Spaceborne radar interferometry: a promising tool for hydrological analysis in mountain alluvial fan environments

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Abstract Morphometric attributes derived from digital terrain models are frequently substituted for hydrological parameters in ungauged basins. In many cases, however, the reliability of such derived data is severely hampered, both by errors inherent in the original data, due to map scale and map age, and by errors derived from interpolation and computation procedures. This is especially true in the case of alpine basins, where sedimentation and flooding typically occur in populated downstream regions on alluvial fans. Data obtained by interferometric SAR (InSAR) techniques can be successfully substituted for DTM-derived data, allowing the direct computation of fundamental, secondary DTM attributes such as slope and aspect. A set of ERS 1/2 SAR images of the Cellina alluvial fan in northeastern Italy has been acquired and interferometrically processed. Experimental results show that, compared to traditional DTM-based measures, SAR-based attributes appear to be more stable and should offer better characterization of the slope surfaces. Furthermore, the present availability of such images allows fast and inexpensive updating of local hydrological characteristics of an area after major flooding events.

Key words alluvial fans; Eastern Italian Alps; Italy; mountain streams; Northern Apennines; radar interferometry; sediment transfer

INTRODUCTION

Among the global environments subjected to hydrological and geological disasters, the areas in which relatively young mountain ranges deposit water and sediment occupy an important place. Along these boundaries, mountain drainage systems usually enter the wide alluvial plain of a major river as gravel-bed braided streams, giving rise to large alluvial fans that are often coalescent and that represent the result of the loss of stream power due to the sudden decrease in gradient. There is general agreement about the processes dominating fan environments (Harvey, 1988). In particular, alluvial fans in Alpine areas are thought of as the result of a succession of glacial cycles (Weissman *et al.*, 2002). Such areas are strongly controlled by episodes of fluvial erosion on the fan, alternating with episodes of high rates of erosion in the source basin, with the consequent increase of sediment discharge to the fan. It is well understood that in the last 1000 years the principal causes of such changes have been human-induced climate change and human activities such as water control structures, draining of wetlands in the lower valleys and streambed quarrying (Guzzetti *et al.*, 1997; Spaliviero, 2002).

For this reason, the factors controlling the present dynamics of large Alpine alluvial fans are complex, and include source basin sediment production and delivery as well as the morphometric and geomorphological characteristics of the fan. In such areas, predicting the recurrence and intensity of floods, as well as assessing the potential sediment delivery, is very difficult, since they depend not only on the hydro-geomorphological settings of the source basins but also on those of the alluvial fans. This is even more problematic in areas where anthropogenic influences are particularly intense and in river basins that are poorly gauged or ungauged. In such cases, the remotely sensed measurement of morphometric parameters that are linked to the hydrological behaviour of the drainage system, such as relief, gradient, curvature and stream power (Strahler, 1952; Hack, 1973; Schumm *et al.*, 1987; Oguchi & Ohmori, 1994), can be obtained faster and cheaper than direct measurements of fluvial discharge and transport monitoring. InSAR has demonstrated its potential usefulness by generating Digital Terrain Models (DTMs) (Rosen *et al.*, 2000) and estimating the ground displacement induced by phenomena such as earthquakes, volcanic activity, land subsidence and landslides (Massonnet & Feigl, 1998). Few attempts have been made, however, to use this technique in geomorphometry (Wegmüller *et al.*, 1994). This paper focuses on the possible applications of spaceborne radar interferometry and differential interferometry (DInSAR) to hydrological and geomorphological studies in areas characterized by short-term sediment transfer processes such as the piedmont alluvial fans of Alpine chains. In particular, the alluvial fan of the Cellina River, located in northeastern Italy, has been chosen as a test area, and satellite radar data have been used as a source for the direct measurement of morphometrical parameters.

