THE ROLE OF EPHEMERIDES AND GCPs DISTRIBUTION IN HIGH RESOLUTION SATELLITE IMAGES MODELLING

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ABSTRACT:

The geometric resolution of the images coming from the new generation satellites is almost competitive with that found in the trational aerial photograms. The aim of this work is to define the role of satellite ephemerides and to optimise the number and distribution of Ground Control Points (GCPs) for the image registration.
A zone of the Campania region in Italy has been used as a test area: it is characterized by a mountainous area without constructions and by flat land areas densely inhabited. The images that have been used relate to different epochs and different satellites such as Spot5, Ikonos2 and QuickBird. Spot5 images have also been used to generate automatic Digital Elevation Models (DEMs).
The assessment of DEM precision has been carried out by comparison with raster DEMs from cartography. The GCPs coordinates have been obtained from a GPS network made up of almost hundred and some of them are used as Check Points (CPs).
Different tests have been performed, either varying the number of GCPs or hypothesizing the presence or absence of satellite ephemeris.
Some numerical evaluations confirm that the use of the satellite ephemeris greatly reduces the amount of residuals on the CPs; in the case of Spot5 images this improvement becomes even more evident.

1. INTRODUCTION

With the advent of the new generation of optical satellites, images are becoming competitive with those ones taken from aircraft as far as geometric resolution is concerned.
As these systems have only recently come into use (and some are still under development), information regarding resolution, use and the compatibility of the images with cartography at a certain scale, is only available from private firms that sponsor them, hence the need to put these products to the test. The aim of this paper is to estimate the degree of accuracy that can be reached georeferencing satellite images at high resolution, and the effect that the use of an increase in GCPs number has on precision with a view to using satellite ephemeris. Residuals obtained on GCPs and CPs, whose mean values and rms were calculated in various situations, were used as a statistical index to estimate georeferencing precision.
The software used for creating the image models is PCI Geomatica 9.0. The images used in the experiments are coming from the QuickBird, Ikonos2 and Spot5 satellites over a Test Area in Campania (Italy), characterized from a mountainous area lacking of manufactures and from areas densely inhabited in the flat land. A GPS network was surveyed, made up of twenty-nine vertices and fifty-nine bases, from which a hundred points were measured, these being Ground Control Points (GCPs) and Check-Points (CPs). The non-unifom distribution of the points is due to the complex morphology of the Test zone and of the scarcity of buildings in the mountainous zone.
To verify the importance of the satellite ephemeris in the elaboration of images, a number of tests were carried out varying the number of GCPs used for georeferencing.

The QuickBird and Spot5 images were registered choosing both the *Satellite orbital modelling* option (known ephemeris) and *Rational function* (unknown ephemeris) and in both cases using an increasing number of GCPs (from 10 to 60). For the Ikonos images, the tests were carrried out using only twelve, twenty-two and thirthy-two points. Figure 1 shows the location of the three images on a part of cartography and the distribution of the measured points on the ground using the GPS.

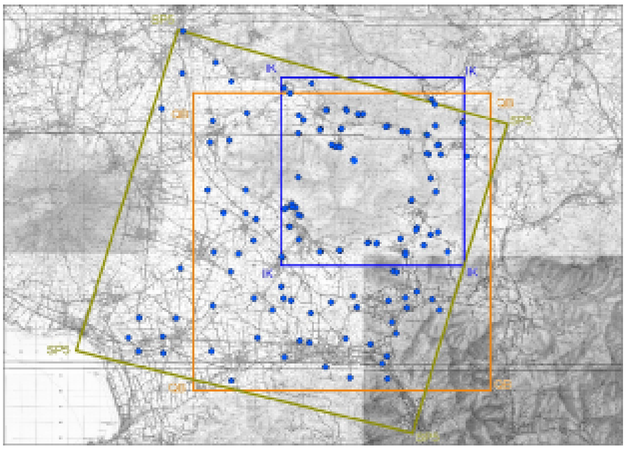

Figure1. Location of the satellite images and the distribution of the points surveyed by GPS

2. IMAGE GEOREFERENCING

The physical-mathematical description which gives a correct and detailed geometry of an image and those transformations which link the object space to the image space are defined as rigorous models. For a point of object coordinate (X, Y, Z) and image coordinates (x, y) the model used more commonly is expressed by the collinearity equations:

$$X = X_0 + (Z - Z_0)\frac{r_{11}(x - x_0) + r_{12}(y - y_0) + r_{13} f}{r_{31}(x - x_0) + r_{32}(y - y_0) - r_{33} f}$$

$$Y = Y_0 + (Z - Z_0)\frac{r_{21}(x - x_0) + r_{22}(y - y_0) + r_{23} f}{r_{31}(x - x_0) + r_{32}(y - y_0) - r_{33} f}$$

Where (X_0, Y_0, Z_0) are the projection centre coordinates, f is the focal length of the camera, (x_0, y_0) are the coordinates of the principal point, and the r_{ij} are the elements of the rotation matrix that describes the rotations (ϕ, ω, κ) of the sensor in the along-track system.

