DEM generation using Cartosat-1 stereo data: issues and complexities in Himalayan terrain

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Abstract
High-altitude Himalayan terrain exhibits extreme geometric distortion along north-facing (dilation) and south-facing (compression) slopes as observed in satellite stereo data with high look angles. In the present study, Cartosat-1 stereo pairs have been used for generating Digital Elevation Model (DEM) using Differential Global Positioning System based Ground Control Points. DEM quality assessment through stereoscopic visualization revealed distortions especially in E-W oriented steep valleys. The study highlights issues and challenges in DEM generation for Himalayan terrain and articulates density of editing required. Quantitative and qualitative assessment of the DEM produced showed considerable improvements after post processing.

Keywords: Cartosat-1, Digital Elevation Model (DEM), Ground Control Points (GCPs), Himalayan terrain.

Introduction
The Indian Remote Sensing-P5 (IRS-P5) Cartosat-1 satellite is dedicated to stereo viewing and its data products utilized for various terrain modeling applications. This stereo capability assists in three-dimensional point determination and enables the generation of detailed Digital Elevation Model (DEM) [Crespi et al., 2008a; Jacobsen et al., 2008]. Cartosat-1 satellite launched in May 2005 is equipped with two cameras, Aft and Fore, tilted along-track by -5° and +26°, respectively; allowing the acquisition of stereo data with a geometrical resolution of 2.5 m with just 52 sec time difference in imaging. This configuration is optimized for stereo data collection in a 30 km swath with a base-to-height (B/H) ratio of 0.62 [Gianinetto, 2009]. The distance between image acquisitions points divided by the height of the sensor is termed as B/H ratio. Cartosat-1 data products have been evaluated for terrain modeling and large-scale mapping applications [Radhika et al., 2007; Martha et al., 2010a; Pieczonka et al., 2011]. Cartosat-1 data have also been used in several other fields namely, natural hazards assessment and estimation of hydrological parameters [Kumar et al., 2006; Gianinetto, 2009; Giribabu et al., 2010]. Present study is an endeavour to generate DEM for largely inaccessible Himalayan terrain...
falling in the upper regions of Alaknanda valley as required for hydropower sites selection at pre-feasibility level. The paper portrays issues and challenges during the DEM generation using Cartosat-1 stereo data for the study area where steep slopes and rugged terrain are dominant. Significant deviation in DEM accuracy was observed in the E-W oriented steep valleys. The reason for the outliers in this sort of terrain was identified due to poor image matching in the stereo pair. Further investigations revealed that poor image matching is because of image feature distortion caused due to high relief and look angles of camera. The paper explains the efforts required and alternatives to improve image matching in the steep slopes. The paper signifies the importance of stereoscopic visualization for outlier detection as a part of accuracy evaluation and reveals the obligatory labour to edit the DEM in stereoscopic environment.

**Data used**
Cartosat-1 stereo Ortho Kits have been used in the present study as shown in Table 1. Among them, one of the scenes was partially under snow cover in the northern direction (Path 535 Row 258 of 29 October 2005). Therefore, an additional scene for the same Path/Row has been used (04 March 2006) which was partially under haze on the southern side. The conjugate use of these two scenes aided in image matching for DEM generation. The IRS-P6, also known as Resourcesat-1, LISS-IV multispectral data of 6 m spatial resolution has been draped on DEM and visually compared with corresponding field photograph to analyse the quality of DEM output generated.

| S. No. | Path | Row | Date of acquisition          |
|--------|------|-----|-----------------------------|
| 1      | 533  | 257 | 20 November 2005            |
| 2      | 534  | 256 | 11 November 2006            |
| 3      | 534  | 257 | 11 November 2006            |
| 4      | 534  | 258 | 11 November 2006            |
| 5      | 535  | 256 | 29 October 2005             |
| 6      | 535  | 257 | 29 October 2005             |
| 7      | 535  | 258 | 29 October 2005 & 04 March 2006 |
| 8      | 536  | 256 | 31 October 2005             |
| 9      | 536  | 257 | 31 October 2005             |

**Methodology**
The methodology adopted in this study for the Cartosat-1 data processing to generate DEM is given in the sequential manner as follows:

