VALIDATION OF CARTOSAT-1 DTM GENERATION FOR THE SALON DE PROVENCE TEST SITE

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ABSTRACT:

Cartosat-1 is the eleventh satellite of the Indian Space Research Organisation series and is primarily meant for topographic mapping and Digital Terrain Model (DTM) generation. In the framework of the Cartosat-1 Scientific Assessment Programme, the Politecnico di Milano University (Italy) evaluated as Co-Investigator the performances of the Cartosat-1 satellite in the generation of DTMs. This paper describes the outcomes for the Salon de Provence test site (France) with respect to existing standards and products actually used in France and also provides a comparison with the global Shuttle Radar Topography Mission's DTM supplied by NASA and widely used in the remote sensing community.

1. INTRODUCTION

The Indian Space Research Organisation (ISRO) launched the Cartosat-1 satellite on May 05, 2005. The satellite was primarily designed for topographic mapping and has two panchromatic Charge Coupled Device (CCD) sensors, both with a spatial resolution of 2.5m: i) the Fore camera, pointing +26 degrees with respect to the nadir, and ii) the Aft camera, pointing -5 degrees with respect to the nadir. These sensors can either acquire along-track stereo images with a 27.5km swath and a base to height ratio (B/H) of 0.6 or mono images with a combined swath of 55km (Indian Space Research Organisation, 2008).

At the beginning of 2006 an agreement has been reached between the International Society for Photogrammetry and Remote Sensing (ISPRS) and ISRO to jointly conduct the Cartosat-1 Scientific Assessment Programme (C-SAP). The aim of the C-SAP was to assess the mapping capabilities of the Cartosat-1 satellite, especially with respect to the generation of Digital Terrain Models (DTMs) for different types of terrain.
As Co-Investigator in the C-SAP, the Politecnico di Milano University (Italy) evaluated the performances of DTM generation from Cartosat-1 stereo data for the Salon de Provence (France) test site (C-SAP TS4). The investigation was carried on with respect to existing standards and products actually used in France (i.e., the French Institut Géographique National's and Spot Image's Reference 3D®, and the French ®DB Alti). Moreover, the investigation also provided a comparison with the global Shuttle Radar Topography Mission (SRTM) DTM supplied by NASA and widely used in the remote sensing community.

Imagery collected with Cartosat-1 were used for the generation of medium-resolution (25m grid cell size) and low-resolution (90m grid cell size) DTMs using commercial off-the-shelf software, so to provide comprehensive and operative hints to final users.

2. DATASET

2.1 C-SAP dataset composition

The standard C-SAP TS4 dataset delivered to the investigating teams was composed of the following items:

- One 2.5m Cartsat-1 stereo pair collected over Salon de Provence (France) on February 6, 2006 (Path=0128, Row=0198) and provided by ISRO;
- A set of 22 Ground Control Points (GCPs) provided by the Principal-Investigator (PI) French Institut Géographique National (IGN);
- One 19m x 26m resolution reference DTM (MNT_DBTOPO® DTM) with IGN69 datum for heights, provided by the PI.

In addition to the standard C-SAP TS4 dataset, it was also used a raster SRTM DTM made available from NASA (National Aeronautics and Space Administration, 2008).

2.2 Standard accuracy of Cartsat-1 images

ISRO delivered to the investigating teams Cartosat-1 imagery as Stereo Orthokit product in the GeoTIFF format (Figure 1) and also supplied predetermined Rational Polynomial Coefficients (Indian Space Research Organisation, 2005). The GeoTIFF Orthokit product is radiometrically corrected and is supplied to produce high precision cartographic products and DTMs: its location accuracy is better than 250m (3σ=220m for

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system level correction, Level 1) (Krishnaswamy and Kalyanaraman, 2002; National Remote Sensing Agency, 2007).

2.3 Standard accuracy of references DTMs

The Root Mean Square Error (RMSE) is a measure often used to assess the accuracy of elevation data and is defined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\Delta Z_i)^2}{n}} \qquad (1)$$

where:
ΔZ_i are the elevation residuals (i.e., the differences of the elevation measures with respect to reference data)
n is the number of measures

Another statistics often used to evaluate the overall accuracy of elevation data at a fixed confidence level (α) is the Linear Error (LEα). LEα performs a comparison in the elevation data towards reference measures: an LE90=2.5m implies that 90% of the measures to be tested vary from the reference measures by 2.5m or less.