It is common practice to call the terms (f, x_0 e y_0) Inner Orientation (IO) parameters while (X_0, Y_0, Z_0, ϕ, ω, κ) are called parameters of Exterior Orientation (EO).The collinearity equations are also applied on single frames and on images obtained from push-broom sensors. It should be borne in mind that in the first case, the collinearity equations are valid for the whole image while in the second case they are time dependent in so far as the sensor changes its position and attitude from one moment to the next. Thus, for images obtained from satellites with linear sensors, every single line of scanning has its own EO parameters.

In this case, to describe the exterior orientation parameter variations, one uses appropriate polynomials that describe the variations and the movements of the sensor starting out from information supplied with the images describing the position, speed and orientation of the satellite at specific instants; this kind of information is known as ephemeris.

Once the ephemerides are known and a good model is available, only a few Ground Control Points (GCPs) are required in order to refine the solution and to get correctly oriented images.The main firms distributing high resolution satellite images usually fail to furnish detailed information on the sensor's rigourous model and so both the scientific community and the software development firms for the treatment of satellite data, have begun to study and develop alternative algorithms for the geometric elaboration of data. Among these, the method based on the use of the Rational Function (RF) is most certainly the most common and widely studied.

From a general point of view, an RF model can be defined as the relationship between two polynomials whose coefficients can be both directly supplied by the distributors of the data or indirectly calculated with the aid of GCPs distributed over the image.

In the first case, the firms owning the satellite that does not wish to spread information on the type and operation of the sensor, starting from the precise model, produces the coefficients to associate to the relationship of polynomials and it supplies them with the images automatically.

The best known case is the Ikonos images, presented by Grodecki (Grodecki and Dial, 2000); the rigorous model is used for determining the object coordinates of a regular grid of image points.

In this case the firm owning the satellite supplies only the file of the coefficients to use with the polynomials of the RFs, while for other images, such as the QuickBird, information is available on the sensor and its position as well as the file with the polynomial coefficients to use with the RFs.

In the second case, the user may want to optimise the results featuring the solutions obtained, by introducing a suitable number of GCPs which will be used for calculating the unknowns present in the RF model.

3. EXPERIMENTAL TESTING

A number of georeferencing tests was carried out (with and without ephemerides), gradually increasing the number of GCPs ranging from about ten points in blocks of 10.

To assess the georeferencing accuracy obtained in the various tests, we calculated the mean and rms values of GCPs and CPs residuals. In choosing the location of the vertices to survey on the ground using the GPS every effort was made to maintain the most uniform planimetric distribution of the points, an operation which was far from simple because of the difficulty found for all three images in identifying the GCPs in the mountainous regions with almost no buidings or other easily identifiable features and also, in the case of Spot5 image, due to the dense layer of cloud that made a substantial portion of the image unusable. In table 2 are listed the number of GCPs and CPs used in each test for the three images.

Points	QUICKBIRD						IKONOS2			SPOT5					
	76						46			74					
GCPs	10	20	30	40	50	60	12	22	32	10	20	30	40	50	60
CPs	66	56	46	36	26	16	34	24	14	64	54	44	34	24	14

Table 2. GCPs and CPs used for each image

In the following sections we give a summary of the results obtained on the three different images.

3.1 QuickBird image

In table 3 the statistical parameters of the residuals (mean value and root mean squares) on the GCPs and on the CPs are listed. It may be seen that increasing the number of GCPs by 10s up to 60, the average of the residuals on the GCPs, when using ephemerides, is of around 23 cm at 10 points, 35 cm at 20, and around 40 cm with a number of points from 30 to 60.

The associated rms vary very little in all and are of the order of 13 cm. If the ephemerides are not used, the residuals on the GCPs are lowest, of the order of 10-15 cm up to 40 GCPs; they climb to around 25 cm in the case of 50 and 60 points.

The associated rms are all around 15 cm, except in the first case (10 GCPs) of only 5 cm.

Turning to an analysis of the residuals on the CPs, one first notes that, with the use of ephemerides, the average of the residuals on the CPs decreases slightly with an increase in the

number of GCPs (from around 50 to around 40 cm), underlining an opposite trend to that observed earlier for the residuals on the GCPs, with and without ephemerides. The associated rms are substantially of the same order of magnitude (a little higher) as those on the GCPs.
There is a notable drop in precision regarding residuals on the CPs when not using ephemerides: the averages of the residuals vary randomly from around 0.6 to 2.0 m, with very high rms (from 0.4 to 3.7 m).

