options to highlight selected elements) were already available in a research prototype called aNimVis (Animated Image Visualization; Blok 2005). But considering the problems above, analytical and visualization functionality to handle long time series should preferably be embedded into existing image processing software, and aNimVis was not linked to any image processing software. In addition, new tools could be added, and existing ones improved. Developing a new toolbox as 'Open Source' enables quick detection of software problems and further development. Free availability is also important since the users will mainly be users of the GEONETCast data, and we want to preserve the original GEONETCast philosophy, which is to make the images and their added value products freely available for educational and research purposes.

ILWIS is free and open software and it already has a plug-in to access GEONETCast data (Maathuis, Mannaerts, and Retsios 2008). Our choice was therefore to extend this further and develop additional functionality for the analysis and animated visualization of time series. ILWIS is software developed over the past 20 years at the ITC. In 2007, the C++ source code of ILWIS was made available as 'Open Source', and maintenance responsibility was passed on to one of the communities of the open source software initiative 52°North (<http://52north.org/>).

Strong points of ILWIS are that it is a lean and fast software, relatively easy to learn for end users. Most of its functionality can be extended through a plug-in mechanism, but if demanding functions require changes to ILWIS itself, it is possible because users have access to all the source code. Additionally, ILWIS already provides analytical image processing functions. This includes basic functions like image visualization, default animation, re-projection/resampling, interpolation, filtering, clustering, overlay and (geo)statistics, but also advanced functions like atmospheric correction and energy balance calculations. Furthermore, it has a strong image mathematics component and a batch processing component with which defined processes can be applied to thousands of images.

3. Case study

3.1 Problem, area and data

Precipitation plays an important role in the water cycle, it is particularly relevant in highly sensitive systems such as semi-arid savannas, where precipitation drives vegetation dynamics. As example of a semi-arid region, we have selected the Ethiopian lowlands, located in sub-Saharan Africa, where 40% of the Ethiopian population lives. Most of the population depends on rainfed agriculture and pastoralism. In areas like these, where precipitation constitutes an important water source in an otherwise water-limited ecosystem, it drives agricultural land-use decisions. Since precipitation is rare, serious droughts occur frequently. For instance, in 2002 – 2003, 22% of the population (13.2 million people) needed help because of a food crisis caused by intense droughts (Broad and Agrawala 2000). This clearly indicates that there is a correlation between precipitation anomalies and food crises (Verdin and others 2005). Thus, proper monitoring of precipitation is a pre-requisite to avoid episodes of food insecurity.

Besides this, monitoring precipitation in semi-arid areas is also important for the forecast of flash floods. Flash floods happen when heavy rain falls in areas where the vegetation cover is limited and the soil is very dry (Lin 1999). In these circumstances, precipitation can result in high flood peaks and rapid flows, than can cause heavy loss of life and property (Delrieu and others 2005). However, forecasting flash floods is problematic since both vegetation cover and precipitation are dynamic features. Given the spatio-temporal coverage of precipitation stations over sub-Saharan Africa, the use of GEONETCast images can be useful to forecast flash floods.

In this respect, SPOT-5 VEGETATION images are typically used to consistently monitor vegetation dynamics over large areas; VEGETATION images are available as 10-days composites (SPOT-VEGETATION S10 products; <http://www.vgt4africa.org/ViewContent.do?pageId=20>) of the spectral channels Blue, Red, Near infrared and Short-wave infrared, or of the most widely used spectral index to monitor vegetation greenness: the Normalized Difference Vegetation Index (NDVI). Additionally, images of the METEOSAT Second Generation (MSG) geostationary satellite are used to produce the Multi-Sensor Precipitation Estimate (MPE) product. This product, also distributed by GEONETCast, consists of the near-real-time precipitation rates in mm/hour for each MSG image (<http://navigator.eumetsat.int/discovery/Start/Explore/DirectExtended.do?EOResourceIdentifier=EO:EUM:DAT:MSG:MPE-GRIB>; Levizzani and others 1999).

