DSM extraction from IKONOS and EROS A stereo imagery: methodology, accuracy and problems

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ABSTRACT: The goal of this work was to evaluate the mean accuracy and its dependency on morphology and land cover types of the digital surface models (DSMs) extracted from IKONOS-II and EROS-A high-resolution satellite in-track stereo imagery. DSMs were generated by the software PCI Geomatica OrthoEngine v. 9.0, which implements the well-known 3D rigorous (physical) model developed at the Canada Centre for Remote Sensing, Natural Resources Canada (CCRS).
The paper illustrates the encountered problems and the achieved results during three experiments regarding two stereo IKONOS-II panchromatic images (with a small overlapping) of the Pozzuoli area (Naples, Southern Italy) and one stereo EROS-A image of the Tivoli area (Rome, Central Italy).
Ground control points (GCPs) were collected by GPS: in the Pozzuoli area 29 GCPs were rapid-static surveyed with a mean 3D accuracy of 0.2-0.3 m; in the Tivoli area 23 GCPs with a mean 3D accuracy of 0.1 m were collected by RTK survey assisted by the GPS permanent network of the Lazio Region, managed by the Area di Geodesia e Geomatica-Università di Roma "La Sapienza".
Three types of comparison were carried out when possible, in order to assess both mean accuracy and its dependency on morphology and land cover types: sample comparison, based on significant numbers of Independent Check Points (ICP) with a mean 3D accuracy of 0.3-0.5 m collected by kinematic GPS surveys; local and global comparisons with DEM generated from available maps, considering both contour lines and single points with photogrammetric derived heights; in this last respect, local comparisons were especially devoted to evaluate the accuracy dependency on morphology and land cover types (residential areas, dense forests, volcanic craters, bare soils, lakes, sea shoreline, Travertino quarries).
A mean sample accuracy (RMS) of 1.9 and 6.0 m were achieved for IKONOS-II and EROS-A respectively. It has to be underlined that mean accuracy decreases remarkably in residential areas and forests, so that it is supposed that the intrinsic accuracy is better represented by the results obtained on bare soil and lakes, where RMS of 1.9 and 5.0 m were achieved for IKONOS-II and EROS-A respectively. The poorer results for EROS-A are probably mainly due to its asynchronous acquisition mode and to the extremely critical radiometric situation occurring on Travertino quarries, which appear almost uniformly white.
Concerning the DEM/DSM classification criteria established by the Technical Steering Committee of the Italian State-Region Conference for GIS under the direction of O. Köebl, IKONOS-II derived DSMs have a quality at level 2-3, EROS-A at level 1-2.

1 INTRODUCTION

The characteristics of the IKONOS-II and EROS-A high resolution satellites and their capability to acquire in-track stereo imagery are well documented in the technical literature and in the web sites of the Companies managing the two platforms (www.spaceimaging.com, www.imagesatintl.com).
Here it is worthwhile to recall some basic information just related to DSM extraction:

- it is well known that in-track stereo imagery has the remarkable advantage to reduce radiometric image variations, (temporal changes, sun illumination, etc.) w.r.t. across-track stereo imagery, and thus increases the correlation success rate in the image matching process (Toutin, 2000), which is crucial for the automatic DSM production
- IKONOS-II is a synchronous satellite and its images are geometrically and radiometrically pre-processed and only distributed in a quasi epipolar-geometry (www.spaceimaging.com, Morgan, 2004) where just the elevation parallax in the scanner direction remains; the image orientation approximately follows the North-South direction
- EROS is an asynchronous satellite and continuously pitches backward and yaws during the image acquisition; therefore the imagery shape is remarkably distorted both as regards geometry and radiometry and the true ground pixel dimension changes remarkably within a image

DSM were generated from two stereo IKONOS-II panchromatic images of the Pozzuoli area (Naples, Southern Italy) and one stereo EROS-A image of the Tivoli area (Rome, Central Italy) by the software PCI Geomatica OrthoEngine v. 9.0, which implements the well-known 3D rigorous (physical) model developed at the Canada Center for Remote Sensing, Natural Resources Canada (CCRS) (Toutin, 2004a; Toutin 2004b). Ground control points (GCPs) were collected by GPS: for the two stereo IKONOS-II images 29 GCPs were rapid-static surveyed with mean horizontal and vertical accuracies of 0.2 and 0.3 m respectively; for the stereo EROS-A image 23 GCPs were collected by RTK survey assisted by the GPS permanent network of the Lazio Region (managed by the Area di Geodesia e Geomatica-Università di Roma “La Sapienza”) with mean horizontal and vertical accuracies of 0.1-0.2 m.

