



Project-Team OBELIX

***Environment Observation through
Complex Imagery***

Vannes & Rennes

Activity Report

2016

1 Team

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2 Overall Objectives

2.1 Overview

Observation is one of the key issues in the understanding of environmental systems. A large amount of possibilities, ranging from local probes or networks to hyperspectral remote sensing images, is at the moment available to sense and extract environmental parameters. Among them, aerial or satellite imaging sensors allows for observation at a very large scale. But Earth Observation raises also fundamental challenges. Its impacts are numerous and related to a wide range of application fields, often related to environmental issues: agricultural monitoring and planning for a better exploitation of crops and fields; urban remote sensing for built-up area assessment, urban-natural interaction understanding, pollution monitoring, etc.; analysis of coastal ecosystems through geomorphology studies; land cover mapping and monitoring for identifying the impact of our society on Earth; crisis management and global security aiming to deliver rapid and critical information to rescue operations, e.g., damage assessment, flood delineation, etc. These last applications require fast and even real-time tools for remote sensing.

Unsurprisingly, the number and the complexity of applications based on earth observation are continuously growing. Indeed, our society benefits from the availability of a wide range of earth observation satellites, and several new sensors are launched every year. Within Europe, the Sentinel Copernicus program aims to freely deliver 4 TB daily within the next few years. The dynamics of the remote sensing field leads today to abundant resources of geospatial image data. This advantage has now turned into a serious issue when one has to explore the available data to find some information of interest, and geospatial big data becomes one of the major challenges to be addressed within computer and information sciences. Indeed, how not to be lost in the massive amount of available geospatial data, not far from reaching the Zettabyte scale (ZB)?

Beyond the exceptional data volume to be handled in remote sensing, image intrinsic complexity also brings hard scientific and technological challenges. With the continuous improvement of earth observation satellite sensors, geospatial data are now: multi- or even hyperspectral delivering rich information about observed objects or lands from across the electromagnetic spectrum, beyond the visible light our visual system is used to deal with; daily observations of the same part of Earth which can be revisited by a satellite with ever higher frequencies; at a high or even very-high resolution, allowing to observe from space (from a distance of more than 500km) what occurs on the ground on only 30 centimeter square. This also raises the problem of multiple observations of the same object or part, at various resolutions, and thus with various viewpoints expecting to deliver a globally better understanding of our environment. Moreover, the generalization of very high spatial resolution sensors has a direct influence on the data volume tackled by methods and systems in the field, with an increase of an order of magnitude of 10,000 (one Landsat pixel was representing 30m² while one WorldView-3 pixel will represent 31cm²). Finally, the complexity also comes from the significant noise, imprecision, and incompleteness that characterized observations provided by remote sensing.

2.2 Key Issues

The overall objective of the team is the processing of complex images for environmental pur-

poses. In such a context, available data form a massive amount of multidimensional (multi- or hyperspectral) noisy observations with high spatio-temporal variability and coming from multiple sources. While understanding these data stays very challenging, environmental systems always come with some additional knowledge or models that are worth being exploited to achieve environment observation. Finally, whatever the task involved (e.g., analysis, filtering, classification, clustering, mining, modeling, etc.), specific attention has to be paid to the way results are provided to the end-users, helping them to benefit from their added value.

3 Scientific Foundations

3.1 Processing complex environmental data

Environment observation requires one to perform various data processing tasks: analysis to describe the data with relevant features; filtering and mining to highlight significant data; clustering and classification to map data with predefined or unknown classes of interest; and modeling to understand the underlying phenomena. In this context, processing complex data brings various challenges that will be addressed by the team, both from theoretical and computational points of view. Highly dimensional images, massive datasets, noisy observations, fine temporal and spatial scales, together motivate the design of new dedicated methods that can handle this complexity. The underlying techniques refer to scale-space models (e.g., using hierarchical tree-based image representations) for feature extraction and manifold learning for the theoretical part, and to massive computing using GPUs networks and data intensive systems (based on Hadoop for instance) for the operational level.

Observing data at multiple scales Multiscale modeling of an image enables the access, analysis, processing, understanding and interaction with the image at various levels of details, but also enables one to provide some independence to raw geospatial data, thus introducing a way to deal with the intrinsic complexity of heterogeneous geospatial image repositories. This will allow real-time global land cover monitoring, and foster geospatial description and learning methods to anticipate future challenges faced by our data-intensive society.

Geospatial objects of interest, such as buildings or military targets, manifest themselves most often at various scales within and across the acquired images. Moreover, the clarity of interactions among landscape components (with the purpose of compound object recognition for instance) can also vary greatly with respect to the observation scale. Consequently, image representation schemes capable of accommodating multiple scales are invaluable in the context of geospatial data analysis. Besides, the wide acclaim of the object-based image analysis paradigm has further emphasized the need for multiscale image representation methods [Bla10]. This paradigm relies on a prior segmentation step that aims to gather pixels into regions for further analysis. The team has introduced various efficient segmentations algorithms, with a focus on supervised techniques that rely on user knowledge or input.

[Bla10] T. BLASCHKE, “Object based image analysis for remote sensing”, *ISPRS Journal of Photogrammetry and Remote Sensing* 65, 1, 2010, p. 2–10.

In particular, given a satellite image at a single resolution, various methods have been designed for constructing its multiscale representation. Wavelets and Gaussian pyramids for example, are popular multiresolution tools in this regard, employed especially with the purpose of image fusion (pan sharpening) and change detection. Unfortunately, they fail to preserve the contours of the image components, and consequently do not lend themselves well for multiscale object-based image analysis. Hierarchical representations form a relevant alternative introduced by the mathematical morphology community. Among the available tree models belonging to this category, partition hierarchies consist of producing segmentation maps of their input at various coarseness levels, with the latter being directly related to the scale under consideration. Inclusion hierarchies rely on the iterative nesting of image components, e.g., from isolated extrema to larger objects. Both models enable efficient representation and direct subsequent extraction of meaningful image regions at arbitrary scales. Hence, multiple tree models relying on these powerful representations have been introduced [SW09], e.g., binary partition trees, or min/max trees. Moreover, certain tree variations can accommodate flexible segmentation strategies according to arbitrary criteria, while additionally preserving the contours of image components [PLCS12]. We explore in the team how to build such hierarchical models from large and multivariate datasets. In order to face the inherent complexity of remote sensing data, we also consider to exploit some prior knowledge when constructing the image model, e.g., in high dimensional spaces.