**Rational polynomial coefficients processing**
Cartosat-1 stereo Ortho Kit enables view geometry in the form of Rational Polynomial Coefficients (RPCs). RPCs define the relationship between normalized pixel coordinates \((l\text{,}_N\text{ and } s\text{,}_N)\) and normalized ground coordinates \((\phi\text{,}_N\text{, } \lambda\text{,}_N\text{, and } h\text{,}_N)\) where \(h\text{,}_N\) is normalized height above the ellipsoid and usually given with respect to World Geodetic System (WGS84) as defined below:
\[ I_N = \frac{\text{Num}_i(\varphi_N, \lambda_N, h_N)}{\text{Den}_i(\varphi_N, \lambda_N, h_N)} \quad [1] \]

\[ S_N = \frac{\text{Num}_s(\varphi_N, \lambda_N, h_N)}{\text{Den}_s(\varphi_N, \lambda_N, h_N)} \quad [2] \]

where, Num\(_i\), Den\(_i\), Num\(_s\) and Den\(_s\) are third-order polynomials in lieu of sensor and satellite parameters. These equations require refinement at block level to achieve mapping accuracy by introducing Ground Control Points (GCPs). The Cartosat-1 stereo pairs have been ingested along with corresponding RPC files and interior orientation was carried out. Interior orientation defines internal geometry of a sensor as it was at the time of image capture and it transforms image pixel coordinate system to image space coordinate system using 2-D affine transformation equations based on six coefficients (i.e., \(a_1\), \(a_2\), \(a_3\), \(b_1\), \(b_2\) and \(b_3\)) given in the RPC file. The positional elements of exterior orientation (\(X_o\), \(Y_o\) and \(Z_o\)) define the position of the perspective centre with respect to the ground space coordinate system (\(X\), \(Y\) and \(Z\)) where \(Z_o\) is referred as height of the sensor above sea level and commonly defined by a datum. The exterior orientation or rotational elements describe part of relationship between ground space coordinate system (\(X\), \(Y\) and \(Z\)) and image space coordinate system (\(x\), \(y\) and \(z\)) [Groddecki and Dial, 2003].

**Ground control points**

The RPCs based stereo model has systematic offsets, which influences its accuracy for location determination. Accuracy of the RPC based stereo model can be further improved by using accurate GCPs. GCPs are points identifiable in real space (on the ground), whose locations are known and they are used to refine the orientation of the images. Data from a Differential Global Positioning System (DGPS) receiver at a known stationary location (base or reference station) is used to correct the data received by a receiver at an unknown location (roving receiver) and hence, DGPS basically involves two GPS receivers. As the base station knows its location exactly because of its continuous observations, it can determine satellite signal errors. This is done by measuring the ranges to each satellite using the received signals, which are compared to the actual ranges calculated from its known location. These differential corrections for each tracked satellite are used in the post-processing software for individual rover GPS point.

The study area falls in upper regions of Alaknanda valley in Himalayas, where six base stations were established for managing rover readings. The base stations selection was optimized such that the distance from the roving receiver lies within 25 km. GCP chips were extracted from the stereo datasets and for navigation purpose, names of the villages (and surrounding villages) and its approachability were attached. Planning of 76 GCPs were done based on the following criteria: a) identifiable on both Aft and Fore bands of stereo pair based on contrast and fidelity; b) distribution on each stereo pair and for the entire block; c) approachability and d) provision for acquiring a GCP amongst multiple choices given in vicinity (within one km radius) based on field conditions. In the present study, after setting-up project definition and data downloading, interior and exterior orientation were
performed using Leica Photogrammetry Suite (LPS) based on RPC information provided in the Cartosat-1 stereo Ortho Kit and GCPs collected using DGPS. Post-processing of the observed rover points were done with six base station points as reference using Spectrum Network Adjustment module of the Sokkia’s Spectrum Survey Suite through least squares adjustments on rover point network with respect to base station points to identify any inherent errors within survey data. Figure 1 shows the distribution of GCPs and check points.

![Figure 1 - Distribution of GCPs and check points. Areas where control points are not obtained are predominantly under glacier or perennial snow cover.](image)

**Image matching**

Image matching is a process to find correspondence between two images in the stereo model. Usually, this correspondence is achieved through matching of identical objects that appear in both the stereo images. The matching can be area based, using sub-matrices of grey values, or feature based using corresponding positions from feature extraction algorithm (points, edges, patches). The area based least squares matching transforms a sub-matrix to the corresponding sub-matrix by affine transformation, improving the grey values by shift and a linear function of output pixel coordinates. It also yields good image matching results for inclined areas where simple image correlation has some limitations.