Three types of comparison were carried out when possible, in order to assess both mean accuracy and its dependency on morphology and land cover types: sample comparisons, based on significant samples of Independent Check Points (ICPs) with a mean 3D accuracy of 0.3-0.5 m collected by kinematic GPS surveys; global and local comparison with DEM generated from available maps, considering both contour lines and single points with photogrammetric derived heights; in this last respect, local comparisons were especially devoted to evaluate the accuracy dependency on morphology and land cover types (residential areas, volcanic craters, dense forests, bare soils, lakes, sea shoreline, Travertino quarries).

The extracted DSMs were classified according to the criteria established by the Technical Steering Committee of the Italian State-Region Conference for GIS under the direction of O. Köebl (Köebl, 2001), considering not only the accuracy on bare soil (which it is supposed to be the actual achievable intrinsic accuracy) but also the mean accuracy all over each DSM (Table 1).

Quality	**Accuracy (bare soil)**	**Main applications**
Level 0	10.0 m	1:10000, 1:5000 orthophotos (from satellite imagery)
Level 1	5.0 m	1:10000 orthophotos
Level 2	2.0 m	1:5000, 1:10000 orthophotos
Level 3	1.0 m	1:2000, 1:5000 orthophotos
Level 4	0.3 m	1:1000, 1:500 orthophotos
Level 5	0.15 m	1:1000, 1:500 orthophotos

Table 1 – DEM/DSM classification according to (Köebl, 2001)

In sections 2 and 3 the results obtained from the IKONOS-II and EROS-A stereo images are discussed respectively, together with the encountered problems; in section 4 some conclusions and future research prospects are outlined.

2 DSM EXTRACTION FROM IKONOS-II STEREO IMAGERY

The study site is the area of Pozzuoli, west of Naples (Southern Italy, N 40º40’, E 14º), quite famous for a remarkable bradyseism along the shoreline since the Roman Era and for several spectacular volcanic

phenomena. Both the land cover and the morphology are extremely variable, with residential areas, dense forests, bare soils, lakes, sea shoreline, large and small volcanic craters with steep slopes.
Two stereo IKONOS-II images (with a small overlapping) of Standard Stereo Products type were available for this area (Figures 1 and 4); they are referred in the following as West and East stereo image. The stereo imagery were acquired on 13/11/2000, so that they show similar illuminations. All the images were acquired at a resolution of 0.96 m but they were released at 1 m resampling (nominal resolution); the overlapping within each stereo pair is almost 100% and the covered areas approximately 13.5×19.5 km. The stereo images were processed separately then analyzed together. An investigation related to the global block adjustment of the four images was also carried out but results are preliminary and will not discuss here.

2.1 WEST STEREO IMAGE

GCPs coordinates were obtained by GPS rapid-static surveys (sampling rate: 5 sec, sessions duration: 15 min) with double frequency geodetic receivers, assisted by the two available GPS permanent stations belonging to the Italian public network closest to the area of study (LATI and TITO), located in Latina (managed by the Area di Geodesia e Geomatica-Università di Roma “La Sapienza”) and Tito (Potenza) (managed by theItalian Space Agency) respectively; it has to be noted that these stations are about 100-200 km apart. A total of 9 GCPs have been collected with mean planimetric and altimetric precision of 0.2 and 0.3 m respectively. DSMs was generated using 9 GCPs and inserting 20 Tie Points (TPs) manually to improve the automatic matching between corresponding points.