The description of image content (or feature extraction) is a stage of crucial importance for various geospatial applications, such as content-based retrieval, classification and mapping. Consequently, a plethora of content descriptors have been elaborated in this regard, either at pixel, region or global level, capturing spectral, textural, shape-based, geometric and even localized image properties. Even though content-description approaches have come a long way in the past couple of decades, the challenges, practical requirements and complexity of the data under consideration have increased just as much, if not more. Indeed, content description has to be robust against global and local illumination, rotation, scale variations and geometric deformations. Moreover, with the advances in terms of spatial and spectral resolutions, content descriptors are expected to adapt to their variations, so as to exploit the additional information; for instance by means of descriptors capable of capturing fine spectral image characteristics, or even particular spatial arrangements of predefined objects. Furthermore, the availability of time series has enabled a whole new level of temporal queries that require suitable temporal features. The team aims to elaborate such original and robust features, e.g., with a focus on morphological attributes taking into account some prior knowledge.

Facing the curse of dimensionality Environmental data usually come with high dimensionality, either in the number of samples or in the number of dimensions per sample. A good example is found in Hyperspectral Imaging, where a pixel is a vector of reflectances sampled over different wavelengths, and an image is therefore a data cube usually containing several

[SW09] P. SALEMBIER, M. WILKINSON, “Connected operators”, *IEEE Signal Processing Magazine* 6, 6, 2009, p. 136–157.

[PLCS12] B. PERRET, S. LEFÈVRE, C. COLLET, E. SLEZAK, “Hyperconnections and hierarchical representations for grayscale and multiband image processing”, *IEEE Transactions on Image Processing* 21, 1, January 2012, p. 14–27.

hundreds of reflectances per pixel. This dimensionality comes with several problems that arise either from a statistical viewpoint (curse of dimensionality) or from computational issues. A good solution is found in dimensionality reduction techniques, which hopefully provide concise representation of the initial information. This reduced information set could be obtained through the embedding of the original data in a lower dimensional but meaningful space. This embedding usually stems from a variety of different energy functions to be optimized, generally associated to the quality of reconstruction of the samples from the embedding space to the original input space. The matrix factorization problem provides a well-grounded framework to a wide class of dimensionality reduction techniques. By decomposing a given data matrix into a product of two matrices (representing respectively the embedding space and the surrogate representation on the data in this space), one can find the expression of several well known transformations by setting constraints on the embedded space or the decomposition. Hence, the Principal Component Analysis is obtained when an orthogonality constraints is set on the vectors of the embedding space. Setting a positivity constraint on both matrices lead to the well known nonnegative matrix factorization. Adding sparsity constraints on the embedding vectors leads to sparse PCA techniques, while imposing it on the reduced coordinates lead to the sparse coding.

We have started in the team to work extensively on the convex formulation of these problems, since it buries strong relations with the underlying physics of the phenomena: the observed data are then assumed to be a mixture of existing, identified, components. As examples, in the case of hyperspectral data, at a given location, and because of the spatial resolution of the captor and scattering effects, the value contained in one pixel is assumed to be a combination of several spectra that describe the reflectance of a "pure" material (e.g., soil, water, asphalt, etc.). Those materials are said to be endmembers. The problem of unmixing [BDPD⁺12] those data amounts to find which of those endmembers are present in the pixel spectrum, and in which proportion (abundance). This constitutes a difficult ill-posed inverse problem for which no closed-form solutions are available, but where matrix factorization techniques provide appealing solutions (e.g. sparsity constraints or convexity constraints). We also plan to use those kind of technique for the analysis and unmixing of time series representing land covers.

Also, the dimensionality problems can be solved to some extent by subsampling the original dataset, and providing this way a subset of the data which contains most of the relevant information. As a matter of fact, this subsampling problem buries a lot of resemblances with the matrix factorization problem, since they both try to identify low ranks approximations of the original data matrix. In the literature, this sub-sampling problem is also referred to as precise definition or, as coarse graining. Several criteria can be defined to evaluate the quality of this approximation: Minimization of the eigenvector distortion, label propagation, spectrum perturbation, maximization of the data coverage and diversity, etc. Sometimes, these methods make the assumption that the dataset lives onto a smooth manifold, the structure of which should be preserved through the sub-sampling process. Among others, it is possible to characterize the manifold thanks to the Laplace-Beltrami operator, which is a generalization

[BDPD⁺12] J. M. BLOUCAS-DIAS, A. PLAZA, N. DOBIGEON, M. PARENTE, Q. DU, P. GADER, J. CHANUSOT, "Hyperspectral unmixing overview: Geometrical, statistical, and sparse regression-based approaches", *Selected Topics in Applied Earth Obs. & Remote Sensing, IEEE J.* 5, 2, 2012, p. 354–379.

of the Laplace operator to Riemannian manifolds. In [CL06], the Laplace-Beltrami operator is shown to be fairly well approximated by the Gaussian kernel, exhibiting a strong link between the manifold study and kernel methods in machine learning (with RBF kernels) from which the team has designed a new manifold learning algorithm [CBJ11]. Furthermore, the team is studying the manifold in the input space, or its image in the feature space induced by a kernel, and is further exploring the problem of low rank approximations with dedicated and scalable kernel methods.

Adapting distributions and correcting data shifts Domain adaptation problems occur naturally in many applications of machine learning to real-world datasets [QCSSL09]. In remote sensing image analysis this problem arises frequently, since the acquisition conditions of the images (cloud cover, acquisition angle, seasonal variations) are most often different. As a consequence, even if the images contain the same type of objects, the observed data distribution undergoes a d -dimensional and often nonlinear spectral distortion, i.e. a distortion that is local, class-specific and that impacts differently each region of the electromagnetic spectrum.