Accuracies of references DTMs is shown as follows:

- MNT_DBTOPO® DTM: RMSE=1m in elevation over the whole France, as from PI IGN specifications;
- SRTM DTM: absolute LE90=6.2m in elevation for Eurasia (Rodriguez *et al.*, 2006).

2.4 Standard accuracy of references GCPs

The GCPs supplied by the PI IGN were derived from the French BD_ORTHO® and had an accuracy better than 1.5m in plan and better than 2.5m in elevation (Gachet and Favé, 2006). Figure 2 shows the GCPs' distribution on the study area.

3. DATA PROCESSING

The Cartosat-1 data processing was done using ENVI 4.3®. A commercial off-the-shelf software was selected for investigating the capabilities and limits of the system in the DTM's generation using standard image processing tools, so from the point of view of a typical remote sensing user. The data processing involved the following aspects: i) pre-processing, ii) optimization of the DTM's extraction procedure and, iii) analysis of the influence of GCPs in the modelled DTMs.

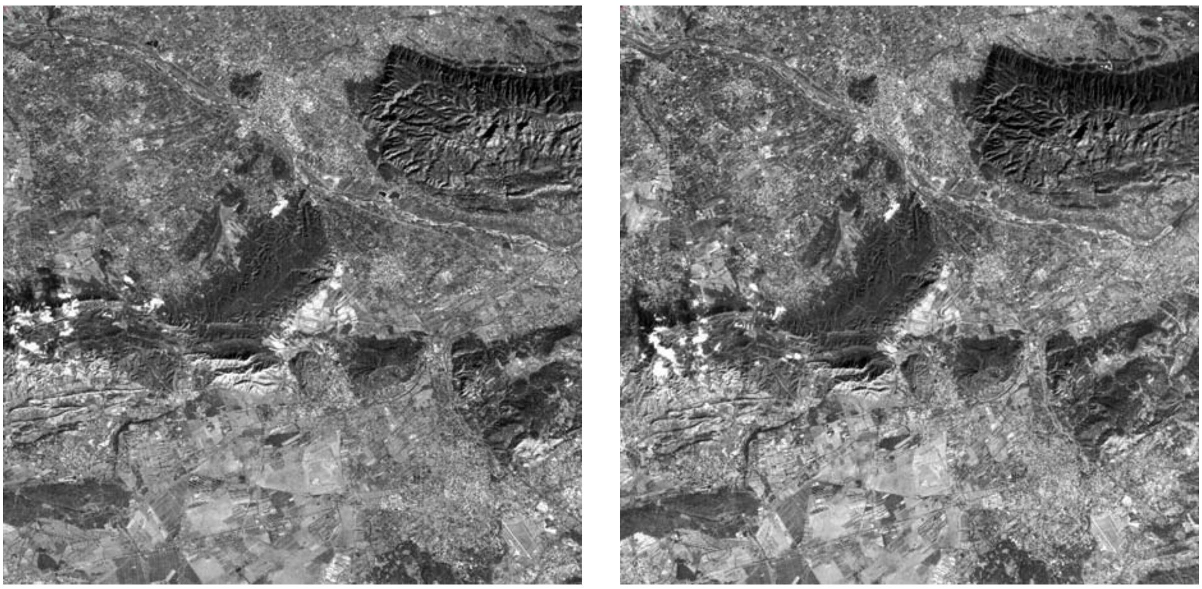
3.1 Data pre-processing

All the dataset were first converted into the UTM-WGS84 F31N reference system. The MNT_DBTOPO® DTM was resampled from its original 19m x 26m cell resolution to 25m x 25m and the SRTM DTM from its original 60m x 90m cell resolution to 90m x 90m.

3.2 Optimization of the DTM's extraction procedure

Before generating the DTMs from the Cartosat-1 images it was investigated the influence of the parameters involved in the generation process (i.e., number of tie points used, search window and moving window sizes, correlation coefficient and terrain detail). A sensitivity analysis led to the final optimal configuration as shown in Table 1.