In the case study, the use of animated visualization of vegetation time series and precipitation could certainly help users, but some visualization and analytical issues need to be solved to facilitate an effective visual exploration of the complex spatio-temporal interrelations of low vegetation and precipitation. In section 2, we already described some of the analytical and visualization functionality to do so. Here we explain how functions can be dedicated to a case, and how the resulting toolbox works.

3.2. Dedicated functionality

As mentioned above, there are various algorithms to track objects. For the case we have implemented an algorithm that uses the spatial properties of the precipitation features¹, to track and bind them into object paths. In our approach, tracking solves an identity problem based on overlap criteria. The underlying assumption of tracking using overlap is that the sampling frequency of the sensor is high enough to detect overlaps in at least large objects.

Generally, tracking can be performed in either a pre-processing or post-processing mode (Samtaney and others 1994). In the pre-processing approach, the objects are extracted on a pixel-to-pixel basis: each pixel of the image in one frame is compared to all, or part of, the pixels of the image in the next frame utilizing simultaneously temporal (motion) and spatial (intensity) segmentation. If the post-processing mode is used for tracking, individual images are first pre-processed to extract features, and then those features are correlated in time to form *objects*. Since precipitation rates, already extracted by the satellite data provider, can be used to establish features, in this study we adapted a previously developed tracking method based on the post-processing approach, using overlap criteria (Turdukulov, Kraak, and Blok 2007).

Our tracking algorithm performs an iterative search for best overlapping combinations, both forward and backward in time. Thus, the correspondence between a given feature (F_l) at time step $i-1$ in the previous image (F_l^{i-1}) and a set of k -overlapping features at time step i in the current image $\{F_1^i, \dots, F_k^i\}$ is found using the following procedure:

1. Fix feature index l in previous time step $i-1$
2. For a given feature index l , determine feature index k_{MO} in current time step i with maximum spatial overlap:

$$k_{MO}(l) = \mathbf{argmax} [Size(F_l^{i-1} \cap F_k^i)]$$
3. For a given feature index k_{MO} , determine feature index l_{MO} in previous time step $i-1$ with maximum spatial overlap:

$$l_{MO}(k_{MO}) = \mathbf{argmax} [Size(F_l^{i-1} \cap F_{k_{MO}}^i)]$$
4. Check if feature indices are the same: $l_{MO} = l$

Algorithm 1. Procedure to detect the continuation of a feature.

¹ Here we refer to a precipitating “feature” instead of a precipitating “object”; to become an object, at least two overlapping spatial features in successive images are needed.

If $l_{MO}=l$ is true, then it is presumed that the precipitating feature $F_{k_{MO}}^i$ corresponds to the feature F_l^{i-1} and they both belong to the path of one precipitating object. For the precipitating features which do not have overlaps (small fast moving features), correspondences are formed by applying user-defined larger buffers till overlaps are found. Finally, all the remaining unmatched precipitating features are marked as appearances/disappearances.

In the case, tracked objects are used as input in the visualization environment, where they are represented as polygons to facilitate exploration of dynamic precipitation features. Additionally, functionality has been developed to visualize the path of an object (Andrienko, Andrienko, and Gatalsky 2005) by a thin line that connects the centroids of the object. The number of time steps to be displayed for the path is user-defined. Finally, to enable comparison with a simultaneously displayed underlying theme (here NDVI), the precipitation objects can be made transparent.

3.3 Use scenario

A possible use scenario of the toolbox in the case study is sketched here. The scenario includes the following steps: overview first, zoom/filter, details on demand of Shneiderman's (1996) visual exploration strategy. It also includes the steps: analyze first, show the important, zoom/filter, analyse further, details on demand of Keim and others (2006) adapted strategy for visual analysis of large data sets. Both analytical steps draw heavily on algorithmic operations.