One way to solve this problem is to perform an adaptation between the two d -dimensional image domains, in order to achieve a relative compensation of the shift by matching the data clouds to each other. Provided that the data are expressed as graphs and embed a topological structure, this problem can be seen as a graph matching problem and has been tackled as such in hyperspectral remote sensing.

Dealing with time series and dynamic patterns With the growing temporal resolution of remote sensors come new challenges including knowledge extraction from these large temporal datasets. New methods should then be designed so as to better understand dynamics of the observed phenomena. One possible application is the monitoring of agricultural plots from series of remote sensing images. Here, data are available and their temporal resolution is such that a fine-grained analysis of farming behaviors can be performed.

Time-sensitive metrics (such as Dynamic Time Warping, DTW) have shown great impact on many time series retrieval tasks. We intend to investigate the use of such metrics at the core of machine learning and/or indexing algorithms. This implies to tackle two main (and related) issues.

First, many of these algorithms rely on the assumption that similarity between objects can be measured using distances, or metrics that are distances in some (possibly unknown) spaces (this is the case of kernel functions), which is not the case for standard time-sensitive metrics. This has several implications on the use of time-sensitive metrics for machine learning. Some algorithms (*e.g.* k -means) make intensive use of barycenter computations: when using DTW-

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- [CL06] R. COIFMAN, S. LAFON, “Diffusion maps”, *Applied and Comput. Harmonic Anal.* 21, 1, 2006, p. 5–30.
- [CBJ11] N. COURTY, T. BURGER, L. JOHANN, “PerTurbo: a new classification algorithm based on the spectrum perturbations of the Laplace-Beltrami operator”, *in: ECML/PKDD*, 1, p. 359–374, 2011.
- [QCSSL09] J. QUIÑONERO-CANDELA, M. SUGIYAMA, A. SCHWAIGHOFER, N. D. LAWRENCE, *Dataset shift in machine learning, Neural information processing series*, MIT Press, Cambridge, MA, 2009.

like metrics, new methods to approximate these as best should be introduced [PKG11]. Other algorithms, in the context of indexing, rely on triangular inequality to prune out the search space at query time. When such inequality does not hold, new pruning methods should be designed so as to perform efficient queries.

Second, most machine learning algorithms make intensive use of distance computations, which can be affordable if the considered distance is fast to compute but becomes a strong limitation when using DTW-like metrics. In order to deal with this issue, fast yet approximate computation of such distances could be used at the core of machine learning algorithms so as to trade accuracy for efficiency.

3.2 Incorporating prior knowledge and models

To deal with the intrinsic complexity of images, environment observation can most often benefit from supplementary information (additional measurements, expert knowledge, physical models). Incorporating such information when processing environmental data is thus highly expected. We will address this issue in four different ways: i) data assimilation when dealing with physical models; ii) data fusion and dimensionality reduction when dealing with additional measurements, iii) active learning for interactions with expert knowledge and iv) supervision in the early steps of computer vision (e.g., feature extraction, image segmentation and representation, etc.). The two first points are discussed below whereas the third one is presented in the next section. Let us recall that the last point has been addressed in the previous section.

Coupling data and models In general many physical models exist to describe an environmental system. However, such models are rarely compatible with data analysis tools (e.g., models are non-linear and thus do not fit the classic assumptions in computer vision) and it is therefore of prime importance to design alternative strategies able to accurately mix the recent physical models with variables derived from images. Mixing data and models is commonly known as the data assimilation problem that has largely been studied in the geosciences community. However some specific difficulties due to the intrinsic nature of images (high dimension, 2D/3D projections, indirect observations, etc.) require the design of adapted methodologies.

From a thematic point of view, we will focus on two main applications: the recovery of small-scale velocity fields and the estimation of bio-physical parameters. Although these two aspects seem to be disconnected, they are of prime importance for us since: (i) they require the use of complementary data (low spatial resolution satellite with high temporal rate for wind fields and conversely, high and very high spatial resolution for biophysical parameters with low temporal rate); (ii) associated models are of different nature; we will thus explore a large panel of solutions; and (iii) as longer-term goal, we plan to use complex models of climate/land cover interactions that require the knowledge of both biophysical variables and local winds (as pollutant dispersion or landscape evolution models).

From a methodological point of view, variational data assimilation and stochastic filtering techniques will be explored. Indeed, promising results have been obtained very recently

[PKG11] F. PETITJEAN, A. KETTERLIN, P. GAŇÇARSKI, “A global averaging method for dynamic time warping, with applications to clustering”, *Pattern Recognition* 44, 3, 2011, p. 678–693.

through approaches relying on optimal control theory and data assimilation. The techniques proposed melt an imperfect modeling (based on Partial Differential Equations) of the physical process and an observation operator, leading to adequate optimal tools for consistent combination of model and observations. In this context the variational approach (3D-4D var) is a popular methodology. For turbulent 2D flows, curve and front tracking or data reconstruction from images, this enabled the recovering of the whole scale range of the flow. However as already mentioned, it has been observed that errors still remain on the fine scale structures. Yet, they are of prime importance in many applications related to climate and land-cover interactions as urban pollution understanding. To deal with fine scales, we will rely on our first works that consist in performing a multi-scale estimation by exploiting the framework of data assimilation where the usual temporal variable is now an artificial time between scales and the models are based on downscaling laws issued from fluid mechanics. We will rely on various observation operators: image-based ones and direct observations (issued from local sensors at lower altitudes) in order to estimate, in a single scheme, the velocities at various layers of the atmosphere by keeping the physical interactions between these layers. To that end, a large variety of physical models of scale interactions will be explored. These models are mainly developed in the Turbulence Laboratory of Tsinghua University (Beijing, China) with which we have many links and projects. The design of adapted image-based observation operators (link between the image luminance and the fine scale velocities) and the adaptation of existing physical models to this specific problem will be the key axes of researches.