# of Points		EPHEMERIS		NO EPHEMERIS	
		Residuals (m)		Residuals (m)	
10 GCPs 66CPs	GCPs	Average RMS	0.23 0.17	Average RMS	0.06 0.05
	CPs	Average RMS	0.52 0.24	Average RMS	0.56 0.37
20 GCPs 56CPs	GCPs	Average RMS	0.35 0.15	Average RMS	0.16 0.14
	CPs	Average RMS	0.48 0.20	Average RMS	0.61 0.42
30 GCPs 46CPs	GCPs	Average RMS	0.40 0.13	Average RMS	0.14 0.14
	CPs	Average RMS	0.46 0.16	Average RMS	0.82 0.94
40 GCPs 36CPs	GCPs	Average RMS	0.42 0.13	Average RMS	0.15 0.15
	CPs	Average RMS	0.44 0.17	Average RMS	1.87 3.65
50 GCPs 26CPs	GCPs	Average RMS	0.42 0.11	Average RMS	0.23 0.15
	CPs	Average RMS	0.43 0.20	Average RMS	0.62 0.98
60 GCPs 16CPs	GCPs	Average RMS	0.42 0.12	Average RMS	0.24 0.15
	CPs	Average RMS	0.42 0.20	Average RMS	0.77 1.50

Table 3. QuickBird. Average and rms of GCPs and CPs residuals

3.2 Ikonos image

The same analyses have been carried out for the Ikonos2 image, this time limited to a number of GCPs equal to 12, 22 and 32, with 34, 24 and 14 CPs respectively, since the image covered a smaller territorial area without easily identifiable points in it (measurable on the ground) throughout the central mountainous part.
Observing the mean values of the residuals, listed in table 4, it is clear that, also in the case of Ikonos2 image, with an increase in the number of GCPs from 12 to 32, the accuracy connected to the residuals on the GPCs, varies very little with mean values varying from between 52 and 64 cm ± 30 if the ephemerides are used, and between 37 and 28 cm ± 20 without ephemerides.
If the residuals are analysed on the CPs, also here the mean value does not depend on the number of points used for georeferencing, and it is on average higher than on the GCPs (around 90 cm ± 40) with ephemerides, while it is rises significantly if the ephemerides are not used, reaching mean rms values of some meters, excessive for an image whose resolution is around one meter and with object coordinates measured by GPS.

# of Points		EPHEMERIS		NO EPHEMERIS	
		Residuals (m)		Residuals (m)	
12 GCPs 34CPs	GCPs	Average RMS	0.52 0.27	Average RMS	0.37 0.22
	CPs	Average RMS	0.88 0.41	Average RMS	1.44 1.08
22 GCPs 24CPs	GCPs	Average RMS	0.53 0.33	Average RMS	0.35 0.23
	CPs	Average RMS	0.89 0.42	Average RMS	3.51 8.46
32 GCPs 34CPs	GCPs	Average RMS	0.64 0.30	Average RMS	0.28 0.25
	CPs	Average RMS	0.91 0.36	Average RMS	2.85 6.80

Table 4. Ikonos. Average and rms of CCPs and CPs residuals

3.3 Spot5 image

The last image used is from the Spot5 satellite, with a pixel resolution of 2.5 m on the ground. In this case the number of points surveyed on the ground was seventy-four and the usual georeferencing tests were carried out, varying the number of GCPs; the results of the experiment are listed in table 5. Observing the trend of the average of the residuals on the GCPs, as the number increases, it appears that, with the use of ephemerides, a fall of almost linear precision occurs, passing from 10 to 30 points, with almost stable values between 30 and 50 points and a new fall at over 60 points.The residuals averages vary from one meter to one and a half meters and are therefore smaller than the dimension of the pixel in any case. The associated rms vary from 40 to 63 cm. Without ephemerides, the averages of the residuals are noticeably always lower in comparison to the preceding ones and the variability linked to the number of points used is more noticeable.

# of Points		EPHEMERIS		NO EPHEMERIS	
		Residuals (m)		Residuals (m)	
10 GCPs 64CPs	GCPs	Average RMS	0.98 0.40	Average RMS	0.13 0.13
	CPs	Average RMS	2.18 1.05	Average RMS	1.99 0.90
20 GCPs 54CPs	GCPs	Average RMS	1.30 0.52	Average RMS	0.67 0.44
	CPs	Average RMS	2.12 1.09	Average RMS	2.79 2.85
30 GCPs 44CPs	GCPs	Average RMS	1.50 0.63	Average RMS	0.73 0.40
	CPs	Average RMS	1.99 0.72	Average RMS	2.55 2.37
40 GCPs 34CPs	GCPs	Average RMS	1.58 0.56	Average RMS	0.84 0.48
	CPs	Average RMS	1.92 0.86	Average RMS	3.19 4.02
50 GCPs 24CPs	GCPs	Average RMS	1.55 0.59	Average RMS	0.99 0.50
	CPs	Average RMS	2.09 0.79	Average RMS	1.93 0.78
60 GCPs 14CPs	GCPs	Average RMS	1.65 0.61	Average RMS	1.17 0.56
	CPs	Average RMS	2.06 0.66	Average RMS	1.53 0.69