The assumption is that a user will first run the animation of the NDVI time series without any interaction to obtain an overview of the vegetation dynamics. This is a strategy that is followed by experienced users of animated time series (Blok 2005). Then the user will probably filter low NDVI values (i.e. areas without much green vegetation), using the sliders of the legends, to learn when and where the vulnerability to flash floods of the area under study is high; the user may zoom in to a particular area, or if dynamics in the surroundings are also relevant, define an area of interest, and display it with a subdued context. Details (relevant values) can be acquired by mouse clicks in the display window.

Next, the user wants to display heavy precipitation rates on top of the NDVI time series. First, high precipitation rates are detected and tracked over time, an analytical process. Once the objects are displayed as transparent polygons on top of the NDVI images, the user tries to get an overview of the dynamic behaviour of the precipitation objects by running the animation. To further explore the relationship with low NDVI values, selections are made, like above. Also, the definition of precipitating objects can be adjusted, needing another analytical process. Of precipitation objects that are expected to cause problems, tracks are represented to predict the path ahead, and details about those tracks are queried.

During exploration, the user can of course also utilize media player and animation speed controls, pan, and display the values of an attribute over time in a graph. This process may have several iterations, and one possible result is visualized in figure 1.

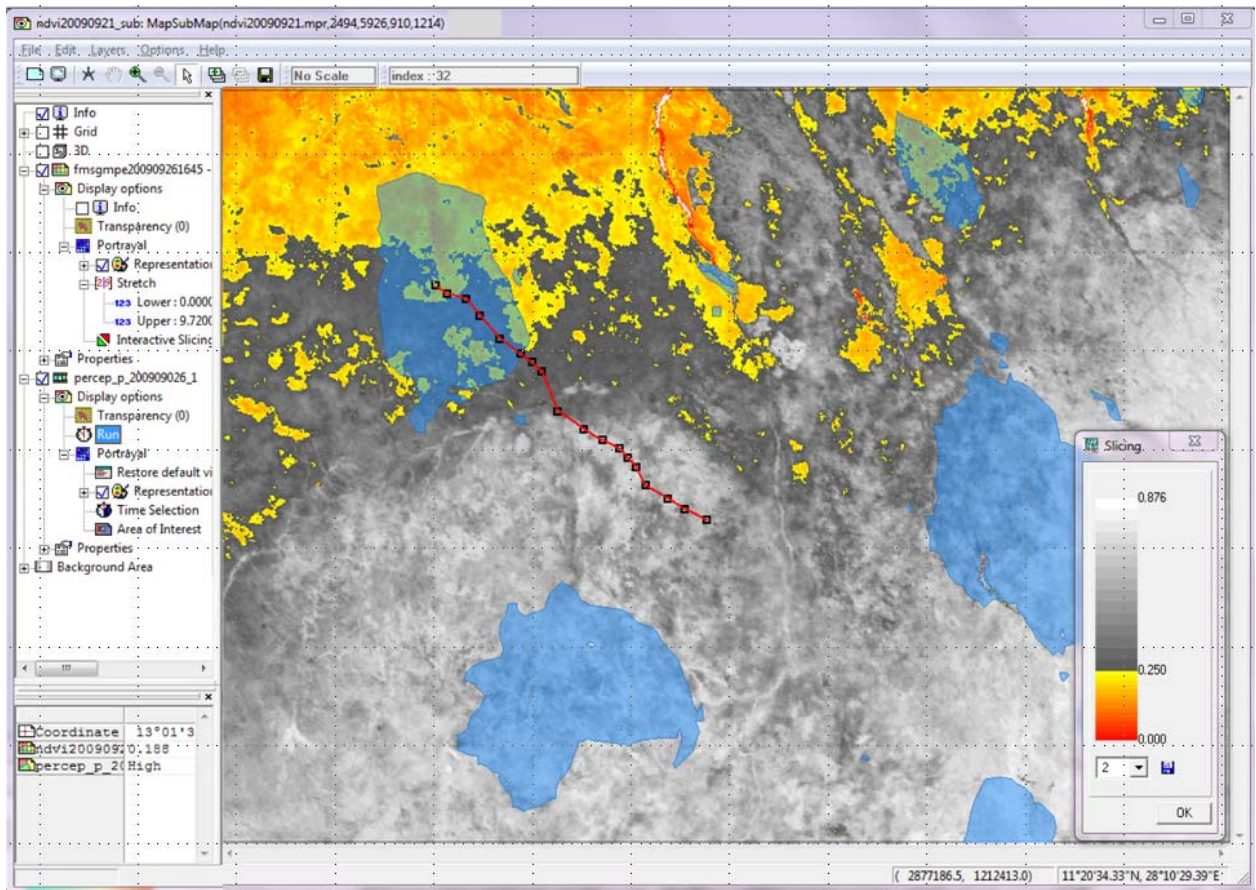


FIGURE 1: The toolbox with a snapshot of an NDVI time series. Attribute slicing highlights low NDVI values (areas vulnerable to flash floods) in a subdued context (here in grey values). As animated overlay, tracked high precipitation objects are displayed transparently, together with the track of a selected object during 18 time steps.

4. Evaluation

4.1 Evaluation of selected visualization functions

A first evaluation has been executed to assess the usability of some selected visualization functions: user defined selections of area of interest and attribute values of interest with the colour and transparency options to enhance the selection relative to the context. The primary goal was to identify usability problems for further improvement. A number of monitoring tasks have been executed by two homogeneous groups, each consisting of 8 potential users. The tasks included identification of areas with constant NDVI values, or with values in a particular range, for either the whole time series (covering two years) or part of it, and for the whole study area (Ethiopia), or a particular region. In addition, comparisons had to be made to find noticeable changes in greenness, variability in an area relative to its surroundings, and to discover in which year a particular value range covered most of the area of Ethiopia. One group used a toolbox *with* the above mentioned functions, the other the same toolbox *without*.