When dealing with land cover studies, main parameters to be extract from remotely sensed data are: kind of land cover (built areas, water, roads or vegetation), surface roughness, temperature, moisture and the LAI (Leaf Area Index, related to the vegetation). In practice all parameters of interest can already be estimated from images. Let us however mention that in specific environments (urban, highly intensive agricultural landscapes), the estimation of the temperature is delicate since many interactions between land cover and temperature occur. We will thus build upon some previous work from OSUR ^[FDQ12] to design precise temperature estimation tools in urban environments. The idea is to adapt the existing models of temperature (at regional scales) to the scale of a city by extracting correlations/statistical relations between land cover and temperature. These relations will be computed from sparse representations and manifold learning techniques discussed in previous section. The specific case of bio-physical parameter and in particular LAI estimation will also be managed through stochastic filtering techniques. The underlying physical process of annual growth of leaves is indeed known and this information is at the moment not taken into account in existing and operational estimation tools. It may therefore be of high interest to take this knowledge into consideration. It has indeed two advantages: i) reduction of the noise and interpolation of missing data associated to the low temporal observations and ii) extraction of some hidden parameters related to the calibration of the dynamic models. We have been involved in this direction for the recovery of bio-physical parameters from medium resolution images in collaboration with the CPLANT team of CASIA (Institute of Automation of Chinese Academy of Sciences) which develops since more than 30 year a well known plant growth model (named GreenLab). Within the OBELIX

[FDQ12] X. FOISSARD, V. DUBREUIL, H. QUENOL, "Spatialization of urban heat island by multi regression in Rennes, France", *in: 8th International Conference on Urban Climate, 2*, Dublin, Ireland, 2012.

team, we plan extend our first works and move from medium resolution to very high resolution data. As the GreenLab model requires many calibration parameters and is highly non linear, we will rely both on reduction techniques (to learn some parameters on known data sets) and particle-smoothing approaches which are more adapted to the manipulation of complex models than the variational data assimilation (in particular they do not require adjoint models which are tricky to design with GreenLab).

Combining various sources of information Since complementary observations are available for analyzing land cover parameters or winds (a wide range of remote sensing data, a set of on site measurements, hemispherical photographs, surveys), a specific care should be done regarding the combination of these data: even if mixing various sources can generally improve the quality of the estimation, an improper handling of this wealth of information is sometimes likely to introduce more noise and uncertainty in the measurement than expected precision. Combining this information is a crucial step since extracting values with a minimum of noise is the key point for analyzing and understanding the land covers. An accurate management and homogenization of this mass of information is then essential in order to extract usable time series. In particular, reducing the uncertainty is the fundamental issue when observations have variable degrees of confidence. Here we will explore the theory of evidence that is particularly suited to decision making by management of uncertainty [Sha76]. We recently explored this aspect to combine observations in order to detect edges in satellite images, to detect changes in remote sensing data from past and present or to evaluate the influence of climatic parameters on the land. Recently, several theoretical extensions have been proposed in order to properly handle sources of data potentially paradoxical, subjective or symbolic [DS06] or to apprehend correlated sources [Den99]. We will explore such solutions that are perfectly suited to the variety of data we have to deal with.

3.3 Putting the user in the loop

Since most of the results of the methodological developments of the team will be aimed towards nonspecialists of computer science (computer vision and image processing, machine learning and data mining), a particular focus will be given to their understanding by the end-user. The objectives are both to facilitate their interactions with the tools, and provide easy ways to understand the results of the different algorithms. We refer to the first category as "active processing", where the user is supposed to interact with the algorithm to achieve a better result, and to the second one as "visual analytics", since the visualization of the algorithm results is meant to provide a thorough understanding of the observed phenomenon.

Active processing Analysis and understanding of EO images is usually performed in a supervised mode, where the expert is able to provide a representative learning dataset. The

[Sha76] G. SHAFER, *Mathematical Theory of Evidence*, Princeton University Press, 1976.

[DS06] J. DEZERT, F. SMARANDACHE, "Introduction to the Fusion of Quantitative and Qualitative Beliefs", *Information and Security 20*, 2006, p. 9-49.

[Den99] T. DENOËUX, "Reasoning with imprecise belief structures", *Int. J. Approx. Reasoning 20*, 1, 1999, p. 79-111.

latter usually contains a sufficient information about the underlying distributions, which is usually not true, mostly because the labelling activity is time consuming (and also prone to errors), and also because only few criteria can be designed to assess the completeness of descriptions. As a matter of fact, increasing the learning set size can be efficiently done if the learning algorithm is endowed with auto-analysis properties, and is capable of determining which is the best information to add to the system (which samples should be labelled to gain accuracy in the class models, or in the boundaries between the classes). It then ask the user to label this data (or a subset of the data). Yet, this problem of active learning has been well studied in the previous decades, and has also been completed by recent advances in the context of semi-supervised learning, which assumes that also the unlabelled samples can be used for learning class models or driving feature extraction. We propose nethertheless to work on this type of active learning strategies, either by designing new strategies to determine the missing pieces of the learning (such as the one developed in the Perturbo framework or by integrating prior knowledges from physical models or simulation methods in the active strategy. Here, the learning set is enhanced by samples that are not collected from real data, but automatically produced by a simulation model. This kind of bootstrapping by synthetic data has recently been shown to work successfully in the context of crowd video analysis, and we foresee to extend these concepts to environmental data.

Following the objectives of the team to develop supervised feature extraction and supervised image representation and segmentation, we also consider involving the expert in the earlier steps of computer vision through the active paradigm. Indeed, the team will build upon its expertise on efficient algorithms for image representation and segmentation to propose interactive segmentation and analysis schemes that will let the user to explore its datasets in real-time. Image representations and segmentations will be produced in real-time by tacking into account user feedback, leading to a specific view of the data that fits user needs.

Visual Analytics The multimodal observation of the environment through a variety of sensors, as well as simulation models running at fine scales, contribute to produce a large amount of information, which complexity cannot be handled directly by the user. For this information to be processed directly by a human operator, new paradigms of representations are to be explored. Those paradigms usually involve the visual system, which demonstrates in our day to day life capacities which computer scientists fail to reproduce with computers. Turning an information in a some visual clues or easy-to-apprehend chart is in itself a challenging task. Environmental data, that are in essence spatialized and temporal, can however be easily mapped on animated geocentric earth representations. It remains nonetheless that complex data will lead complex representations, that require one to pre-analyze the data before its visualization, either for computational issues, or either to extract the meaningful information inside.