Table 5. SPOT5. Average and rms of GCPs and CPs residuals

The rms are also very low, varying from 13 to 56 cm. Also in this case, the residuals on CPs are noticeably higher, around 2 m with an rms of around 70 cm - 1 m with ephemerides, independently of the number of GCPs used, and varying randomly from 1.5 m to around 3 with rms of up to 4 m without ephemeredes.

4. SUMMARY OF THE EXPERIMENT RESULTS

All the tests carried out on the three available satellite images, with a varying number of GCPs for georeferencing, show a remarkable difference in accuracy depending on whether it was a question of residuals on the GCPs or on the CPs.
Analysing the residuals on the GCPs, it was evident that using a greater or lesser number in georeferencing has little influence on the accuracy given by the value of the residuals on the GCPs themselves, whose mean value always remains below the nominal precision given by the size of the pixel on the ground. Variability is still less marked in the case of the use of ephemerides, but it is more evident however from 30 GCPs upwards. The values of the rms of the GCPs residuals are more or less of the same magnitude independently of their number and from the use or otherwise of ephemerides.Table 6 lists the extremely summarised values on the average of the residuals on the GCPs and associated rms, for all the tests (therefore, an average of the averages).

GCPs QuickBird	Ephemeris YES	0.4 m ± 0.1
	Ephemeris NO	0.2 m ± 0.1
GCPs Ikonos	Ephemeris YES	0.6 m ± 0.3
	Ephemeris NO	0.3 m ± 0.2
GCPs Spot5	Ephemeris YES	1.4 m ± 0.6
	Ephemeris NO	0.8 m ± 0.4

Table 6. Mean value and rms of the GCPs residuals

It is interesting to notice how in every case the averages and rms are lower and lower when ephemerides are not used.
Figure 7 shows a summary of the results of the residuals on the CPs, both with and without the use of ephemerides.

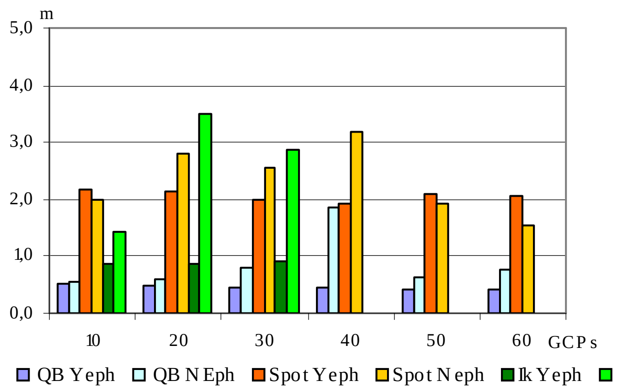

Figure 7. Average of CPs residuals

4.1. Georeferencing using Rational Function model

Figures 8 - 13 show the vectors corresponding to the residuals on the GCPs and CPs for the QuickBird image; the residuals on the CPs are in blue while those on the GCPs are in red. It should be noted that where the RF models are used (with calculation of the coefficients of the polynomials in function of the GCPs), the residuals on some points have peaks of values; such points are always CPs with high elevated heights differing from those of the surrounding GCPs. This behaviour of the CPS residuals in the RF model has been noticed for all three images used in these tests.

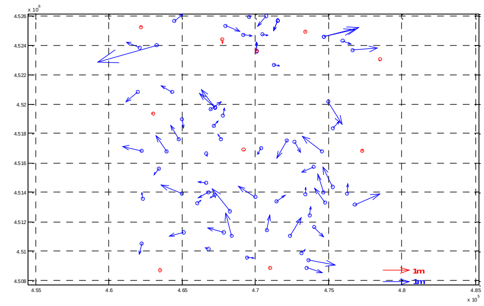

Figure 8. QuickBird image with ephemerides unknown (10 GCPs - 66CPs)

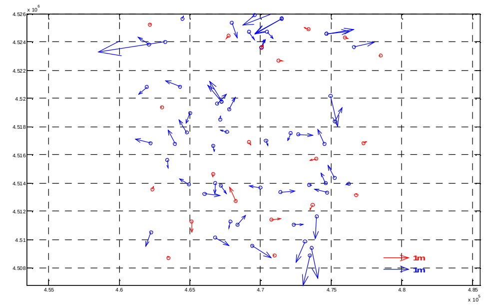

Figure 9. QuickBird image with ephemerides unknown (20 GCPs - 56CPs)

