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River morphology monitoring using multitemporal SAR data: preliminary results

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Abstract

In this paper, we test the capability of satellite synthetic aperture radar (SAR) images to enhance the monitoring of river geomorphological processes. The proposed approach exploits the recently introduced Level-1α products. These products are bi-temporal RGB composites in which the association color-object, being physical-based, is stable whatever the scene is considered. This favors the detection of temporary rivers' characteristics for classification purposes in a change-detection environment. The case study was implemented on the Orco river (northwest Italy), where a set of 39 COSMO-SkyMed SAR stripmap images acquired from October 2008 to November 2014 was used to monitor channel planform changes. This preliminary study is devoted to assess the suitability of Level-1α images for geomorphologist, with particular reference to the detection of phenomena of interest in river monitoring. This is prior for semi-automatic or automatic classification activities.

Keywords: Time-series analysis, river morphology, SAR, RGB representation, river remote sensing.

Introduction

As stated in the European Union Water Framework Directive (EU WFD, 2000/60/EC), the evaluation of rivers' morphological quality is one of the essential issue to define the alteration level, and for implementing management strategies involving also hazards related to fluvial processes and channel dynamics.

Concerning large-scale effects, river morphology is driven by low and high water flows over time. As for medium and fine scales, large woody debris [Abbe and Montgomery, 1996; Piegay and Gurnell, 1997; Gurnell and Sweet, 1998; Curran and Wohl, 2003] and riverbed morphology [Bergey, 2006], are driver forces to be considered. These factors influence river biota, functionality, and riverscapes [Galante et al., 2010].

The monitoring of the above-cited aspects is usually carried out by field surveys (such as ground measurements and observations, see [Raven et al., 1997; Belletti et al., 2015] for details). They represent a fundamental and irreplaceable activity in river morphology studies, but require expensive campaigns supported, where available, by manual interpretation of aerial imagery [Rinaldi et al., 2013]. Moreover, field surveys are often based on subjective opinions of an expert operator. Therefore, their operative implementation is limited to an exiguous number of rivers and not extended to the entire river network scale, as it should be for monitoring purposes.

An effective monitoring demands an objective and repeatable assessment method, applicable on large scale. To this end, the exploitation of innovative monitoring techniques able to improve the knowledge about river processes and allowing repeatable characterization methods is extremely needed to face the challenge of a better river management.

In the last decades, advances in remote sensing techniques are deeply contributing in analyzing water resources and in particular river systems. The growing need for data to explore the full range of spatial and temporal variations in river systems and the new technologies, enabling for lower cost data acquisition, processing and analysis at different scales, led to an increasing interest about fluvial remote sensing [Marcus and Fonstad, 2010; Carbonneau and Piégay, 2012].

Remotely sensed data allow for the quantitative estimation of hydro-morphological indices at multiple spatial scales. Lane [2000] proposed a review of the ways in which fluvial geomorphologists make use of digital photogrammetry to determine Digital Elevation Models (DEMs) or specific attributes of river channels, such as channel banks, exposed gravel-bar surfaces or cross-sections. Marcus and Fonstad [2008] highlighted strengths and weaknesses of optical remote mapping of rivers at high resolution and watershed extents. Surian et al. [2009] used aerial photographs to assess morphological effects of different discharges in a gravel-bed river. Some other authors employed passive optical sensors [Bertoldi et al., 2010; Lane et al., 2010], hyperspectral [Fonstad, 2012], or multispectral images [Bertoldi et al., 2011a] to detect channel morphological changes and analyze the dynamic of riparian vegetation. LiDAR (Light Detection And Ranging) was also used in combination with aerial photographs to observe the impact of riparian vegetation on channel forms [Bertoldi et al., 2011b], and in combination with high resolution multispectral images [Demarchi et al., 2016] to map the riverscape units.

These techniques are very powerful tools in understanding river processes. However, some problems may arise using them. As an example, the use of passive sensors is not effective in case of cloud coverage. LIDAR surveys are still too expensive to allow river managers for monitoring river processes over time with the necessary sampling frequency and ground coverage.