The team intends to first specialize some methodologies to achieve this goal (e.g., explain some unobserved data by a combination of known data, as can be done with matrix factorization techniques), before considering visualization methods. This last point belongs to the category of visual analytics and can be considered as a crucial step to help decision makers exploit rapidly scientific advances. those aspects constitute some middle-term objectives for the development of the team. To ensure dissemination among the scientific communities, the

team aims to follow open-source initiatives and to deliver a series of tools dedicated to the end-user appropriation of results.

4 New Results

4.1 Morphological image analysis

Participants: Sébastien Lefèvre, Luc Courtrai.

Mathematical Morphology (MM) is a rich framework for image processing. It consists in non-linear operators that take into account the spatial information contained in the image. Among the works conducted this year on this topic, we have completed our study on region-based path opening for road detection in a journal paper [4]. We have also explored the potential of MM in the context of microwave radar data [26], with the objective of disseminating widely this toolbox to some new user communities (e.g. for detection of Radio Frequency Interferences).

4.2 Hierarchical image analysis

Participants: Sébastien Lefèvre, François Merciol, Laetitia Chapel, Petra Bosilj, Yanwei Cui.

Hierarchical representations provide a powerful way to model, analyze and process images beyond the simple grayscale ones. Tree construction has received some specific attention with the design of a new, efficient algorithm through a collaboration with TU Brno and a journal publication [6]. To face the lack of client resources when dealing with big data (large images), we have introduced a client-server solution that allows a client to delegate the tree construction to a server and to later access remotely only to some parts of the overall representation [27]. We were also considering hyperspectral images and introduce an original solution to compute multiscale features (a.k.a. attribute profiles). This solution was defined as a relevant compromise between marginal and vectorial strategies [1], featuring a collaboration with Mauro Dalla Mura and Erchan Aptoula.

The doctoral study conducted by Petra Bosilj on image retrieval was completed, and her results on local pattern spectra and their application to satellite image retrieval were consolidated through two journal publications ([3] with Michael Wilkinson and [2] with Erchan Aptoula, respectively).

Following our preliminary work in designing kernels tailored for morphological hierarchies (PhD of Yanwei Cui), we have proposed a bottom-up approach aiming at classifying a pixel through its context (i.e. its ancestors in the tree) [17]. Combining this approach with the previous top-down strategy allowed us to use the two kinds of kernels to tackle multiple data sources, leading to significant gain in classification accuracy for land cover mapping [18].

4.3 Deep Learning for Remote Sensing

Participants: Sébastien Lefèvre, Nicolas Audebert.

We have engaged in the field of deep learning applied to Earth Observation, and more precisely we have explored how semantic segmentation could be used for land cover mapping. To do so, a preliminary study was focusing on the spatial support used in the semantic segmentation process: we show that the sliding window used for a CNN can be favorably replaced by some contextual neighborhood, preferably provided through superpixels than with a standard segmentation procedure [12]. We then adopted a fully-convolutional approach through the novel semantic segmentation network (SegNet). We have extended this network to deal with multiple inputs (e.g. RGB and DSM/NDVI features) and to consider information available at multiple scales [14]. Furthermore, the semantic segmentation that was provided by this network was also used as an intermediate step in an deep learning-related object-based image analysis approach to perform object (vehicle) detection and recognition in the public ISPRS 2D semantic labeling dataset [13].

4.4 Optimal Transport for machine learning and remote sensing

Participants: Nicolas Courty, Sina Nakhostin, Thomas Corpetti.

Following our works on optimal transport for domain adaptation initiated in 2014, we developed an activity centered around the theme of optimal transport for machine learning.

Image fusion based on optimal transport. In this work we tackle the problem of the fusion of hyperspectral (HS) and multispectral (MS) satellite images. The aim of the fusion process is to merge the spectral quality of the HS images with the better spatial resolution of the MS images. The final result is an image having both high spectral and spatial resolution. In order to perform the fusion task, we suggest an approach based on optimal transport theory that highlights the idea of energy transfer from the starting images HS and MS to the resulting final image. In this sense, the map transport can be thought as the transfer of characteristics of one image to another. We published another foundation paper on the use of optimal transport for data fusion in remote sensing [16].

Mapping estimation We are interested in the computation of the transport map of an Optimal Transport problem. Most of the computational approaches of Optimal Transport use the Kantorovich relaxation of the problem to learn a probabilistic coupling but do not address the problem of learning the underlying transport map linked to the original Monge problem. Consequently, it lowers the potential usage of such methods in contexts where out-of-samples computations are mandatory. In this work we propose a new way to jointly learn the coupling and an approximation of the transport map. We use a jointly convex formulation which can be efficiently optimized. Additionally, jointly learning the coupling and the transport map allows to smooth the result of the Optimal Transport and generalize it to out-of-samples examples. Empirically, we show the interest and the relevance of our method in two tasks: domain adaptation and image editing. This work was published at NIPS [29].

Unmixing with Optimal Transport This work is focused on spectral unmixing and presents an original technique based on Optimal Transport. Optimal Transport consists in estimating a plan that transports a spectrum onto another with minimal cost, enabling to compute an associated distance (Wasserstein distance) that can be used as an alternative metric to compare hyperspectral data. This is exploited for spectral unmixing where abundances in

each pixel are estimated on the basis of their projections in a Wasserstein sense (Bregman projections) onto known end-members. In this work an over-complete dictionary is used to deal with internal variability between endmembers, while a regularization term, also based on Wasserstein distance, is used to promote prior proportion knowledge in the endmember groups. Experiments are performed on real hyperspectral data of asteroid 4-Vesta. This work was part of Sina Nakhostin PhD [28].