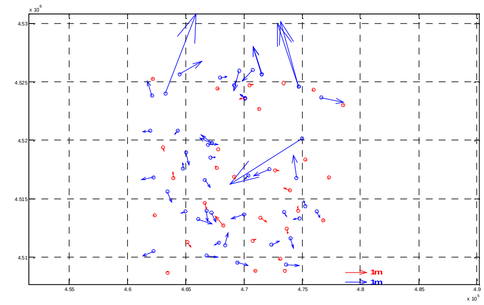

Figure 10. QuickBird image with ephemerides unknown (30 GCPs - 46CPs)

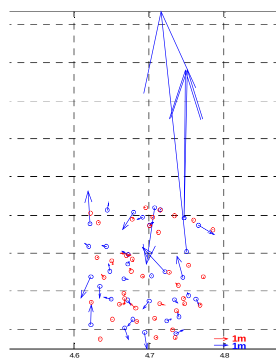

Figure 11. QuickBird image with ephemerides unknown (40 GCPs - 36CPs)

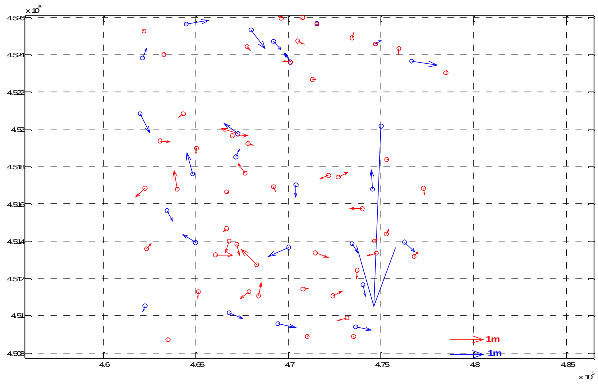

Figure 12. QuickBird image with ephemerides unknown (50 GCPs - 26CPs)

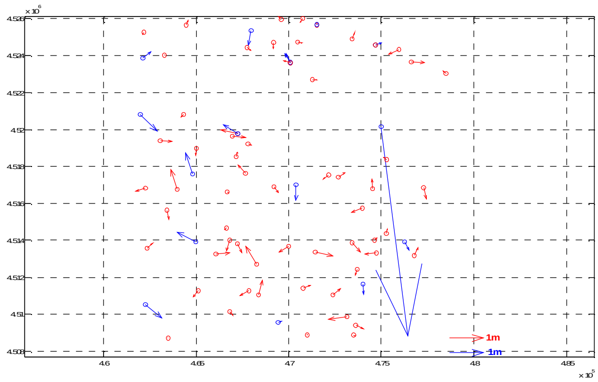

Figure 13. QuickBird image with ephemerides unknown (60 GCPs - 16CPs)

4.2 Georeferencing using Rational Polynomial Coefficents

The following figures show a number of graphs of CPs residuals on QuickBird image georeferenced using polynomial coefficients delivered with the image.

It should be noted that, in figure 14, if no GCP is used, the residuals on all points, considered as CPs, are very high, on average 17 meters, and they show a certain systematism. It seems evident that the use of a single GCP (in red in figure 15) drastically reduces the amount of the residuals on the CPs and a prudent choice of its position seems crucial, in that the reduction of the value of the residual results much stronger if this point is central with respect to the CPs (figure 15 and 16).

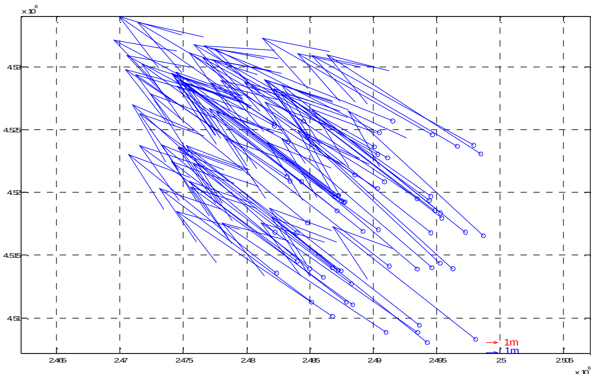

Figure 14. QuickBird image with RPC known. No GCP used

Looking at figure 17 it is also clear that increasing the number of GCPs produces a few noticeable improvements on the residuals of the CPs, and it is therefore enough to use a single point to georeference a QuickBird image supplied by RPC.