Sixty tie points were used in all the tests. They have been automatically detected using a regular grid scheme covering the entire images, obtaining an Y parallax of 1.27 pixel (corresponding to 3.18m). By increasing the number of tie points, it was not observed any improvement in the Y parallax.



(a) (b)

Figure 1. Cartosat-1 stereo orthokit collected over Salon de Provence (France) on February 6, 2006. (a) 2.5m Aft panchromatic image, (b) 2.5m Fore panchromatic image.

Parameter	Value
Number of tie points	60
Search window size	800 pixel
Moving window size	30 pixel
Correlation coefficient	> 0.8
Terrain detail	level 6 (over 7 levels)

Table 1. Optimization of the DTM's automatic extraction procedure.

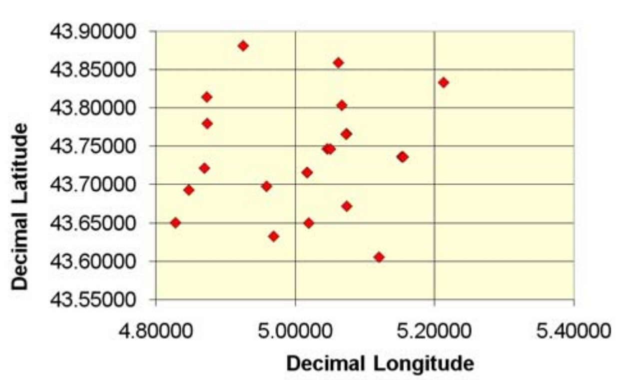


Figure 2. Ground control points distribution over the study area.

One of the major factor determining the accuracy of the generated DTM, as well as the processing time needed for its generation, is the 'terrain detail level' parameter. Since the DTM extraction is carried out by means of automatic image matching to find homologous features on the Aft and Fore images of the stereo pair, the terrain detail level determines the number of image pyramids used during the image matching. The use of the 'minimum terrain detail level' stops the process after the coarsest level of the image matching, while the use of the 'maximum terrain detail level' iterates until the image matching is performed at the highest resolution as possible.

In this study it was observed that the use of terrain detail level 6, instead of the maximum level (level 7), reduced the computing time by a factor of 4.6 without any sensible decrease in the final DTM's accuracy.

3.3 Ground control points selection

Because the satellite's pointing and ephemeris information are often inadequate for their use in applications involving high-resolution imagery, DTMs must be referenced to a map coordinate system using GCPs (Lang, 1999). The use of GCPs in the DTM generation process brings to the so called 'absolute DTMs', where 'absolute' means that the terrain's elevation values are referred to a geodetic datum.

When no GCPs are available it is still possible to produce DTMs from stereo pairs by means of automatic image matching algorithms,. In this case the so called 'relative DTMs' will be produced, where 'relative' means that the terrain's elevation values are not referred to a geodetic datum but to an arbitrary plane (e.g., the lowest value in the scene).

This study investigated the DTM's generation for both the relative (rDTM) and the absolute (aDTMs) methods, with particular emphasis for the second. With respect to the former, the accuracy of the DTMs were also verified for geocoded rDTMs (geocoded after the generation process), while for the latter it was deeply studied the influence of the GCPs (number and the geometric distribution) on the DTM's accuracy.

4. RESULTS AND DISCUSSION

4.1 Medium-resolution DTM generation

4.1.1 The influence of GCPs in the generation of relative DTMs:

When generating relative DTMs, the output is not correctly georeferenced and elevation data are referred to an arbitrary plane. Thus, without properly geocoding the error (in the z coordinate) of the Cartosat-1 rDTM was observed to be many hundreds of meters. After georeferencing the rDTMs using 5 GCPs of the original C-SAP dataset, the vertical accuracy drastically increased to less than 20m (LE90).

The DTM's accuracy was tested at two different scales: i) at local level using as Independent Check Points (ICPs) the remaining 17 GCPs of the original C-SAP dataset, and ii) at global scale using the MNT_DBTOPO® DTM as ground truth for the whole test site.