Another line of work for unmixing with optimal transport was applied to signal (music analysis). Many spectral unmixing methods rely on the non-negative decomposition of spectral data onto a dictionary of spectral templates. In particular, state-of-the-art music transcription systems decompose the spectrogram of the input signal onto a dictionary of representative note spectra. The typical measures of fit used to quantify the adequacy of the decomposition compare the data and template entries frequency-wise. As such, small displacements of energy from a frequency bin to another as well as variations of timbre can disproportionately harm the fit. We address these issues by means of optimal transportation and propose a new measure of fit that treats the frequency distributions of energy holistically as opposed to frequency-wise. Building on the harmonic nature of sound, the new measure is invariant to shifts of energy to harmonically-related frequencies, as well as to small and local displacements of energy. Equipped with this new measure of fit, the dictionary of note templates can be considerably simplified to a set of Dirac vectors located at the target fundamental frequencies (musical pitch values). This turns out to give ground to a very fast and simple decomposition algorithm that achieves state-of-the-art performance on real musical data. This work was published at NIPS [21].

4.5 Classifier Selection

Participants: Bharath Bushan Damodoran, Nicolas Courty, Sébastien Lefèvre.

Generating accurate and robust classification maps from hyperspectral imagery (HSI) depends on the user's choice of the classifiers and input data sources. Choosing the appropriate classifier for a problem at hand is a tedious task. Multiple classifier system (MCS) combines the relative merits of the various classifiers to generate robust classification maps. However, the presence of inaccurate classifiers may degrade the classification performance of MCS. In this paper, we propose a supervised classifier selection strategy to select an appropriate subset of accurate classifiers for the multiple classifier combination from a large pool of classifiers. The experimental results with two HSI show that the proposed classifier selection method overcomes the impact of inaccurate classifiers and increases the classification accuracy significantly. This work is part of Bharath Bushan Damodoran post-doc, was published at IGARSS [19].

4.6 Clique Neural Networks

Participants: Nicolas Courty, Romain Huet, Sébastien Lefèvre.

This work was done in the context of the SENSE project, and is part of Romain Huet's PhD. Neural networks that are able to retrieve and store information constitute an old but still active area of research. Among the different existing architectures, recurrent

networks that combine associative memory with error correcting properties based on cliques have recently shown good performances on storing arbitrary random messages. However, they fail in scaling up to large dimensions data such as images, mostly because the distribution of activated neurons is not uniform in the network. We propose here a new penalization term that alleviates this problem, and shows its efficiency on partially erased images reconstruction problem. Published at ESANN [23].

4.7 Unmixing for Planetary Hyperspectral Images

Participants: Nicolas Courty, Sina Nakhostin, Thomas Corpetti.

Hyperspectral images are commonly used in the context of planetary exploration, especially for the analysis of the composition of planets. As several instruments have been sent throughout the Solar System, a huge quantity of data is getting available for the research community. Among classical problems in the analysis of hyperspectral images, a crucial one is unsupervised non-linear spectral unmixing, which aims at estimating the spectral signatures of elementary materials and determining their relative contribution at a sub-pixel level. While the unmixing problem is well studied for earth observation, some of the traditional problems encountered with earth images are somehow magnified in planetary exploration. Among them, large image sizes, strong non-linearities in the mixing (often different from those found in the earth images) and presence of anomalies are usually impairing the unmixing algorithms. This work is a new method that scales favorably with the problem posed by this analysis. It performs an unsupervised unmixing jointly with anomaly detection capacities, and has a global linear complexity. Non linearities are handled by decomposing the hyperspectral data on an overcomplete set of spectra, combined with a specific sparse projection, which guarantees the interpretability of the analysis. A theoretical study is proposed on synthetic datasets, and results are presented over the challenging 4-Vesta asteroid dataset. This work was done in the context of Sina Nakhostin PhD and was published as a journal paper in IEEE TGRS [8], and featured a collaboration with Harold Clenet from EPFL.

4.8 Coupling data and models

Participants: Thomas Corpetti, Pascal Zille.

Super-resolution of fluid-flows. The problem of improving the quality of low-resolution passive scalar image sequences has been addressed. This situation, known as “image super-resolution”, aroused very few applications in the field of fluid visualization (despite the fact that most image acquisition devices have limited spatial resolution and users often require higher-resolution images for further processing and analysis).

The originality of our work has been to link the image super-resolution process together with the large eddy simulation framework in order to derive a complete super-resolution technique. We started by defining two categories of fine-scale components we aim to reconstruct. Then, using a deconvolution procedure as well as data assimilation tools, we have shown how to partially recover some of these missing components within the low-resolution images while ensuring the temporal consistency of the solution.

This work was done in collaboration with Shao Liang (Ecole Centrale Lyon) and has been published in [11]. In another context, we have applied similar techniques to interpret Myocardial Strain and Contraction Phase in medical images [10].

4.9 Change detection and time series analysis

Participants: Adeline Bailly, Arthur Le Guennec, Romain Tavenard, Sébastien Lefèvre, Nehla Ghouaiel, Laetitia Chapel, Thomas Corpetti.

Time series analysis From a thematic point of view, the analysis of crops and the way they are managed is a very hot point. Therefore, High Spatial Resolution (HSR) remote sensing time series are of prime importance to monitor those systems. However, because of the complexity of the resulting time series, the identification of various practices using conventional tools is no easy task. We have studied the use of computer vision inspired feature extractors for time series classification and their application to crop classification [15]. We have also studied the impact of data augmentation strategies on classification performance [25]. On a more prospective side, we have worked on early classification problems in which one aims at being able to provide accurate classifications as early as possible [31]. In the context of emerging SENTINEL satellite sensor (10m spatial-resolution, one image/day), we have worked 1) on the updating of Copernicus HRL (High Resolution Layer, a product of European Commission for land cover classification) using data fusion and Dempster-Shafer theory [7] and 2) and the clusterisation of resulting time series using affinity propagation [32].

Multimodal Change detection. While change detection is usually performed between two images acquired from the same sensor at different dates, we have addressed this problem in the context of multimodal input data. Our goal was to compare an aerial image (possibly outdated) with a ground-level image that can be provided through VGI or mobile platforms such as Google Street View. The overall process made of several steps, including top-down view construction, ground and aerial views registration and comparison, led to promising results that were published in a journal paper [5].

4.10 Active learning to assist annotation of aerial images in environmental surveys

Participants: Romain Dambreville, Chloé Friguet, Mathieu Laroze, Sébastien Lefèvre.