The image matching depends on image quality parameters i.e., radiometric resolution and its accuracy, represented by noise level, geometrical resolution and sharpness, described by the Modulation Transfer Function (MTF). The noise is intensity dependent showing smaller noise values for the bins of low grey levels than for the high grey ones [Crespi et al., 2008a]. The MTF values in along-track direction (the direction on the ground along the satellite path) are always larger (and thus, better) than those for across-track direction (the direction on the ground perpendicular to the satellite path) and the Aft image has a
remarkable better quality than Fore Image [Crespi et al., 2008b]. Jacobsen et al. [2008] reported that if there is no contrast on the ground, no optical sensor is successful. Crespi et al. [2008b] reported that a crucial factor influencing the matching is different texture between two images due to large time span between their acquisitions. Martha et al. [2010b] used Cartosat-1 stereo data at high Himalayan terrain and concluded that a low sun-elevation angle data showed 45 per cent higher spatial accuracy than the Digital Surface Model (DSM) extracted from high sun-elevation angle data. The along-track viewing geometry with Aft and Fore camera mounted on Cartosat-1 satellite yields superior image matching [Nandakumar et al., 2008]. However, the Cartosat-1 stereo images, especially the Fore image for high altitude Himalayan terrain shows extreme geometric distortion along the north-facing (dilation) and south-facing (compression) slopes of E-W valleys. This creates problems in the process of image matching. Figure 2 shows the typical examples of image matching constraints caused due to very high-relief in Himalayan region which distorts shape of the features and also causes differences in texture and pattern.

Figure 2 - Typical examples of image matching constraints imposed due to very high relief in Himalayan region which distorts shape of the features (a, b) and also causes differences in texture and pattern (c).
During the image matching process, the tie points were automatically generated throughout the image overlap areas using the LPS software with parameters as shown in Table 2. Tie points are the points whose ground coordinates are not known but they can be identified in the overlapping areas of the images. In order to have an even distribution of tie points throughout the image overlap areas, feature-specific image enhancement functions (linear and non-linear) were applied on stereo images to improve tie points concentration in the regions where automatic process failed; especially for areas that are under shadow and poor contrast in the scene. Manual method of identifying tie points was also employed in the regions under dense forest and snow cover.

Table 2 - LPS software parameters used to generate automatic tie points.

| S. No. | Parameter         | Setting | Remarks                                           |
|-------|-------------------|---------|--------------------------------------------------|
| 1     | Search size       | 21 * 21 | Window size (in pixels) to search for corresponding points |
| 2     | Correlation size  | 7 * 7   | Window size (in pixels) for cross-correlation     |
| 3     | Least square size | 21 * 21 | Window size (in pixels) for least-square matching |
| 4     | Feature point density | 200 | Feature point density (percentage) |
| 5     | Coefficient limit | > 0.80  | Limit for cross correlation                      |

Results and discussion

DEM generation

The block adjustment project in LPS environment with ten Cartosat-1 stereo pairs was created for the study area using 76 GCPs collected from the DGPS survey. Titarov [2008] suggested that in the case of single stereo pair, four well-distributed and reliable GCPs are sufficient to achieve sub-pixel orientation accuracy. In the present study, the block adjustment project consists of ten stereo pairs therefore; at least one GCP in the overlap/ sidelap with respect to the neighboring scenes was placed to get a rigid bundle block solution. Iterations were carried out with varying number and distribution of GCPs to reduce the Root Mean Square Error (RMSE) at check points. Checkpoints are points identifiable on the image with known ground space coordinates and used for assessing the accuracy. Model RMSE is indicative of modeling and GCPs’ accuracy whereas check point RMSE reflects restitution accuracy, which conveys the feature extraction error and are indicators for final positional accuracy of planimetric features. The sub-pixel orientation accuracy was achieved with 65 GCPs whose distribution is shown in Figure 1. Remaining 11 points were opted as checkpoints. Orientation at sub-pixel accuracy can be achieved with lesser number of GCPs but the redundancy in the control points provides confidence about the reliability of geo-position process [Fraser, 2004].

Later, the Cartosat-1 data was triangulated after generating tie points. The ground coordinates for the tie points were calculated during triangulation. Triangulation resolves the problem of finding the position of any given point in space, if its position on two images is known [Hartley and Sturm, 1997]. The information resulting from
triangulation is required as input for the ortho-rectification process. Ortho-rectification is a process of correcting the imagery into a planar, map-like form by accurately removing all sensor, camera and terrain related distortions with the help of camera/sensor models, terrain models and GCPs. After performing the triangulation with 65 GCPs and 124654 tie points, the model’s RMSE was 0.503 pixel indicating that the residual error in the model is within a pixel. The DEM was generated after achieving the above model accuracy.