For geocoded rDTMs, results showed no significant difference in the mean value of residuals (μ) for both the comparison to the ICPs and the MNT_DBTOPO® DTM, respectively 4.33m and 4.24m. On the contrary, this is not true for standard deviation (σ), RMSE and LE90, which showed higher values when computed with respect to MNT_DBTOPO® DTM (σ=13.55m, RMSE=14.19m and LE90=19.00m), indicating that the statistics of the ICPs (σ=8.09m, RMSE=9.02m and LE90=16.10m) could not be assumed as a correct term of comparison for the complete elevation range.

4.1.2 The influence of GCPs in the generation of absolute DTMs:

When generating absolute DTMs, the number and geometric distribution of the GCPs have a great impact in the final DTM's accuracy. For this reason, the original set of 22 GCPs was divided into a first subset of j GCPs used for the DTM's georeferencing and a second subset of 22-j ICPs used for the evaluation of results.

Several tests have been done, varying j form 2 to 22 to find the optimum number of GCPs to be used. Table 2 shows a summary of results.

With the exception of test #5, the comparison of the Cartosat-1 aDTM with the ICPs showed a RMSE between 1.41m using 9 GCPs (for test #14) and 5.17m using 2 GCPs (for test #3), while the LE90 was between 1.91m using 6 GCPs (for test #11) and 8.91m using 2 GCPs (for tests #2 and #3). Even if the observed mean values of residuals were small and between -0.12m (for test #13) and -2.80m (for test #3), they were not null, thus indicating a small bias in the output data. Regarding their standard deviation, the observed values were between 1.36m (for test #11) and 4.49m (for test #1).

The best overall performance was obtained for test #14 using 9 GCPs (μ=0.47m, σ=1.39m, RMSE=1.41m and LE90=2.77m), thought also using fewer GCPs (tests #13, #11 and #9) similar results were achieved (Table 2). Even if using only 4 GCPs (test #9) led to better result in terms of LE90 (1.91m), altogether it gave worst performances and produced more biased results (μ=-1.03 m, σ=1.59m, RMSE=1.67m) than the previous.

The minimum number of GCPs necessary to obtain a good DTM was determined to be three (test #5). Using this configuration it was obtained a mean value of residuals of 1.15m, a standard deviation of 1.97m, a RMSE of 2.24m and a LE90 of 3.23m, which are 58.9% and 16.6% worst if compared to the best one, respectively in terms of RMSE and LE90.

Comparing the Cartosat-1 aDTM with the MNT_DBTOPO® DTM it was observed a similar behaviour than that described above. Generally speaking, increasing the number of GCPs the aDTM's residuals decreased until the values of μ=-1.22m, σ=6.79m, RMSE=6.90m and LE90=10.00m (for test #14). Once again, the use of three GCPs (test #5) gave good results.

In any case, no significant improvement was observed using more than 9 GCPs both when comparing results with the ICPs and with the MNT_DBTOPO® DTM. Table 3 shows a summary of results.

4.1.3 The influence of the terrain's elevation and slope: Once optimized both the algorithm's parameters and the configuration of the GCPs used in the generation process, two aDTMs were selected as 'best DTMs' (test #5 and test #14) and further analysis was carried on to study the DTM's accuracy with respect to the terrain's elevation and slope characteristics.

Regarding the first issue, both the aDTMs behaved similarly and in near flat terrain they showed a high accuracy (RMSE<4.49m and LE<7.00m). With increasing the elevation the RMSE and LE90 rapidly increased until values of 17.74m and 29.00m for test #14 and 16.45m and 28.00m for test #5, respectively.

Regarding the influence of the terrain's slope, again both the

Test ID	GCPs (nr.)	GCPs configuration	ICPs (nr.)	μ (m)	σ (m)	|μ| (m)	RMSE (m)	LE90 (m)
1	2	UR, LL	20	-1.50	4.49	3.47	4.63	7.91
2	2	UL, LR,	20	-2.46	3.90	3.36	4.53	8.91
3	2	LR, LL	20	-2.80	4.47	3.78	5.17	8.91
4	3	UL, LL, LR	19	-2.12	2.15	2.43	2.98	4.91
5	3	C, LR, LL	19	1.15	1.97	1.77	2.24	3.23
6	3	C, UL, UR	19	1.82	2.63	2.82	3.14	4.70
7	4	UL, UR, LL, LR	18	-1.52	1.80	1.78	2.32	3.97
8	4	C, UR, LL, LR	18	-0.63	2.24	1.95	2.27	2.98
9	4	C, UR, LL, UL	18	-0.31	1.59	1.31	1.58	2.97
10	5	C, UL, UR, LL, LR	17	9.26	2.50	9.26	9.57	13.38
11	6	UL, UR, LL, LR, RC, LC	16	-1.03	1.36	1.21	1.67	1.91
12	7	C, UL, UR, LL, LR, RC, LC	15	-1.46	1.68	1.59	2.18	4.70
13	8	UL, UR, LL, LR, RC, LC, C, CL	14	-0.12	1.64	1.26	1.58	3.77
14	9	UL, UR, LL, LR, RC, LC, C, CL, CR	13	0.47	1.39	1.23	1.41	2.77
15	22	all	0	0.47	1.61	1.39	1.64	2.38