Remote sensing technologies greatly ease environmental assessment using aerial images. Such data are most often analyzed by a manual operator, leading to costly and non scalable solutions. In the fields of both machine learning and image processing, many algorithms have been developed to fasten and automate this complex task. Their main common assumption is the need to have prior ground truth available. However, for field experts or engineers, manually labeling the objects requires a time-consuming and tedious process. Restating the labeling issue as a binary classification one, we propose a method to assist the costly annotation task by introducing an active learning process, considering a query-by-group strategy.

This work started mid-2016, with the PhD of Mathieu Laroze. As a baseline, a preliminary work was made with a full supervised pipeline using SVM classifier and HOG features [24].

5 Contracts and Grants with Industry

5.1 ANR, Jeunes Chercheurs (2013–2017)

Sébastien Lefèvre acted as coordinator for the ASTERIX project on spatio-temporal analysis by recognition within complex images for remote sensing of environment. This project gathers IRISA, OSUR, LIVE and IPGS (Strasbourg), DYNAFOR (Toulouse).

5.2 CNES, TOSCA (2014–2017)

Thomas Corpetti acted as coordinator for the VEGIDAR project on urban vegetation analysis by coupling very high resolution optical remote sensing and Lidar data. This projects gathers IRISA, LETG (Rennes), Lab-STICC (Brest), IGN (Paris) and LIVE (Strasbourg).

5.3 International Space Science Institute / ISSI Beijing, international team (2014–2016)

Thomas Corpetti acted as coordinator for the RESIDUAL project on remote sensing image data assimilation for pollution monitoring: application to urban and ocean pollution. This project gathers IRISA, INRIA (Rennes & Grenoble), LMBA (Vannes), LSCE (Paris), Florida State University (USA), Harbin Institute of Technology (China), Tsinghua University (China), Vietnamese Academy of Science (Vietnam), Russian Academy of Sciences (Russia).

5.4 PHC, Pamoja program (2016–2017)

Sébastien Lefèvre acted as a coordinator for the OBIATS project on monitoring of tree species with object-based satellite image time series analysis. This project is jointly conducted with TU Kenya.

5.5 Labex Comin Labs (2013–2016)

Nicolas Courty and Sébastien Lefèvre contribute to the SENSE project on sparse neural coding and bionic vision system. This project gathers IRISA and Lab-STICC (Lorient & Brest).

5.6 Pôle Images & Réseaux AAP PME (2016–2018)

Sébastien Lefèvre and Minh-Tan Pham contribute to the DELORA project on detection and localization of buried networks through augmented reality. This project gathers 2 SMEs, Tellus (Bruz) and ARTEFACTO (Betton).

5.7 UBS, PPI program (2013–2017)

Sébastien Lefèvre and Luc Courtrai contribute to the Littoralg project on coastal monitoring and seaweed valorisation. This project gathers several labs from UBS (IRISA, GMGL, LBCM, Geoarchitecture, IREA, CRPCC).

5.8 WIPSEA (2016–2019)

SME located in Rennes aiming to deliver imaging solutions for wildlife monitoring. A contract has been signed to support the CIFRE PhD thesis of Mathieu Laroze in the field of interactive object detection.

5.9 SIRS (2016–2017)

SME located in Lille aiming to deliver mapping products to public authorities for decision making. A contract has been signed to explore novel approaches for large-scale mapping based on hierarchical image representations

5.10 MGDIS (2013–2016)

SME located in Vannes aiming to deliver software solutions to public authorities for decision making. A contract has been signed to study how aerial and satellite images can provide ancillary knowledge to complement existing data sources.

5.11 CNRS PEPS Fondements et Applications de la Science des Données TOPASE (2015-2016)

This CNRS PEPS project is conducted in collaboration with LITIS (Rouen) and OCA (Nice). TOPASE goals are to draw a bridge between machine learning problems and the theory of optimal transport, by looking at new computational tools for optimal transport problems, as well as new applications in the case where data at hand can be seen as probability distributions.

6 Other Grants and Activities

6.1 International Collaborations

- Gebze Technical University, Kocaeli, Turkey: Erchan Aptoula (Associate Professor) is collaborating with the team on several topics, mainly related to image retrieval/classification with morphological hierarchies [1, 2, 26].
- University of Groningen, Netherlands: following the 3-month visit of Petra Bosilj (PhD student) in the team of Michael Wilkinson (Associate Prof.), some joint work was conducted on image description based on morphological trees [3].
- Brno University of Technology: following a 6-month visit of Jiri Havel (PhD student) a few years ago, we have continued some joint work on efficient algorithms for constructing hierarchical image representations [6].
- EPFL, Lausanne and University of Zurich, Switzerland: Nicolas Courty spent 2 months at EPFL in 2014 as invited professor. Joint works have been initiated with Harold Clenet on Planetary Hyperspectral Images Unmixing [28].

- Chinese Academy of Sciences, Institute of Automation and Institute of Remote Sensing and Applications. In the context of LIAMA (Sino-French Lab in Computer Sciences in Beijing), Thomas Corpetti is heading a research group entitled CARIOCA¹ which associates 3 chinese and 3 french researchers. During this period, one chinese PhD in co-supervision (Zheng Zhang) stayed 6 months in France. This activity is supported by CNRS and various contracts (see above).
- Universitat de Valencia, Espagne : Gustavo Camps-Valls (full Professor) is collaborating with the team on domain adaptation for time series data, in the context of a 6-month visit of Adeline Bailly (PhD student).
- Université des Iles Baléares (UIB), Espagne, with Bartomeu Coll (full Professor). We are co-supervising the PhD of Jamila Mifdal on image fusion.