A complementary set of methods was deployed to collect user data on effectiveness, efficiency and satisfaction: think aloud, observation, questionnaires and an interview.

According to the effectiveness metrics set for the test (complete, incomplete and wrong answers) the group that used the extended toolbox exhibited a better performance: 72.9% complete answers (versus 66.7% for the other group) and 12.5% (versus 16.7%) wrong answers; the remaining answers were incomplete. Three out of the eight participants of the group that used the toolbox with new functions gave complete answers for each task, against none of the eight in the other group. Efficiency was measured by the average time taken per task. Overall, the group using the new tools performed a bit faster, on average 3.85 minutes per task (versus. 4.19 minutes for the other group). Satisfaction levels were comparable, and relatively high for both groups: (almost) 4 on a scale from 1 (very poor) to 5 (very good), but users of the extended toolbox were more confident in task execution than the other group.

The difference in results for the two groups was lower than expected. Main reason was that there were still some bugs causing performance problems, and deficiencies. It already led to implementation of some improvements. The main ones are: a dynamic link between thematic legend and display area, so that selected transparency levels are not only visible in the display area, but also in the legend; more precise selection of attribute values of interest, and instead of masking the selected range of attribute values, display of variations within the range. In addition, the display speed control and some buttons and dialogue boxes in interface were improved. Further evaluation including more functions will follow, but we will first extend and improve the functionalities of the toolbox (see section 5).

4.2 Aspects related to the overall performance of the toolbox

Much of the rendering of digital raster images and animations in the toolbox is not performed in the software, but by the graphics hardware using the industry standard OpenGL (<http://www.opengl.org>), which is installed on all modern computers. This results in a significant performance gain.

The performance of the graphics hardware depends, amongst others, on the speed of the graphics-processor, and the available graphics RAM memory. Typical graphic boards have between 128Mb and 1Gb of memory (2011). For this toolbox, the amount of available graphics RAM memory is the main performance bottleneck. If rendering of images and animations requires more memory than is available on the graphics board, the graphics processor will swap data from the graphics memory to the physical memory of the computer to accommodate for the extra need. The data has to go through the graphics bus, which is much slower than the channels that are typically implemented locally on the graphics hardware, resulting in serious performance degradation.