**DEM editing**

After performing the triangulation, the epipolar images were generated during the DEM editing process and kept as background in 3D environment. Epipolar images are stereo pairs that are re-projected such that conjugate images have a common orientation and matching features between the images appear along a common horizontal axis. Stereo vision is feasible with the help of these images which are along epipolar plane. The mass points are overlaid on these epipolar images to check their consistency. Mass points are irregularly distributed sample points which are used as the basic element to build a Triangulated Irregular Network (TIN). The TIN model represents a surface as a set of contiguous, non-overlapping triangles. After generating the TIN using Automatic Terrain Extraction (ATE) module of LPS, the next step is thorough quality verification through its analysis under stereoscopic visualization. During this process, the mass points that are on top of the surface or digging below the surface are construed as erroneous points. Each mass point has important, yet equal, significance in terms of defining the TIN surface. If the mass points associated with a terrain dataset are off the ground, specific DEM editing tools available in Terrain Editor of LPS software has been used to ensure that the terrain dataset does conform to model’s surface. The LPS Terrain Editor facilitates visualization, verification and editing of DEM. During the DEM editing process, mass points which were off the ground have been edited or densified by adding new mass points in the stereo environment. The location of each mass point was intelligently chosen to capture important variations in the surface morphology. Dynamic range adjustments of the visible area for clarity during on-screen operations were applied during the process of editing of existing mass points or identification of new mass points. Approximately, 15% of mass points were edited and 20% of mass points were completely removed in regions under high relief or poor contrast and new mass points were added for every window of 50 m by 50 m size. Further, breaklines have been added that define abrupt changes in elevation (natural or manmade) in topographical shapes to improve the DEM quality. Breaklines (hard and soft) define and control surface behavior in terms of smoothness and continuity. Hard breaklines define interruptions in surface smoothness and are typically used to define streams, ridges and other locations of abrupt surface change. Soft breaklines were used to ensure that known elevation values along a linear feature (such as a roadway) are maintained in a TIN. Soft breaklines were also used to ensure that linear features and polygon edges are maintained in the TIN surface model by enforcing the breakline as TIN edges. Soft breaklines, however, do not define interruptions in surface smoothness. Table 3 and Figure 3 show the mass points and breaklines drawn during DEM editing process in the upper regions of Alaknanda valley. Figure 4 shows the DEM quality improvement after the editing process.
Table 3 - Characteristics of breaklines digitized during DEM editing.

| S. No. | Pattern                        | Breakline type       | Remarks                                                      |
|--------|--------------------------------|----------------------|--------------------------------------------------------------|
| 1      | Broad river (in the up-hill direction) | Double breakline & hard type | 98 km of breaklines covering Alaknanda river and its major tributaries |
| 2      | Narrow river (in the up-hill direction) | Single breakline & hard type | 87 km of breaklines covering sub-tributaries of Alaknanda river |
| 3      | Shear face features             | Single breakline & hard type | 110 km covering ridges, 3rd order drainages                  |
| 4      | Roads                          | Soft breakline       | 165 km covering major roads                                 |
| 5      | Other features (using pseudo contours) | Hard or Soft breakline | 175 km covering lakes, major ditches, etc.                   |

Figure 3 - Mass points and breaklines generated during DEM editing.
Ortho-image generation
Ortho-image is generally defined as an image that has been geometrically corrected for displacements caused by terrain and relief. In an ortho-image, the projecting rays are perpendicular to the plane of projection and hence, any part of the object that is parallel to the plane of projection will appear in its proper shape and correct scale. The Aft scene of Cartosat-1 has been used for ortho-rectification due to its better Ground Sampling Distance (GSD) (~2.2 m as compared to 2.5 m for the Fore scene) and viewing angle closer to nadir. It has slightly smaller ground coverage but the larger footprint covered by the Fore scene is not fully collected in stereo [Lutes, 2006]. The DEM as generated after editing was used for ortho-image generation. The resolution of the ortho-image was set to 2.5 m.

DEM accuracy
A DEM is not a true representation, but a model of the earth’s surface and is subjected to errors like other spatial data [Wechsler, 2006]. These errors can be quantified by calculating the RMSE of the respective DEM. Usually, DEM accuracy assessment is achieved through
comparing the DEM values with reference values and concluded by standard deviation (SD) or RMSE [Nikolakopoulos et al., 2006; Tsutsui et al., 2007]. Accuracy assessment of DEM by means of RMSE requires accurate reference values in the form of checkpoints. Table 4 shows the DEM and ortho-image evaluation using 11 checkpoints. The RMSE errors using 11 checkpoints were obtained as 3.3 m, 3.5 m and 7.8 m in along-track, across-track and height, respectively.