6.2 National Collaborations

- DTIS team from ONERA, through a collaboration (PhD cosupervision of Nicolas Audebert [14, 12, 13]) with Bertrand Le Saux (CR ONERA)
- LINKMEDIA team from INRIA/IRISA, through a collaboration (PhD cosupervision of Petra Bosilj [2, 3] and of Mathieu Laroze) with Ewa Kijak (MCF U. Rennes 1)
- Geosciences Rennes, through a collaboration (PhD cosupervision of Arthur Le Guennec) with Dimitri Lague (DR CNRS)
- Grenoble INP, GIPSA, through a collaboration with Mauro Dalla (MCF Grenoble INP) Mura [1]
- University of Grenoble-Alpes, CEA (iRTSV/BGE), INSERM (U1038), CNRS (FR3425) through a collaboration with Thomas Burger (CR CNRS)
- University of Nice / Observatoire de la côte d'Azur: collaboration with Rémi Flamary [21, 29, 16]
- Agrocampus Ouest and IRMAR, Rennes, through a scientific collaboration with David Causeur (Prof. in Statistics) and Emeline Perthame (PhD candidate, Statistics) [22]

¹Climate and lAnd cover InteractiOns with Complex datA, <http://liama.ia.ac.cn/research/liama-projects/>

7 Dissemination

7.1 Scientific Responsibilities and Involvement in the Scientific Community

- Sébastien Lefèvre serves as the deputy head of the doctoral school SICMA (head for UBS). He leads the team project OBELIX. He is Member of the Scientific Council of the Natural Regional Park of the Gulf of Morbihan since 2016. He is co-chair of the international conference GEOBIA 2016 (Enschede, The Netherlands). He is a member of various program committee for international (VISAPP, ICISP) and national (EGC) conferences and serves as regular reviewer in international journals (Remote Sensing, ACM Computing Reviews) and conferences (ICASSP, ICIP, IGARSS, EUSIPCO). He was reviewer for 4 doctoral theses (Viktor Slavkovikj, Univ. Gent, Belgium; Gabriele Cavallaro, Univ. Iceland, Iceland; Andrès Troya-Galvis, Univ. Strasbourg; Joris Corvo, Univ. Paris Sciences et Lettres / Mines ParisTech) and chair for 1 PhD defense committee (Joris Corvo, Univ. Paris Sciences et Lettres / Mines ParisTech). He was member of 3 PhD committees (R. Lguensat, B. Gunadharma Gautama, and T.K. Nguyen, Telecom Bretagne). He is the scientific supervisor of Antoine Masse (postdoc CNES). He serves as an expert for French Ministry of Research (CIR/JEI). He was chair of a Recruitment Committee in Psychology (IUT Vannes). He is a member of the International Board and an invited member of the Scientific Board of UBS. He was an invited speaker at University of Ghent (Belgium).
- Thomas Corpetti is animating the CARIOCA action in LIAMA, Beijing (see above for details). In Rennes, he is in charge of the image analysis platform of OSUR (Observatory for Universe Sciences of Rennes) which aims at proposing the access, either inside OSUR or to the entire research community, to the computer vision techniques developed in the various groups of OSUR (and in particular OBELIX). In this context, he has led the answer to the CPER call related to the “numerical tools for environment” axis where a larger platform, entitled LOVE (french acronym for “Virtual Observatory for Environment”), will be developed and will embed analysis, modelisation and visualization tools. For this activity, he is a member of the direction team of OSUR. He is a regular reviewer of IEEE (Image Processing, Geosciences and Remote Sensing, Selected Topics in Applied Earth Observations and Remote Sensing) and other related journals (Remote Sensing for Environment, Experiments in Fluid, Journal of Mathematical Imaging and Vision). He has been reviewer of IEEE ICIP (International Conference on Image Processing) and co-organized two scientific animations days with approx. 50 people per day (Processing tools for earth observation and UAV for earth observation).
- Nicolas Courty co-leads the team project OBELIX. He served as regular reviewer in international journals (Expert Systems with Applications, Journal of Image and Vision, IEEE JSTAR, ISPRS PHOTO, Springer Machine Learning, GRSL, Remote Sensing) and conferences (IGARSS, NIPS, ECML/PKDD). In 2016, he is the recipient of the U.V. Helava Award, an international prize given by ISPRS (International Society for Photogrammetry and Remote Sensing) every 4 years to a selected publication in the ISPRS journal. He is one of the organizer of Statlearn’16 workshop.

- Romain Tavenard serves as reviewer in international journals (IEEE Transactions on Geoscience and Remote Sensing, Springer Knowledge And Information Systems) and conferences (IJCAI, NIPS). He has served as an expert for the evaluation of one project for Agence Nationale de la Recherche.
- Chloé Friguet: Chair program and organising committees of Statlearn'16 conference, Vannes.
- Laetitia Chapel serves as a regular reviewer in international conferences (NIPS, AISTAT, IGARSS). She is part of the program and organising committee of Statlearn'16 conference.
- François Merciol serves as reviewer in international conferences (IGARSS, ESWA, IEE SPL).

7.2 Software

- François Merciol
 - FramesStudio a Java free software to build hierarchical representation of remote sensing image <http://frames-studio.parlenet.org>.
 - TRISKELE stands for Tree Representations of Images for Scalable Knowledge Extraction and Learning for Earth observation. <https://gitlab.inria.fr/obelix/triskele/> (CeCILL-B licence)
 - Broceliande aims to use TRISKELE and Random Forest for classification. <https://gitlab.inria.fr/obelix/broceliande/> (CeCILL-B licence)

7.3 Teaching

- Laetitia Chapel teaches statistics and computer science at the statistical department of IUT Vannes.
- Chloé Friguet teaches statistics at the statistical department of IUT Vannes.
- Thomas Corpetti has taught 24h in Machine Learning in ENS Rennes (2016) and 20h in GIS and Image processing (ArcGis 10 / Python), Univ. Rennes II, in 2016.
- Luc Courtrai teaches various computer science courses at Licence and Master level.
- Nicolas Courty teaches computer graphics and multimedia coding in the second year of the Master Web, Image and Networks of UFR SSI.
- Sébastien Lefèvre teaches programming, software engineering, digital imaging and big data at the computer science department of IUT Vannes. He is in charge of the 1st year coding projects and the 2nd year final projects.
- François Merciol teaches system and network administration and programming at the computer science department of IUT Vannes.

- Romain Tavenard teaches programming, data mining, databases and the basics of computer science at Univ. Rennes 2, where he is deputy director of the statistics department.

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Miscellaneous

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