The performance degradation depends on the size of the digital raster image as seen on the computer screen (thus not the actual size of the image in rows and columns). Therefore, performance degradation due to low memory conditions is normally not a problem for single images, but for animations it might become a bottleneck. To avoid reaching the memory limits of the graphics hardware, as a rule of thumb, the digital images in a series that must be animated smoothly should be limited to:

on-screen image size (x * y) * number of images in the series * bytes per pixel < graphics memory size.

Thus if an animation does not run smoothly because the memory requirement exceeds the memory on the graphics board, one can either reduce the number of images in the series, or the window size.

Tracking results in vector (polygon) maps. In OpenGL rendering, polygons consist of a mesh of triangles that cover the area of the polygon. Although these triangles are invisible in the final rendering because edge and interior of each triangle have the same colour, they are drawn. Graphics hardware is very efficient in rendering triangles; the size of the polygons does not influence the performance, but their number and complexity (related to the number of triangles) do. Therefore, vector images with a few thousand polygons usually suffer from reduced rendering performance, though it depends on the complexity of the polygons.

5. Conclusions and future work

We have presented some functionality to improve visual exploration of animated time series compared to using a conventional animation. The functions described are expected to mitigate some common change blindness problems in use of animations by supporting users to focus attention on items that are relevant for the task at hand. Sequences of changing pixel values can be transformed by analytical processing into animated polygons, or in a range of attribute values or areas of interest that stand out as 'figure', which can be displayed in isolation or in a subdued context.

Analytical processing was implemented using two stage process - the feature extraction and tracking stages. In this way, the feature extraction stage can take advantage of various image classification/segmentation algorithms developed in the domain areas and present in ILWIS. Especially in cases when the features can be easily separated using the intensity or shape information only, such as precipitation estimations. Secondly, the overlap -based tracking limits the number of features that must be compared. Therefore, the tracking becomes a real-time process which is important for resulting visualization of the object paths. Lastly, the spatial overlap is a useful measure for detecting the events in the history of spatial objects. Events are stages in the evolution of the phenomena such as: continuation, creation (appearance), dissipation (disappearance), bifurcation (split) and amalgamation (merge) of the features (Samtaney et al., 1994).

Feature extraction and quantification contributes a rise in the level of abstraction: from data containing interesting features to data describing the features, their states and events in their history. The number of characteristics describing each feature can be extended to add other measurements of the statistical and spatial distribution, depending on the purpose of the application and the events the user wants to represent. This offers richer graphical and interactive functionality. Although some ideas, like visualizing the events and object paths, are not entirely new (Andrienko, Andrienko, and Gatalisky 2005), the novelty of our approach is that access to the GEONETCast distribution system, pre-processing, analytical

and extensive animated visualization functionality will be packaged into a single Open Source environment, ILWIS.

ILWIS already has some functions to support image projection, re-sampling, filling of missing pixels, smoothing, filtering, classification, slicing and tracking. But investigation into their application in (multi-sensor) time series still needs to be done. As example, we mention the investigation into tracking algorithms for different applications or phenomena.

An alpha version of the toolbox described here is ready, but we still want to extend the functionality. First of all, we want to look into challenges related to the pre-processing needed to run animated time series. For example, daily images need to be projected to a common grid (an operation known as gridding) to create the time series. This step is far from trivial since Earth observing satellites scan the Earth surface from slightly different orbits and this implies that the ground area covered by each pixel in each image is slightly different (Gomez-Chova and others 2011). In addition to this, the analyst should consider the best method to resample the images while projecting them to a common grid.

Although there is already support for common visual exploration and analysis strategies, options to see details can still be improved, e.g. by providing additional (visualized) information about the (tracked) features, like their size, spectral/spatial properties, and quantification of their behaviour. We also plan to improve options to compare and synchronize time series, and we want to investigate optimization and integration of the usually frequently consulted temporal legend, so that it does not distract too much from what is happening in the animated display.

Last but not least, the question if the tools support users to focus attention, and if they reduce change blindness need to be answered. A user evaluation of the software is planned, taking the above question, in addition to utility and usability of the toolbox, into account.

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