The use of synthetic aperture radar (SAR) data can be a solution to these limitations. In fact, SAR sensors are independent from weather and illumination conditions, being active and working at microwave frequencies [Franceschetti and Lanari, 1999]. Moreover, they can cover large areas with short revisit time.

On the other hand, SAR data are very complex to be understood without a strong background in electromagnetics. Often, fluvial geomorphologist and, more in general, river managers do not have the expertise to handle them properly. However, SAR data have been successfully employed for water resources management and hydrologic applications, as explained, as an example, in Amitrano et al. [2014], Zhang et al. [2016], and Liebe et al. [2009].

In this paper, we present an innovative methodology in which SAR data are used, for the first time, for the monitoring of large-scale morphological effects on rivers driven by low and peak discharges. The proposed approach exploits Level-1α images introduced in Amitrano et

al. [2015], whose principal characteristics are the interpretability (thanks to an user-oriented RGB displaying of information), and the possibility to be processed with simple information extraction tools, i.e. those usually implemented in the major commercial/open source software suites. This way, the required expertise to handle SAR data is lowered, allowing for their exploitation in applications even by multidisciplinary users [Amitrano et al., 2016].
The case study is implemented in Northwest Italy through the monitoring of the Orco river. The Orco river has shown in the past to be prone to fast changes in its form and, for this reason, fits very well with the short temporal scale of the availability of high resolution SAR data.

Case study: the Orco river

The Orco river is a large Italian stream located in Piemonte region in northwest Italy (Fig. 1). It originates on Gran Paradiso mountain at 3865 m above sea level, and Its length is approximately 80 km from the head to the confluence with the Po river. The Orco river drainage basin area is about 900 km2, and contains an important hydroelectric complex, consisting of five hydropower dams. Its hydrology is characterized by a relatively high perennial discharge, ranging from 13 m3/s in February to 45 m3/s in June.

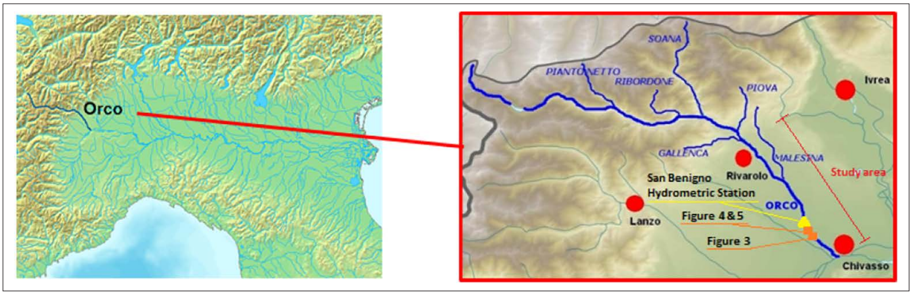

Figure 1 - Chorography of the area. Modified from Wikipedia.

In the upstream part of the catchment, the Orco river is an alpine, gravel-bed, high-energy river with a single-thread, sinuous channel (meandering). Downstream, approximately 40 km before joining the Po River, the channel begins to wander and becomes multi-threaded with vegetated and un-vegetated sediment bars.
The river experienced severe riverbed incision during the 20th century, particularly in its downstream reaches due to gravel mining activities, dam construction and land use changes that occurred in the basin. Therefore, the wandering multi-threaded river stretch was transformed into a single-thread, sinuous configuration. This progressive simplification of the fluvial pattern resulted in the abandonment of secondary channels, the joining of islands into the surrounding floodplain, and a significant deepening of the riverbed (1-2 m on average and a local maximum of 3.5 m). After gravel mining, activities have been regulated and limited this phase of riverbed incision has decreased. In 1993 and 2000, severe floods occurred and significantly modified the channel geometry, bringing the river back to its wandering pattern [Pellegrini et al., 2008]. In this study, we focused on the downstream wandering part of the Orco river, about 35 km upstream the junction with Po River (Fig. 1).