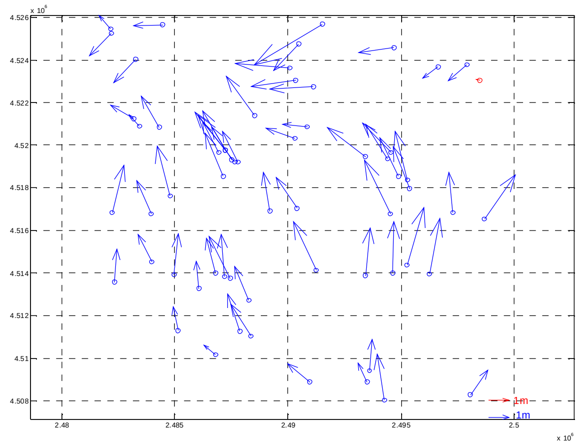

Figure 15. QuickBird image with RPC known. 1 GCP on the border of the image

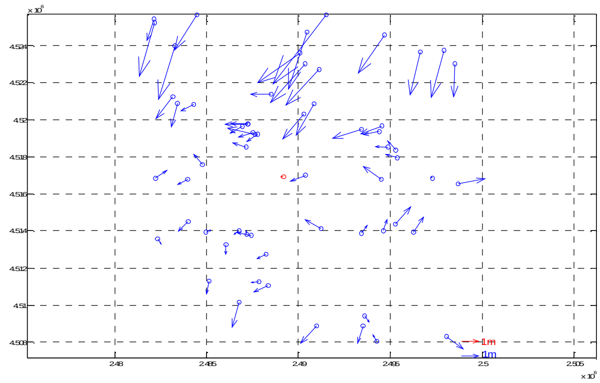

Figure 16. QuickBird image with RPC known. 1 GCP in the middle of the image

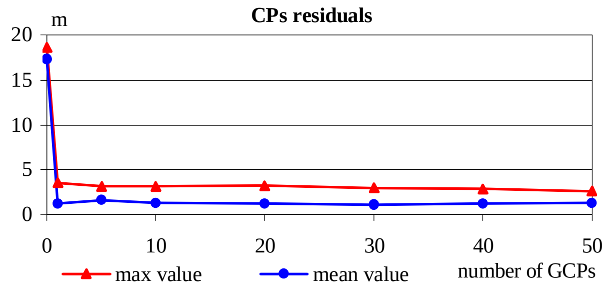

Figure 17. QuickBird image. Maximum and mean valur of CPs residuals depending on number of GCPs

6. DEM FROM STEREO SPOT5 IMAGES

Some tests on the automatic DEM extraction from two stereo Spo5t5 images have also been performed. We remind that the optimal geometric configuration in the stereo-modelling is obtained when the ratio base to height is between 0.7 and 1.2, corresponding to an angle α of 30°- 60° in the center of scene (figure 18).

The two Spot5 images used were acquired in November 2002 at a distance of five days and exhibit different conditions of radiance owing to different cloud coverage, so it was possible to extract the DEM automatically only over single areas.

Even if the georeferencing results of the two images taken singly are good (residuals of about one pixel), when the stereo model is reconstructed, the residual values on stereo GCPs amount of nearly one or two pixels in horizontal coordinates but very much higher (25 m on average and around 58 m for the maximum value) on the vertical ones.

This is due to the poor geometric configuration of the stereopair; there is in fact a base to height ratio of 0.1, corresponding to an angle α of only 1.02° in centre scene.

Figure 19 shows the areas on which the automatic DEM extraction was carried out.

The first was done over the whole area of overlap of the two images and two more on small areas of surface 7.5 x 7.3 km (zone A) and 6.2 x 4.6 km (zone B) outlined in yellow in the figure.

These areas were chosen because they were free of cloud and had a good correlation index.

For comparison with the data obtained (in red in the figure), the DEM of the IGMI, the official cartographic body of the Italian state, was used. The DEM has been obtained from cartographic data and interpolated onto a 20 m grid.

All DEMs were automatically extracted both on a 2.5 m and on a 20 m grid, equal to the size of the pixels on the ground, in order to make a comparison with the DEM of the IGMI.

The automatic DEM on the 2.5 m grid were obviously much "noisier" than those on the 20 m grid.

The latter are shown in figures 20 (zone A) and 21 (zone B) while the DEMs of the compared IGMI are shown in figures 23 and 24.