METHODOLOGY

The importance of morphometric parameters in mountain-basin hydrology is well established; first, because of the significance of these physically based parameters as controls of hydrological processes (Kirkby, 1971); and second, because they represent measurable quantities. Using morphometric proxies for hydrological quantities becomes of paramount importance when studying ungauged basins, for which no flow or sediment data are available. In such cases, fundamental proxy variables are usually derived from DTMs or topographic maps at a suitable scale. Unfortunately, the derivability from a simple, widely available topographic map or DTM also constitutes a weakness. In fact, errors in elevation quickly propagate when deriving secondary attributes, especially the first and second derivatives of elevation, resulting in a strong sensitivity to errors and artefacts in the original data. There are two main causes of errors in DTMs, namely interpolations and errors in the source data (Burrough & McDonnell, 1998). Small artefacts due to interpolation, even when controlled and limited by appropriate methods such as the ANUDEM approach (Hutchinson, 1989, 1997), might amplify in first and second derivatives. This effect is often seen as terrace-like features in maps of slope and curvature generated from DTMs derived from contour lines (Burrough & McDonnell, 1998; Wilson & Gallant, 2000). The second source of errors is linked to the accuracy and reliability of the source data. If, as in the preceding example, national or regional printed topographic maps form the source data, it is very likely that some of the information is not up to date.

SAR interferometry (InSAR) is a useful technique that can be used to partially overcome such drawbacks and to obtain terrain parameters with high accuracy (Rosen *et al.*, 2000). The accuracy and limitations of interferometrically derived DTMs depends on factors such as the interferometric configuration and phase noise. Instead of computing the main terrain attributes such as slope and aspect from a DTM, it is possible to derive them directly from the fringe pattern of the complex phase of the interferometric image. Hence, all uncertainties related to interferometric processing can be avoided, in particular because of the solution of the phase unwrapping problem (Rosen *et al.*, 2000). Another contribution of SAR interferometry to hydrological studies is related to the study of fluvial dynamics of gravel-bed braided rivers. This study shows that morphological changes within gravel-bed rivers caused by erosion and sedimentation activity can be estimated.

STUDY AREA

The Cellina River is located in the northeastern Italian Alps, a few kilometres west of the Tagliamento River (Fig. 1). The river basin is characterized by mountainous headwaters and a large alluvial fan that is built out onto the Tagliamento plain and is coalescent with the Meduna alluvial fan to the east. The drainage area of the mountain headwaters is approximately 465 km^2, and the alluvial fan covers an area of about 190 km^2. These general morphometric features characterize the Cellina fan as a typical Italian Alpine alluvial fan (Fig. 2), based on data from Guzzetti *et al*. (1997). Elevations range between 350 and 2600 m a.s.l. in the source basin and between 91 and 640 m a.s.l. on the alluvial fan. The fan extends for about 17 km in the northwest to

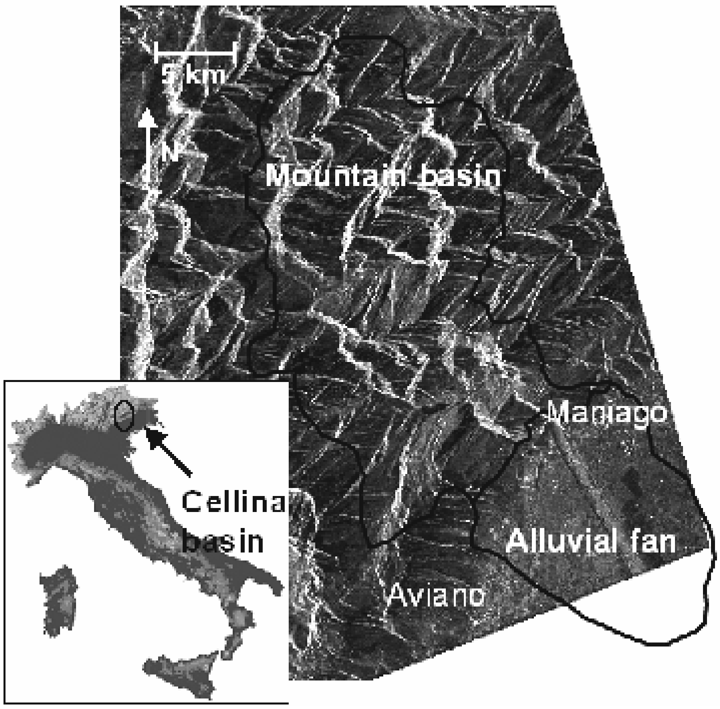

Fig. 1 Location of the study area.