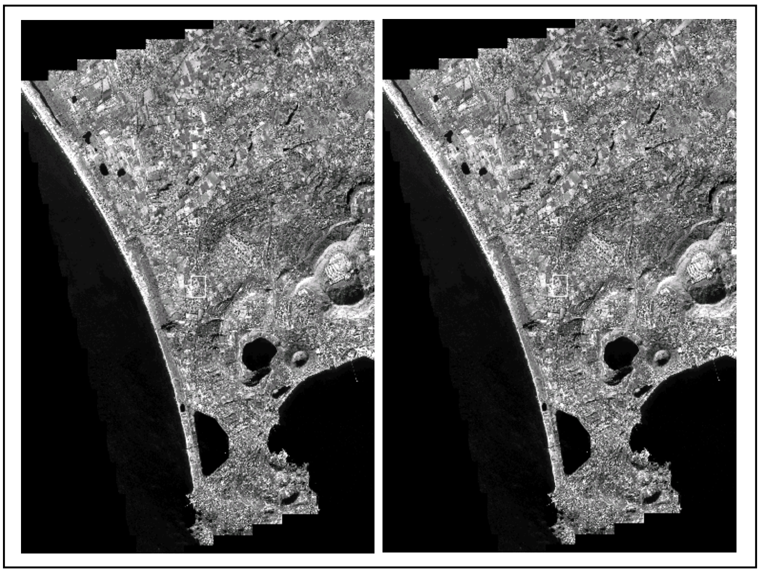

Figure 1 - West stereo IKONOS-II image

A sample DSM validation was carried out by collecting a significant number of homogenously distributed points in the whole area in a kinematic GPS survey. This was carried out (sampling rate: 1 sec, mean speed: 40-50 km/h, 1 point/10 m) some days later GCPs rapid-static surveys driving for about 90 km (Figure 2) along roads crossing zones with different features about land cover and morphology. Three GPS receivers were used, two as rover (Figure 3) and one as master station. The rover antennas (Leica System 1200 and Topcon Legacy E_GGD) were fixed on to car roof almost perpendicularly to the car longitudinal axis by magnetic supports. The distance between the two antennas was set at 0.445 m and their phase centers were 1.60 m above the road; thanks to the fixed antenna distance inner constraint, the use of a pair of rover receivers in a GPS kinematic survey is very useful to find out possible outliers. The master station was installed in an almost central position w.r.t. the surveyed area, so that its distance form the car was not greater than 20 km.

Figure 2 – GPS kinematic survey in Pozzuoli area

Figure 3 – Installation of the two rover receiver antennas on the car

DSM sample accuracy was evaluated by the difference between the DSM and the mean GPS heights (mean value of the two GPS antennas heights - 2691 points), after having applied the geoid undulation correction according to the public model of national geoid ITALGEO95 (www.iges.polimi.it); considering the mean vertcal GPS accuracy, the sample mean accuracy (RMS) of the DSM resulted 1.9 m.
It has to be underlined that the estimated accuracy does not consider some tens of point along the DSM edges, characterized by considerable distortions (up to several tens of meters), and after having eliminated some outliers through a standard rejection procedure of the normalized residual w_i (Rousseeuw and Leroy, 2003); if:

$$|w_i| = \frac{|v_i|}{\sigma_v} < 3$$

where v_i is the i-th residual, the corresponding point is accepted, otherwise it's assumed due to an outlier and the point is rejected; the procedure is iterative since σ_v depends on the accepted residuals and changes during outliers elimination.
As regards the sample validation, besides accuracy other statistical indices were considered (Table 2): they show the presence of a bias of about 1 m and a good symmetry of the residual frequency distribution.
In order to evaluate the accuracy dependency on morphology and land cover types, DSM was locally compared to a DEM (1.5 m mean vertical accuracy) generated by contour lines and single points with photogrammetric derived heights extracted from a 1:5000 numerical map; some zones of four different types were selected: bare soils and lakes (intrinsic accuracy), residential areas and volcanic craters with and without forests. The results shows that the accuracy remarkably decreases in the residential and volcanic craters areas in comparison to bare soils and lakes; in this last respect, however, significant systematic effects due to correlation problems during the images matching over lakes may occur (Table 3).
Altogether DSM intrinsic accuracy is within 1-2 m (Quality Level 2-3) whilst sample accuracy on roads is within 2-3 m (Quality Level 1-2).

Statistics	**Roads**
Sqm (m)	1.8
Average (m)	-0.6
Rms (m)	1.9
Median (m)	-0.7
S(median) (m)	1.5
Asymmetry	0.1

Table 2 – Sample comparison statistics (sample accuracy)

Statistics	**Bare Soils**	**Residential Areas**	**Lake**	**Volcanic Crater**
Sqm (m)	0.6	3.3	1.2	11.4
Average (m)	1.6	5.1	-1.5	2.5
Rms (m)	1.8	6.1	2.7	11.7
Median (m)	1.6	4.4	-1.7	-0.1
S(median) (m)	0.7	2.8	0.0	0.0
Asymmetry	0.0	0.2	0.2	0.2

Table 3 – Local comparison statistics (accuracy dependency on morphology and land cover types)

2.2 EAST STEREO IMAGE

Also for this stereo image GCPs coordinates were obtained by GPS rapid-static surveys (sampling rate: 5 sec, sessions duration: 15 min) with double frequency geodetic receivers, assisted by two public GPS permanent stations; in this case the station M0SE (managed by the Area di Geodesia e Geomatica-Università di Roma "La Sapienza"), located in Rome 150 km apart, was used instead of TITO. A total of 20 GCPs have been collected with mean planimetric and altimetric precision of 0.2 and 0.3 m respectively. DSMs were generated using 24 GCPs (4 GCPs were already used for the West stereo image processing) and inserting 20 Tie Points (TPs) manually.