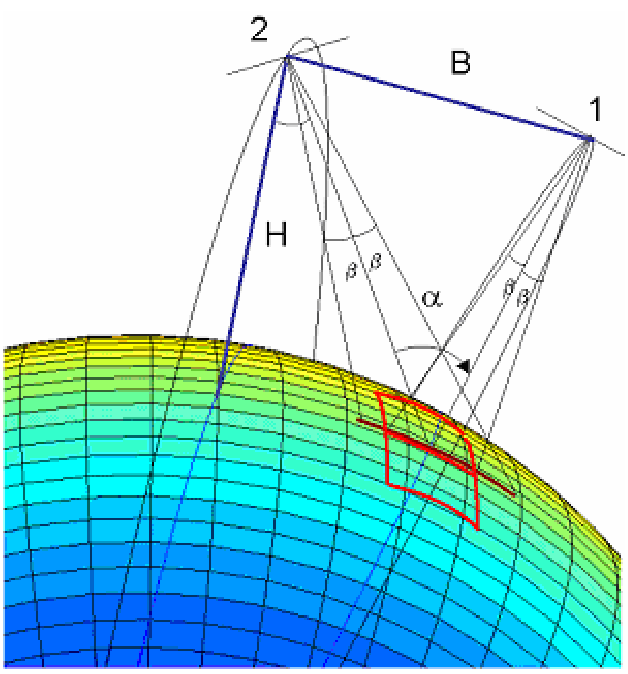

Figure 18. Geometry of stereopair

Apart from a few small areas, including those mentioned, image-matching on the entire stereo area did not give good results, probably on account of the different cloud cover existing between the two images.

Some parts of the image are obscured by clouds and others are in shadow because of these clouds and such areas are different in the two images of the stereopair causing a radiance difference between the two that prevents, at a local level, the correlation from being successful.

The success rate of automatic correlation however, was good in zone A (approx. 70%) and excellent in zone B (approx. 90%).

Zone A features a broad highland area, about 600 m at its highest altitude, which slopes steeply towards a flatland area at about 25 m.

The area is completely devoid of clouds and is sparsely populated.

The peaks of error present in the DEM are caused by strong shadows cast by the uneven morphology of the terrain.

Zone B features a central hilly area which attains an altitude of about 600 m and which is devoid of buildings, as well as two densely-populated flatland areas.

The greatest problems experienced with the automatic auto-correlated DEMs of this area occured in the flatland areas due to the strong shadows cast by built structures.

Another factor that influenced the result negatively was the presence of small clouds and their consequent shadows on the borders of the area, causing visibile peaks at the edges of the figure.

Finally, the automatic DEMs were compared to those of the IGMI by calculating the difference between the two grids.

In zone A the differences between the two grids vary from -843 m to 502 m with a mean value of 81 m, while in the zone B such differences vary from -130 m to 893 m with a mean value of 40 m.

The results are shown in figures 22 and 25.

It is clear from the data that in the flat region the automatic DEMs give height values that are smaller than the real ones, while in high elevation regiones one observes the opposite pattern.

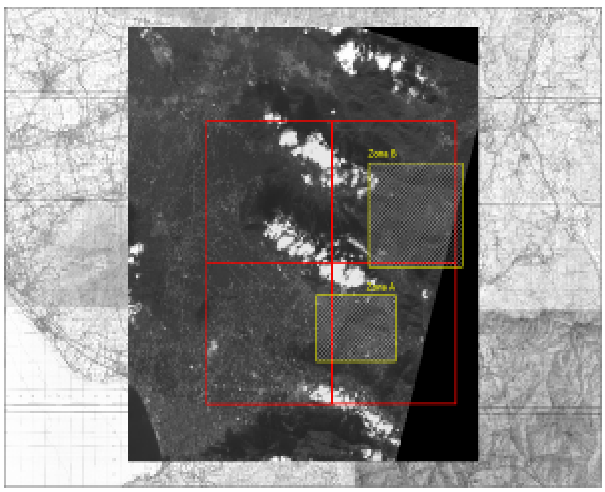

Figure 19. Location of DEMs on the Spot5 image

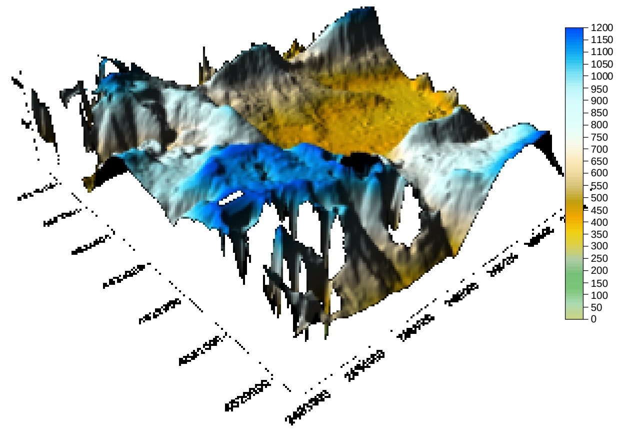

Figure 20. Automatic DEM on zone A (20 m node grid)