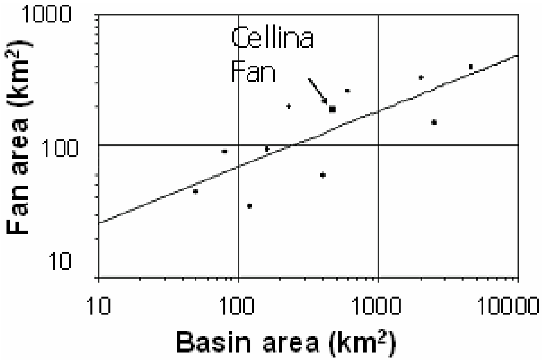

Fig. 2 Classification of Italian Alpine alluvial fan (after Guzzetti *et al.*, 1997).

southeast direction onto the Tagliamento plain. The geological and geomorphological settings of this river are common to the majority of Alpine streams entering the Padana Plain and surrounding areas. Three prevailing types of bedrock outcrop within the source basin: (a) massive, Triassic to Liassic dolomitic limestones; (b) Cretaceous calcareous formations; and (c) red Eocene shales, sandstones and marls. The main fan is made up of a complex juxtaposition of sediments derived from the aforementioned parent materials (Guzzetti *et al.*, 1997; Weissman *et al.*, 2002). The region has undergone important man-made modifications, among which is the establishment of several settlements and the development of significant stream control facilities. The climate is characterized by the abrupt change between the high mountain environments of the source basin, where the average annual rainfall is about 1800 mm, and the alluvial fan area, which exhibits average annual rainfalls between 1200 mm near the mountain range and 900 mm at the fan toe.

DATA ANALYSIS AND DISCUSSION OF RESULTS

Derivation of terrain attributes from InSAR images

As a first step, the fringe pattern is transformed, from the range/azimuth coordinate system typical of SAR images, to the ground range and azimuth coordinates, where the ground range coordinates are obtained by projecting the range coordinates on a horizontal plane (Fig. 3). It is worth noting that the azimuth direction *az* is along the satellite flight track, whereas the ground range *gr* direction is perpendicular to the track. The topographic gradients along these two directions, namely d*z*/d*gr* and d*z*/d*az*, are computed as:

$$\begin{bmatrix} \mathrm{d}z/\mathrm{d}gr \\ \mathrm{d}z/\mathrm{d}az \end{bmatrix} = \begin{bmatrix} -\cot\vartheta \\ 0 \end{bmatrix} + R_1 \frac{\lambda}{4\pi B} \{\sin\alpha + \cos\alpha\tan(\vartheta - \alpha)\} \cdot \begin{bmatrix} \mathrm{d}f/\mathrm{d}gr \\ \mathrm{d}f/\mathrm{d}az \end{bmatrix}$$

where d*z*/d*gr* and d*z*/d*az* are estimates of the absolute phase gradients along the ground range and azimuth directions, respectively, measured directly on the interferogram. Starting from these estimates of topographic gradients, the morphometric analysis is

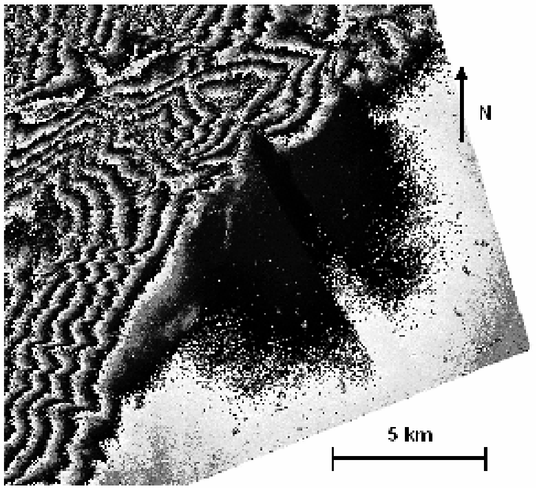

Fig. 3 Georeferenced interferogram of the study area obtained from two ERS 1/2 SAR images. The alluvial fan shape can be recognized in the fringe pattern.