A sample comparison was based on a significant number of homogenously distributed points in the whole area collected by a kinematic GPS survey in this case too. After outliers rejection and neglecting points close to DSM edges, the same statistics as for the West DSM were computed on the basis of 2123 GPS points.
The overall results are quite close (slightly better) to those obtained with the West stereo image; no accuracy increasing was obtained by employing 24 GCPs instead of 9.
It has to be underlined that unacceptable errors as large as 100 m due to correlation problems during the images matching were found in zone with fast height variations (volcanic crates steep slopes), responsible for completely different illuminations of the same details on the two images.

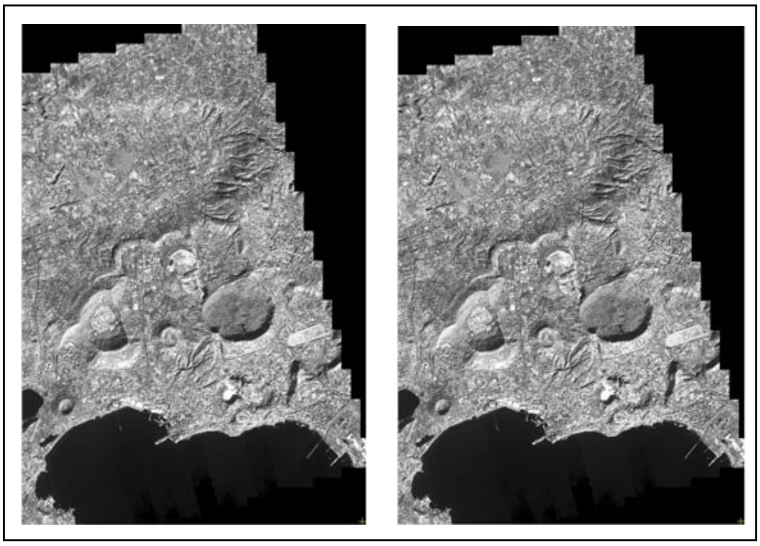

Figure 4 - East stereo IKONOS-II image

These errors may be remarkably mitigated manually inserting several TPs (some tens) in these critical areas. Moreover, a global comparison with the DEM generated by the elevation data extracted from the 1:5000 map sharply evidenced the residential areas, suggesting a possible application of IKONOS-II DSMs to monitor the urban volumes at least at the Quality Level 2-3, representative of the intrinsic accuracy.

Statistics	Roads
Sqm (m)	1.6
Average (m)	0.9
Rms (m)	1.8
Median (m)	0.8
S(median) (m)	1.3
Asymmetry	0.1

Table 4 – Sample comparison statistics (sample accuracy)

Statistics	Bare Soils	Residential Areas	Volcanic Crater
Sqm (m)	1.0	5.4	4.3
Average (m)	0.8	8.2	2.7
Rms (m)	1.4	9.9	5.0
Median (m)	0.8	8.1	1.8
S(median) (m)	0.8	4.6	0.0
Asymmetry	0.0	0.0	0.2

Table 5 – Local comparison statistics (accuracy dependency on morphology and land cover types)

The values related to the sample comparisons are in intermediate position among those related to the bare soil and the mean global situation (accuracy 5.9 m); this does not have to surprise, since, even if roads are smooth and well defined surfaces, their vertical reconstruction accuracy may suffer for the complex morphology of the zones they cross (e.g. residential areas and volcanic craters).

3 DSM EXTRACTION FROM EROS-A STEREO IMAGERY

The study site is the area of Tivoli (Figure 5), east of Rome (Central Italy, N 42º, E 12º40'), worldwide famous for the Travertino quarries and the archaeological site of Villa Adriana. The stereo pair belongs to the category 1A, therefore the images are only radiometrically correct; it was acquired on 06/07/2002 and the mean ground geometric resolution is 2.4 m (nominal resolution 1.8 m); the overlapping is almost 100% and the covered area approximately 12.5×17 km (Figure 6).
The coordinates of 23 GCPs were collected by a RTK survey assisted by the GPS permenent network of the Lazio Region, (managed by the Area di Geodesia e Geomatica-Università di Roma "La Sapienza"), with mean horizontal and vertical accuracies of 0.1-0.2 m.
To evaluate the influence of the GCPs number on the DSM accuracy for EROS-A too, 2 DSMs were genarated with 18 GCPs and 10 TPs (DSM 1) and with 11 GCPs and 10 TPs (DSM 2) respectively.