Methodology

The case study was implemented using a set of 39 COSMO-SkyMed SAR stripmap images with three meters spatial resolution. The images were provided by the Italian Space Agency at free of charge under the aegis of the project ASI COSMO-SkyMed OPEN CALL for SCIENCE "Use of high resolution SAR images for monitoring river morphodynamics". All the data were acquired with a look angle of about 30° and HH polarization in order to enhance the land-water contrast.

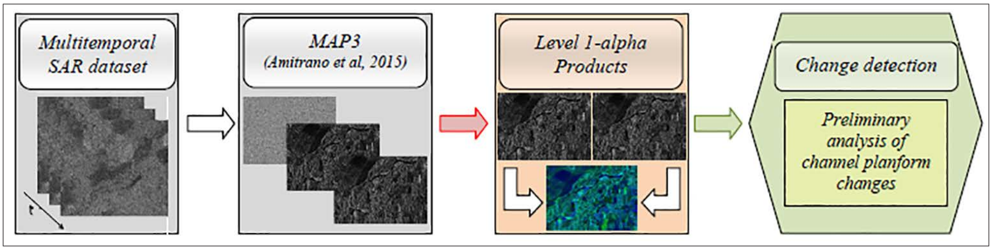

Figure 2 - Block diagram of the proposed workflow.

Figure 3 - Orco River, COSMO-SkyMed Level-1α product. Blue band: 23 May 2010 (before peak discharge of 16 June 2010, 651 m3/s); Green band: 24 June 2010 (after peak discharge); Red band: interferometric coherence.

In Figure 2, the block diagram of the proposed workflow is shown. As first, the MAP3 framework has been implemented using the available multitemporal stack (see Amitrano et al. [2015] for details). It allows for obtaining the Level-1α products exploited for the case study. These products, are bi-temporal RGB composites, which, enhancing data understanding through a physical-based association color-object, allows for an easier management of classification applications in a change-detection environment (see Amitrano et al. [2015] for details).

In Figure 3, we show one of the Level-1α product obtained by processing the Orco river dataset. According to their rationale stated in Amitrano et al. [2015], on the blue band ("reference image") a reference situation for the current application is loaded. On the green band ("test image"), the image in which the analyst wants to evaluate changes is placed. Finally, the red band is reserved to the interferometric coherence. In particular, we used an image acquired on the 23 May 2010 as reference image, and an image acquired on the 24 June 2010 as test image.

For the ease of the reader, the physical interpretation of the colors displayed in a standard Level-1α products are here briefly recalled (see Amitrano et al. [2015] for details):

- Blue color indicates a strong dominance of the electromagnetic response of the reference image. When dealing with rivers, blue areas has to be interpreted as regions covered by water only during the test image. In fact, at microwave frequencies, the water acts as a reflector, determining a decrease of the response of the backscattered energy;
- Black color indicates that the response is low in both the intensity images. Dealing with rivers, this testifies the presence of persistent surface water;
- In general, the balance between the two intensity channels means that no changes have occurred between the two acquisitions. Hence, this characteristic is proper of stable features. The intensity level at which the two channels are balanced identifies different objects. As an example, a balance at medium intensity level of the two primary colors indicates grasslands. The balance at low levels of green and blue indicates bare soil;
- Tonalities of green color indicate low vegetation and crops when observed on land. When dealing with river, pure green has to be interpreted as surface water present only during the acquisition of the reference image;
- Bright targets identify buildings due to the high contribution of both coherence and intensity channels. However, in this application, dealing with natural (and changing) objects, the interferometric coherence contribution is not of interest.

Coming back to Figure 3, the last step of the proposed workflow is the preliminary analysis of channel planform changes detected through the RGB images. In this preliminary phase, we propose a qualitative analysis of the landscape performed through the analysis of the RGB composition colors, which is preparatory for supervised classification activities [Amitrano et al., 2016].

Experimental results

We applied the proposed framework to a set of COSMO-SkyMed images acquired over the Orco River between October 2008 and November 2014.