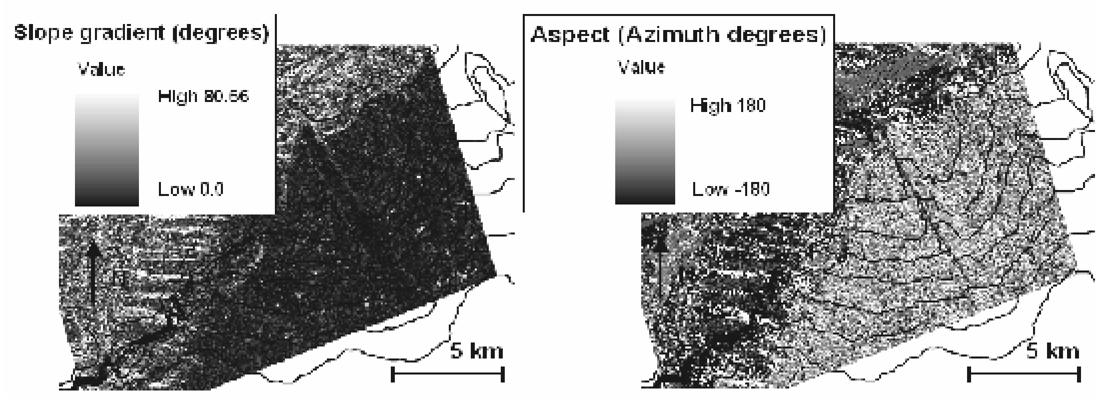

Fig. 4 SAR-derived slope and aspect of the alluvial fan.

performed following the classical approach. For instance, the slope *sl* and aspect *as* (Fig. 4) are computed as:

$$sl = \sqrt{1 + \left({}^{\mathrm{d}f}\!/_{\mathrm{d}gr} \right)^2 + \left({}^{\mathrm{d}f}\!/_{\mathrm{d}az} \right)^2}$$

and

$$as = -\left({}^{\mathrm{d}f}\!/_{\mathrm{d}gr} \right) \cdot \left({}^{\mathrm{d}f}\!/_{\mathrm{d}az} \right)^{-1}.$$

Comparison with attributes derived from contour lines

The main statistical parameters derived from elevation were computed for the entire basin based on a relatively low-resolution DTM of the area with a cell size of 100 m

Table 1 Main parameters derived from the Cellina basin DTM.

	Elevation (m) Mean	Dispersion	Median	Relief (*H*)	Melton's ruggedness number	*H*/*L* ratio
Mountain basin	1248	466	1240	2250	0.104	0.077
Alluvial fan	219	75	213	299	0.022	0.013
Entire basin	951	611	930	2509	0.098	0.053

Table 2 Comparison between DTM and SAR-derived terrain attributes for the mountain and alluvial fan portions of the Cellina Basin.

Slope (degrees)	Mean	Standard deviation	Min.	Max.
Mountain basin DTM slope	20.09	10.77	0	53.37
Mountain basin SAR slope	24.04	12.62	0.355	54.96
Alluvial fan DTM slope	2.13	3.12	0	24.95
Alluvial fan SAR slope	10.35	8.25	0.16	52.44

(Table 1). The parameters are: mean and median elevation, dispersion (standard deviation) of elevation, relief, a relief index represented here by Melton's ruggedness number (Melton, 1965), which is the ratio between relief and the square root of drainage area, as suggested by Guzzetti *et al.* (1997) for alpine fans, and the relief/length (H/L) ratio. As expected, the mountain basin shows a higher relief than