C=centre image, UR=upper right, UL=upper left, LR=lower right, LL=lower left, RC=right centre, LC=left centre, CU=centre upper, CL=centre lower, all=all the 22 available GCPs.

Table 2. Accuracy of the Cartosat-1 absolute DTM. Statistics on residuals computed with respect to the Independent Check Points.

Test ID	GCPs (nr.)	GCPs configuration	ICPs (nr.)	μ (m)	σ (m)	|μ| (m)	RMSE (m)	LE90 (m)
1	2	UR, LL	20	-1.84	8.09	8.30	12.00	-1.84
2	2	UL, LR,	20	-2.86	7.77	8.28	12.00	-2.86
3	2	LR, LL	20	-3.14	7.52	8.15	12.00	-3.14
4	3	UL, LL, LR	19	-3.57	6.70	7.59	11.00	-3.57
5	3	C, LR, LL	19	-0.43	6.43	6.45	9.00	-0.43
6	3	C, UL, UR	19	-0.02	7.47	7.47	10.00	-0.02
7	4	UL, UR, LL, LR	18	-3.08	6.98	7.63	11.00	-3.08
8	4	C, UR, LL, LR	18	-1.94	6.87	7.14	10.00	-1.94
9	4	C, UR, LL, UL	18	-1.72	7.10	7.31	10.00	-1.72
10	5	C, UL, UR, LL, LR	17	8.06	10.00	12.85	16.00	8.06
11	6	UL, UR, LL, LR, RC, LC	16	-2.24	7.10	7.44	10.00	-2.24
12	7	C, UL, UR, LL, LR, RC, LC	15	-2.81	7.07	7.61	11.00	-2.81
13	8	UL, UR, LL, LR, RC, LC, C, CL	14	-1.69	6.98	7.18	10.00	-1.69
14	9	UL, UR, LL, LR, RC, LC, C, CL, CR	13	-1.22	6.79	6.90	10.00	-1.22
15	22	all	0	-0.76	6.81	6.86	9.00	-0.76

C=centre image, UR=upper right, UL=upper left, LR=lower right, LL=lower left, RC=right centre, LC=left centre, CU=centre upper, CL=centre lower, all=all the 22 available GCPs.

Table 3. Accuracy of the Cartosat-1 absolute DTM. Statistics on residuals computed with respect to the French DTM

aDTMs behaved similarly and in near flat terrain they showed a high accuracy (RMSE<4.52m and LE<7.00m). With increasing the slope the RMSE and LE90 rapidly increased until unacceptable values (greater than 22.00m for the RMSE and greater than 35.00m for the LE in the range of 30°-40° for slopes). It is to be noted that for the Salon de Provence test site 94.12% of samples had a slope less than 20°, consequently the resulting DTM's accuracy was better than 10.74m for RMSE and better than 17.00m for LE90.

Another term of comparison used for evaluating the DTM's performances were the requirements for IGN's and Spot Image's Reference 3D®. The Reference 3D® is a DTM generated using automatic correlation from SPOT-5/HRS data. Its specifications are given in Table 4 (Buillon *et al.*, 2006).
As shown in Table 5, the Cartosat-1 aDTM fulfilled the Reference 3D® requirements while the rDTM did not.

4.2 Low- resolution DTM generation

The performances of the Cartosat-1 satellite were also tested for the generation of low-resolution DTM (90m grid resolution).
As term of comparison it were used:

- The NASA's SRTM DTM;
- The MNT_DBTOPO® DTM downsampled to a 90m cell resolution;
- A set of ICPs extracted from the original C-SAP dataset.