The implementation of the case study was performed with the aid of freely available hydrological data from the Regional Environmental Protection Agency of Piedmont region (ARPA Piemonte). The historical series of discharges recorded at the San Benigno Orco hydrometric station were used (yellow triangle in Fig. 1). It has been reported in Figure 4, which shows the hydrograph (light blue line) recorded during the year 2010. A relevant peak flow discharge of 651 m^3/s recorded on 16 June 2010 (the highest recorded in the

2008-2014 period). The red lines on this picture concern the discharge in correspondence with the acquisition of some SAR images which will be used to assess the river state (see below).

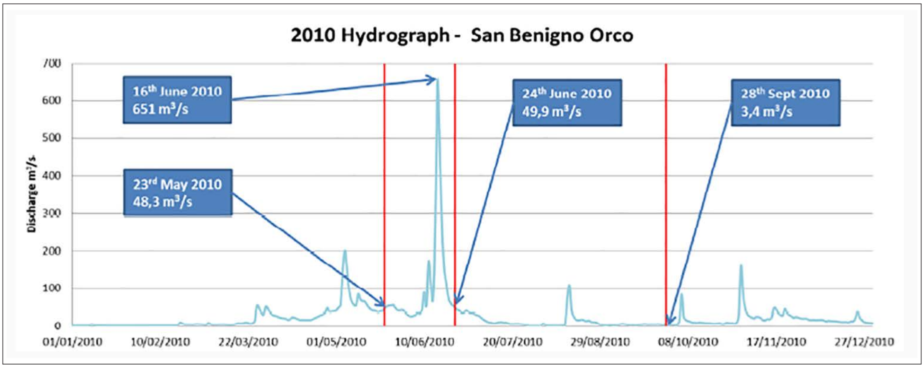

Figure 4 - Hydrograph recorded at San Benigno Orco hydrometric station in the year 2010. The red lines indicate the discharge flow corresponding with the SAR acquisitions exploited for the evaluation of changes in the river planform (see Fig. 5 and Fig. 6).

The framework depicted in Figure 2 was applied to the whole available dataset, so that 38 Level-1α products were obtained from the 39 SLC SAR images. The choice of the most significant Level-1α products for this application was made looking at the historical series of discharges, in order to allow for the observation of the river in both low and peak flow conditions.

The product shown in Figures 5 involves three images acquired on the 23 May 2010 (reference image, blue band, in Fig. 5), on 24 June 2010 (test image, green band, in Fig. 5). The corresponding discharges are reported in the hydrograph of Figure 4 (see red lines). In particular, referring to the most relevant event, i.e. the peak flow discharge occurred on 16 June 2016, it arises that the images acquired on 23 May and 24 June represent a pre-event image (reference image) and a post-event image (test image).

The analysis of changes in the landscape (according to the Level-1α products rationale) made it possible to highlight at least three planform changes in the river segment.

In the circle marked with the letter A (see annotations on Fig. 5), the river exhibits an increased sinuosity of the channel. In fact, the new path of the channel represented by blue pixels (significantly lower electromagnetic response in test image than in reference one: new water surface) curves more than the old one represented by green pixels (significantly higher electromagnetic response in test image than in reference one: no more water on this surface) that follow a more straight path. Moreover, an increased width of the channel is registered, even if the discharge was almost the same in both the dates. The circle B points out two threads of the river (black and blue pixels) converging in a point more upstream in the test image than in the reference image (green pixels). In the circle C, the channel changes radically its path cutting the meander. Probably, this is due to a flood event that created a straight path in alternative to the old bent one, which remain active in the test image, as testified by black pixels.