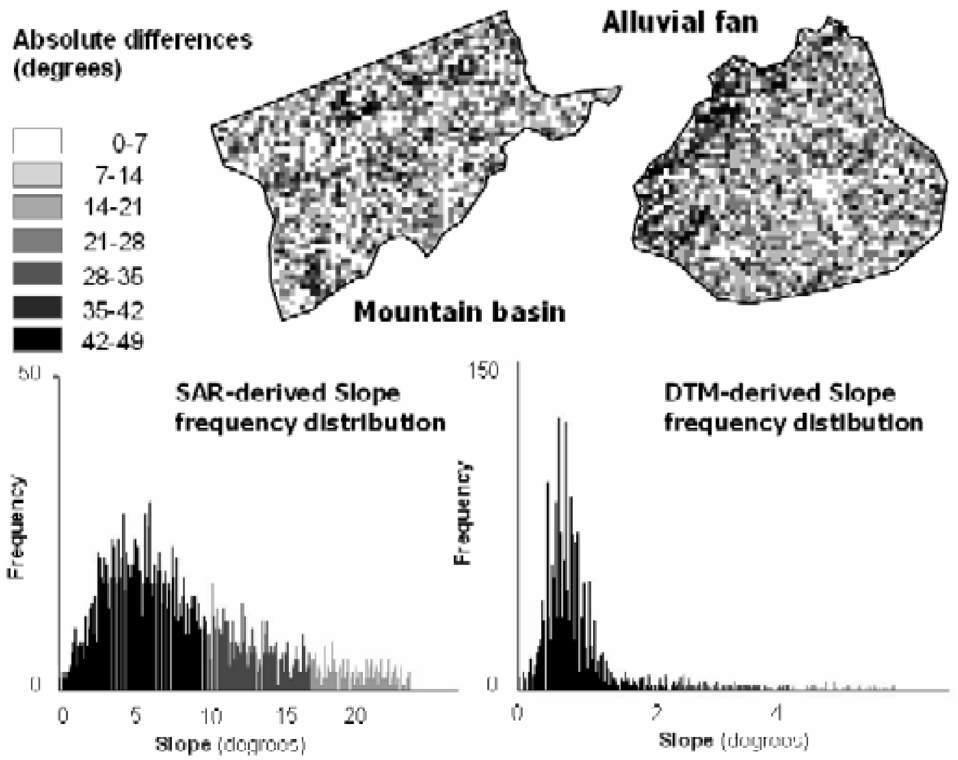

Fig. 5 Upper: Absolute differences between the DTM and SAR-derived slopes for the mountainous (left) and the alluvial fan (right) portions of the basin. Lower: Frequency distributions of the DTM and SAR-derived slopes for the entire basin.

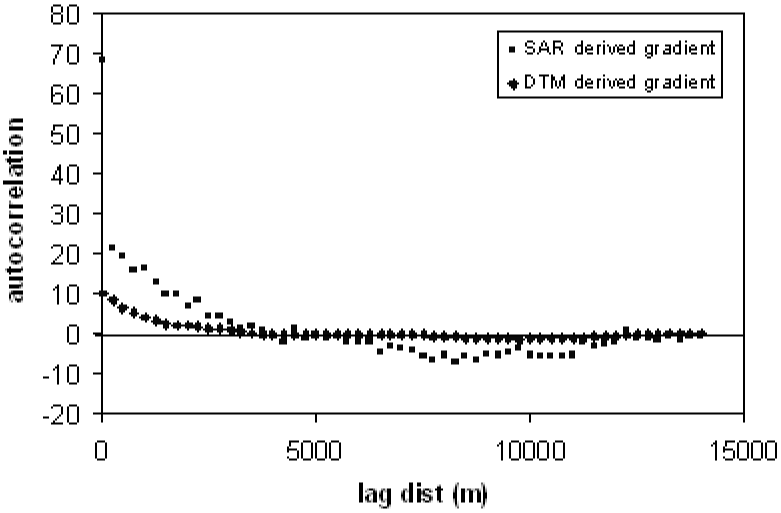

Fig. 6 Autocorrelation for SAR and DTM-derived slopes.

the fan. Ruggedness indexes and H/L ratios are within the limits known for other, similar Alpine alluvial fans (Guzzetti *et al.*, 1997). Using state-of-the-art computation techniques (Wilson & Gallant, 2000) slope, aspect and curvature maps were derived from the DTM, and the resulting data were statistically analysed (Table 2). The results of the DTM analysis indicate better performances on the mountain basin while giving very poor results on the alluvial fan, where the low resolution of the available DTM and the intense human activity contribute equally to the erroneous or insufficient rendering of many of the hydrologically-relevant topographic details. Conversely, SAR-based measures of slope are easily updated and have a better resolution. The differences between the two methods can be highlighted by comparing the slopes in the fan area. In Fig. 5, the frequency distributions of slope show a less frequent occurrence of noise and spikes in the case of the SAR-derived data. This difference is even clearer in the autocorrelation figure (Fig. 6). Even though the two autocorrelation distances are similar (about 3700 m), the SAR data are more autocorrelated over short distances than the DTM-derived data, and thus are more accurate and reliable. As a consequence, SAR-derived data can bring out important geomorphological features neglected in the DTM-derived data, such as the alluvial fan terraces clearly visible in Figs 3 and 4. Moreover, SAR-based parameters are more stable and robust and do not suffer from the errors inherent in contour line-derived DTMs.

CONCLUSIONS

The use of spaceborne radar interferometry for hydrological analysis in a piedmont alluvial fan environment has been investigated. Experiments have been carried out on the Cellina basin in northeastern Italy. Morphometric parameters were estimated by interferometric ERS-1/2 SAR data and compared, by means of statistical analysis, to morphometric information obtained from a traditional DTM. Results show that the InSAR-derived morphometric parameters appear to be more stable and robust, and do not suffer from the inherent errors affecting a contour line-derived DTM.

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