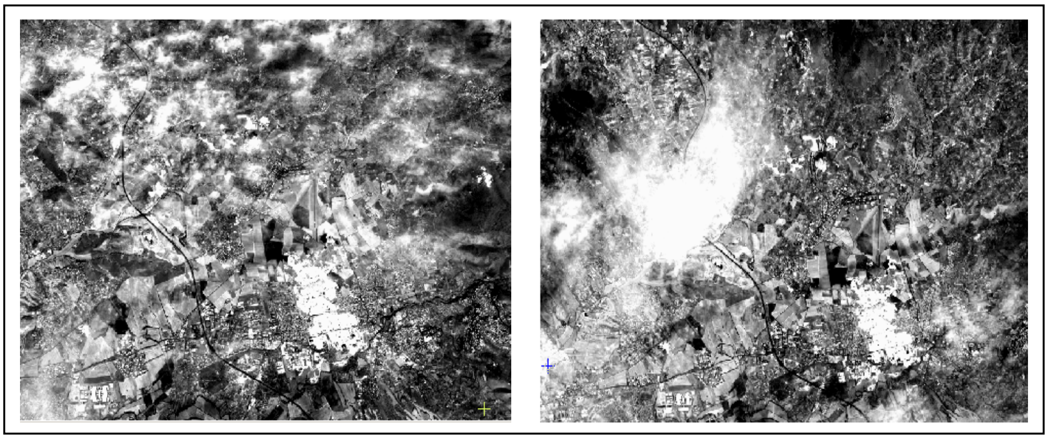

Figure 5 - Stereo EROS-A image

First of all, it has to be underlined that very poor results (errors of several tens of meters) were obtained for about 25% of the area covered by the stereo image (northern part), mainly for correlation problems due to clouds; this area was excluded from all the subsequent analyses.
In this case, considering the results discussed in (Toutin, 2004a) as regards EROS-A DSMs (LE68 between 10 and 20 m) and for the lack of more accurate maps, a preliminary comparison to a DEM generated from 1:25000 map (vertical accuracy of 5-10 m) was performed considering 8 zones (A to H) with different morphologies and land covers (plain, hill, residential areas, Travertino quarries).

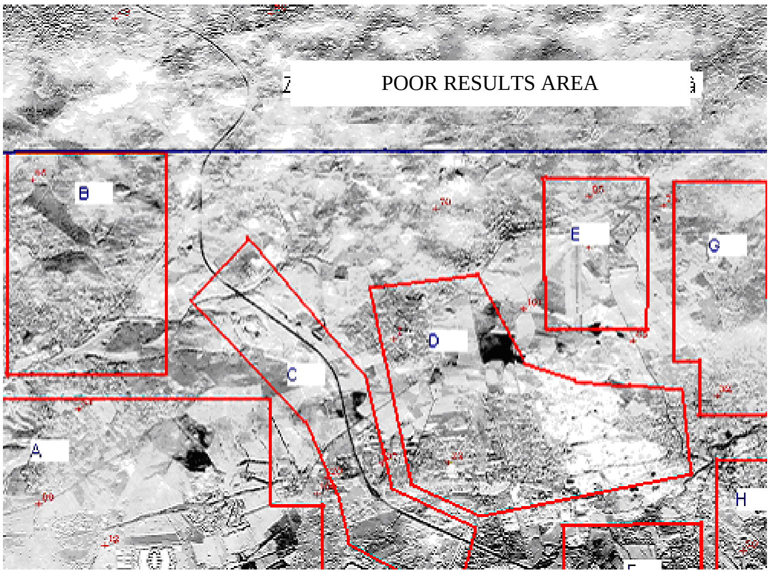

Figure 6 – Local comparison zones

It has to be noted that the number of GCPs may have an impact on the results, since sometimes DSM 1 is significantly better than DSM 2 (Table 6), especially in zones close to DSM edges (B, G, H); the results related to zone F may seem anomalous but it have to be considered both the small dimension of this zone and the mean accuracy of the cartographic reference DEM. Moreover, the best results are obtained in quite homogeneous and bare soils zones (C, E), where both DSMs display similar accuracy.