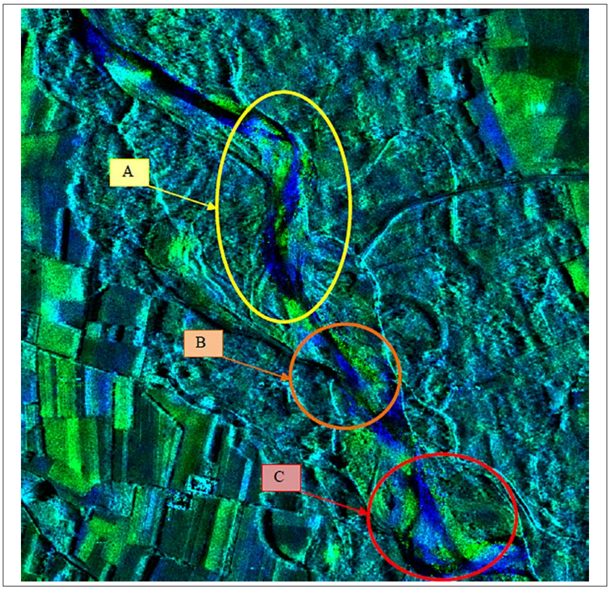

Figure 5 - Orco River, COSMO-SkyMed Level 1α product. Blue band: 23 May 2010 (before peak discharge of 16 June 2010, 651 m^3/s); Green band: 24 June 2010 (after peak discharge); Red band: interferometric coherence. Circles marked with the letters A, B and C highlight planform changes.

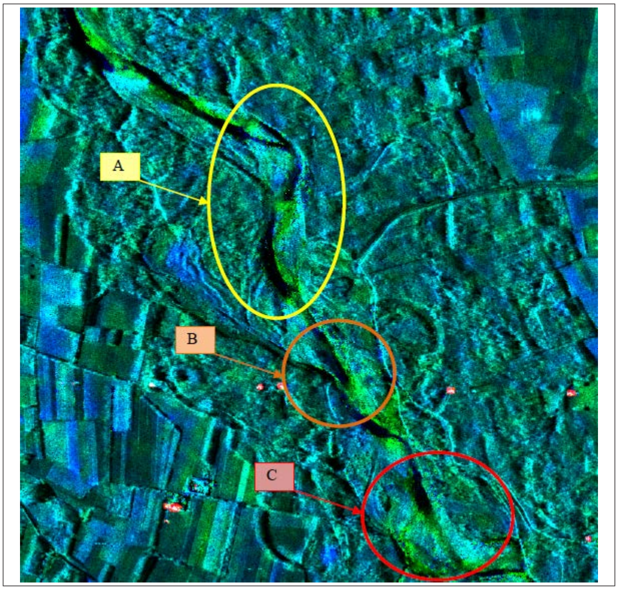

Figure 6 - Orco River, COSMO-SkyMed Level-1α product. Blue band: 24 June 2010 (reference image); Green band: 28 September 2010 (test image, low flow discharge); Red band: interferometric coherence. Circles marked with the letters A, B and C highlight planform changes.

The analysis of the river state was repeated using another Level-1α product (see Fig. 6). In this case, the reference image (blue band) and the test image (green band) were acquired, respectively, on 24 June and 28 September 2010 (the correspondent discharges are reported in the hydrograph of Fig. 4). In this representation, the overall path of the observed river segment remain the same, but with a decreased width of the channel as testified by green pixels beside black ones. This decrease of width is probably due to the significantly lower discharge in the date of the test image acquisition.

Conclusions

In this paper, we presented an innovative methodology that for the first time uses satellite SAR data for river morphology monitoring. Level-1α products were exploited to improve users' awareness about SAR data interpretation. In particular, they made it possible the detection of discharge-driven river planform changes by using colors, which represent a simple tool for understanding complex electromagnetic scattering mechanisms. The case study was implemented exploiting a dataset acquired on the Orco river (northern Italy), and the obtained results are encouraging for a further development of the proposed methodology. In fact, this work represents a first step in the study of the potential use of SAR in monitoring river morphology. Further research will concern the automatic extraction of water surface masks, the measurement of morphometric parameters of rivers, and, consequently, the classification of fluvial morphological units. Tracking planform changes over time in response to flood events, vegetation growth and transport of large woody debris and sediments could represent an important step forward in the assessment of river morphological dynamics and its influence on biodiversity. Since SAR data can guarantee an almost continuously observation in every weather and light condition, they could become soon an important tool for river managers and river scientists.

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