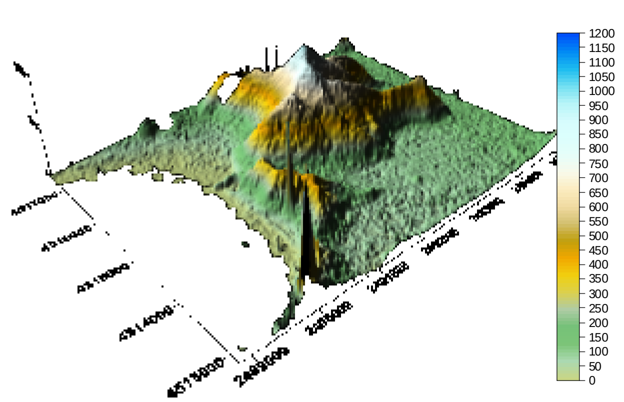

Figure 21. Automatic DEM on zone B (20 m node grid)

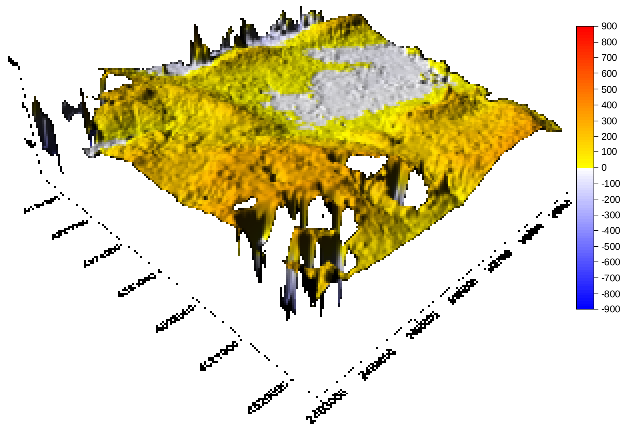

Figure 22. Comparison between DEMs on zone A

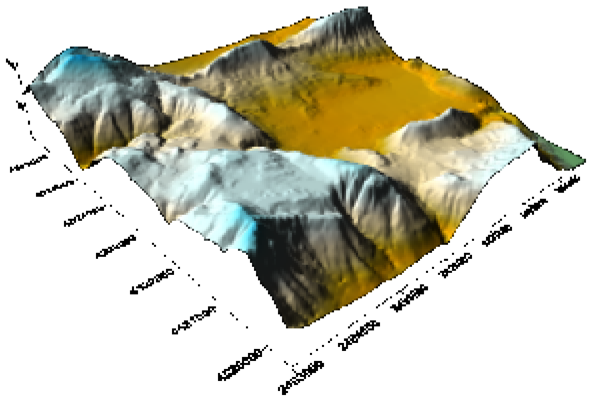

Figure 23. Reference IGMI DEM on zone A (20 m node grid)

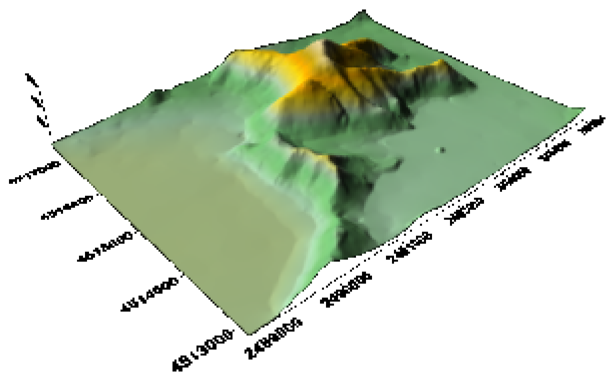

Figure 24. Reference IGMI DEM on zone B (20 m node grid)

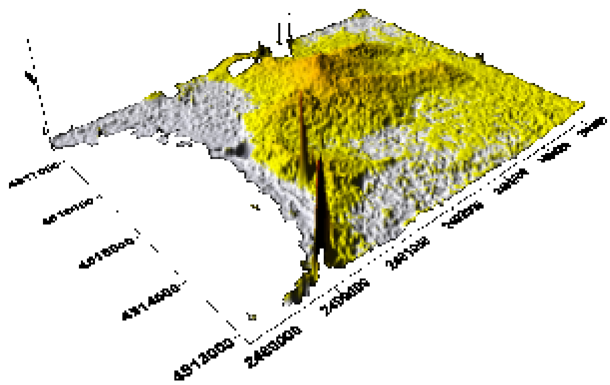

Figure 25. Comparison between DEMs on zone B

7. CONCLUSIONS

From the results of the tests carried out, the expectations of the three satellite images were met as far as accuracy is concerned. The residuals on the GCPs and CPs are normally below the level of their nominal precision.

There is always however a deterioration in the case of the use of images without ephemerides, particularly marked in the case of Spot5, though less noticeable with Ikonos and QuickBird.

The steropair of Spot5 images allowed automatic DEM extraction with a good correlation index in only two cloudless zones with low radiometric differences between the two images.

The resulting DEM was then compared with that provided by the IGMI; the statistics of the result show the poor stereo configuration of the pair used, far from acceptable in terms of the base to height ratio.

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