Results show that the 90-meters Cartosat-1 aDTMs performed better than the SRTM DTM and overcome the SRTM's specifications, while the 90-meters Cartosat-1 rDTM poorly performed and did not met the SRTM's specifications.
Regarding the comparison to the higher precision ICPs, the best results were obtained for test #14 (μ=-0.12m, σ=3.16m, RMSE=3.09m and LE90=4.09m), followed by test #5 (μ=0.69m, σ=3.32m, RMSE=3.32m and LE90=5.34m) and the SRTM performed worse (μ=0.51m, σ=3.37m, RMSE=3.33m and LE90=7.38m).

Even if looking at mean values of residuals, standard deviations and RMSEs the Cartosat-1 aDTM and the SRTM have similar values, the former is more accurate in terms of LE90: that means that the Cartosat-1 low-resolution aDTM has fewer gross errors than the SRTM.

Parameter	Specifications
DEM resolution	1arc second (~30m on the Equator; 21m at 45° of latitude)
Planimetric absolute accuracy	15m at 90% confidence level
Altimetric absolute accuracy	10m at 90% confidence level, for slopes lower than 20% 18m at 90% confidence level, for slopes included in 20% and 40% 30m at 90% confidence level, for slopes greater than 40%
Planimetric relative accuracy:	10 m at 90% confidence level
Altimetric relative accuracy	5m at 90% confidence level, for slopes lower than 20% 15m at 90% confidence level, for slopes included in 20% and 40% 28m at 90% confidence level, for slopes greater than 40%

Table 4. Reference 3D® specifications.

When comparing all the low-resolution DTMs to the downsampled MNT_DBTOPO®, it seems that the SRTM has a better accuracy (μ=-0.87m, σ=5.92m, RMSE=5.99m and LE90=8.00m) than the Cartosat-1 low-resolution aDTMs (respectively μ=-0.41m, σ=6.47m, RMSE=6.48m, LE90=9.00m for test#5 and μ=-1.21m, σ=6.82m, RMSE=6.93m and LE90=10.00m for test#14), but these results may be due to an inaccurate estimation of the elevation data in the downsampled MNT_DBTOPO® DTM.
As expected, the Cartosat-1 low-resolution rDTMs showed inaccurate results (μ=4.20m, σ=13.51m, RMSE=14.14m and LE90=19.00m).

When considering the requirements for IGN's and Spot Image's Reference 3D®, the Cartosat-1 low-resolution DTMs (both relative and absolute models) met the requirements only for slope less than 20%, while for higher slopes they did not met the requirements.

5. CONCLUSIONS

For the Salon de Provence test site, it was fully investigated the potentialities and limits of the 2.5m Cartosat-1 stereo images for generating DTMs using commercial off-the-shelf software, so from the point of view of a typical user.

When generating relative DTMs, if not properly geocoded it was observed an error in the elevation values of some hundreds of meters. After georeferencing, the RMSE was between 9m and 14m and the LE90 between 16m and 19m.

When generating absolute DTMs, the optimum number of GCPs was found to be nine, with a regular geometric distribution (i.e., three in the upper part of the image, three in the centre of the image and three in the lower part of the image), while the minimum number of GCPs needed to get good DTMs was found to be three (i.e., one in the centre, one in the lower left and another in the lower right). In this cases, the absolute DTMs fulfilled the standards required for the IGN's and Spot Image's Reference 3D® and could be used for deriving such product.

Finally, the comparison of the downsampled Cartosat-1 DTMs with the NASA's SRTM showed that the former fulfilled the SRTM's specifications and could be successfully used to fill gaps in SRTM's DTMs. A similar conclusion was also found investigating the Mausanne les Alpilles test site (Gianinetto, 2008).

Slope range (%)	Reference 3D® requirements (LE90)	rDTM (LE90)	aDTM (LE90)
0-20	10.00	12.00	6.00
20-40	18.00	36.00	14.00
>40	30.00	58.00	27.00

Table 5. Accuracy of the Cartosat-1 relative and absolute DTMs. Statistics on residuals (LE90) computed with respect to Reference 3D® requirements

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