Rms (m)	Zone A	Zone B	Zone C	Zone D	Zone E	Zone F	Zone G	Zone H
DSM 1	5.4	7.8	5.2	2.6	3.8	7.3	4.4	13.5
DSM 2	7.9	22.9	3.3	6.0	5.0	2.1	17.1	23.4

Table 6 - Local comparison statistics (accuracy dependency on morphology and land cover types)

A sample comparison was based on a significant number of homogenously distributed points in the whole area collected by a kinematic GPS survey (55 km, sampling rate: 1 sec, mean speed: 40-50 km/h, 1 point/10 m) in this case too.
After outliers rejection and neglecting points close to DSM edges, the same statistics as for IKONOS-II DSMs were computed on the basis of 310 GPS points. Significant bias of 2.5 m and asymmetry of the residual frequency distribution were found, together with a mean accuracy (RMS) of 6.0 m.

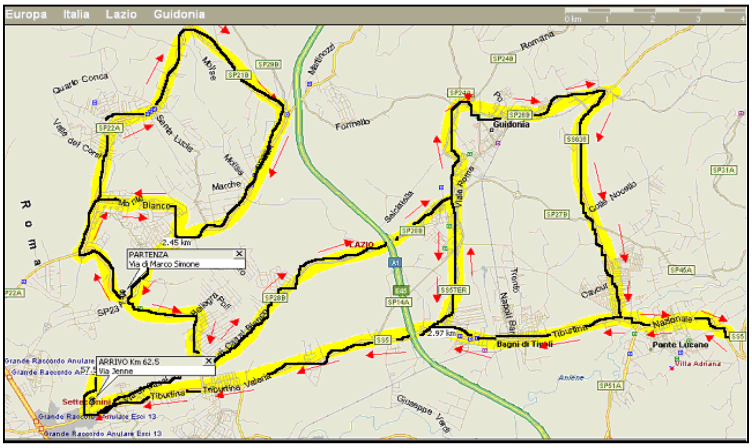

Figure 7 – GPS kinematic survey in Tivoli area

3 DISCUSSION AND CONCLUSIONS

The discussed study about the evaluation of the quality of DSMs derived from high resolution stereo images (IKONOS-II and EROS-A satellites) showed significant powers of this kind of images in this respect too: intrinsic accuracies ranging from 1-2 m (IKONOS-II) to 5-6 m (EROS-A) are achievable, provided careful image processing with rigorous (physical) models are performed and deep attention is paid to edge effects and to possible correlation problems during image matching. This kind of problems arises for lack of contrast, different illuminations of the same objects on the two image or for remarkable differences in pixel ground dimensions due to asynchronous acquisition (for EROS-A satellite) and may happen both in complex morphology areas and on water surfaces (lakes); correlation errors may be mitigated by inserting several TPs. Accuracy is also strictly dependent on morphology and land cover.
In details, IKONOS-II derived DSMs accuracy is essentially independent from the GCPs number, provided at least 10 GCPs homogeneously distributed are available, in agreement with (Toutin, 2004b); intrinsic accuracy (1-2 m) has a Quality Level 2-3 according to (Köebl, 2001), whilst mean accuracy along roads is only slightly worse (2-3 m), with a Quality Level 1-2. Therefore, besides standard applications of DSMs with such a quality, IKONOS-II DSMs seem quite useful to monitor the urban volumes evolution at least at the Quality Level 2-3 (useful for demographic studies in developing countries) and to define roads vertical profile at the Quality Level 1-2 (useful for roads cadaster in conjunction with kinematic surveys).
As regards EROS-A derived DSMs, intrinsic accuracy (5-6 m) has a Quality Level 0-1 and the mean accuracy along roads is of the same order of magnitude (6-7 m). In this case, accuracy is conditioned by GCPs number and really highly dependent also on edge effects and on morphology and land cover.
Future investigations will be oriented towards the following items: Stereo Quickbird images accuracy assessment (Toutin, 2004c, Oki et al., 2004); further analyses on IKONOS-II and EROS-A with better reference DEMs and possible LIDAR derived DSM; IKONOS-II block adjustment analysis. Moreover, already outlined applications of IKONOS-II DSMs to urban volumes evaluation an roads cadastre will be also considered.

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metodologici ed indicazioni pratiche per la loro realizzazione, gestione ed impiego" – Local Principal Investigator: C. Nardinocchi).

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