Table 4 - DEM and Ortho-image evaluation using checkpoints.

| S. No. | GPS observations | Ortho-image observations |
|--------|------------------|--------------------------|
|        | Latitude | Longitude | Height | Latitude | Longitude | Height |
| 1      | 360416.30   | 3390152.00 | 1919.89 | 360417.81 | 3390153.77 | 1911.00 |
| 2      | 344935.70   | 3376173.00 | 2393.17 | 344937.88 | 3376175.70 | 2385.00 |
| 3      | 365131.10   | 3394513.00 | 2540.99 | 365135.43 | 3394518.60 | 2528.00 |
| 4      | 367308.60   | 3397091.00 | 4149.66 | 367307.71 | 3397086.99 | 4138.00 |
| 5      | 363395.90   | 3381085.00 | 1813.47 | 363390.09 | 3381087.11 | 1809.00 |
| 6      | 362140.30   | 3388297.00 | 1763.33 | 362145.91 | 3388294.68 | 1760.00 |
| 7      | 338401.20   | 3364955.00 | 1404.05 | 338402.02 | 3364959.01 | 1392.00 |
| 8      | 340674.80   | 3362382.00 | 1560.23 | 340675.63 | 3362385.20 | 1563.00 |
| 9      | 345995.70   | 3346909.00 | 1628.39 | 345991.17 | 3346911.58 | 1625.00 |
| 10     | 356341.90   | 3355109.00 | 2529.02 | 356340.19 | 3355104.98 | 2528.00 |
| 11     | 357857.50   | 3352013.00 | 1879.08 | 357858.59 | 3352008.69 | 1874.00 |

| S. No. | Latitude errors (m) | Longitude errors (m) | Height (m) |
|--------|---------------------|----------------------|-----------|
|        | Diff. | Square | Diff. | Square | Diff. | Square |
| 1      | -1.51  | 2.28   | -1.37  | 1.88   | 8.89  | 79.03 |
| 2      | -2.18  | 4.75   | -2.70  | 7.29   | 8.17  | 66.75 |
| 3      | -4.33  | 18.75  | -5.60  | 31.36  | 12.99 | 168.74 |
| 4      | 0.89   | 0.79   | 4.01   | 16.08  | 11.66 | 135.96 |
| 5      | 5.81   | 33.76  | -2.11  | 4.45   | 4.47  | 19.98 |
| 6      | -5.61  | 31.47  | 2.32   | 5.38   | 3.33  | 11.09 |
| 7      | -0.82  | 0.67   | -4.01  | 16.08  | 12.05 | 145.20 |
| 8      | -0.83  | 0.69   | -3.20  | 10.24  | -2.77 | 7.67 |
| 9      | 4.53   | 20.52  | -2.58  | 6.66   | 3.39  | 11.49 |
| 10     | 1.71   | 2.92   | 4.02   | 16.16  | 1.02  | 1.04 |
| 11     | -1.09  | 1.19   | 4.31   | 18.58  | 5.08  | 25.81 |

RMSE (m): 3.27 (~3.3), 3.49 (~3.5), 7.82 (~7.8)
**Visual quality assessment**

As DEMs are representation of a ground surface that is commonly used to produce topographic maps, data quality assessment is crucial for the DEM and the ortho-rectified image produced. Besides, quantitative assessment of DEM accuracy through checkpoints collected using DGPS, visual quality assessment has also been carried out by comparing the ortho-image draped over DEM and the field photographs of random sites. Perspective view representation of the terrain and visual inspection can be of high importance for the evaluation of spatial data and can balance some weaknesses of statistical methods [Podobnikar, 2009]. A perspective view has been generated using Resourcesat-1 LISS-IV multispectral and Cartosat-1 merged product draped over Cartosat-1 DEM and visually compared with corresponding field photograph of the valley surrounding Kurkuti village, Dhauliganga valley, Chamoli district, Uttarakhand state, India (Figs. 5a and 5b, respectively). The two products generated confirm their close resemblance in terms of alignment of ridges and valleys.

![Perspective view (a) generated using Resourcesat-1 LISS-4 multispectral and Cartosat-1 merged data draped over Cartosat-1 DEM and corresponding field photograph (b) showing a view of Kurkuti village, Dhauliganga valley, District Chamoli, Uttarakhand, India.](image)

**Conclusions**

In mountainous regions like Himalayas, the DEM generation poses challenges due to occlusions and shadow regions. The Cartosat-1 stereo pairs utilized for generating DEM for the upper regions of Alaknanda valley in high altitude Himalayan terrain using 76 GCPs collected using DGPS yielded the model’s total RMSE as 0.503 pixel indicating
that the model error is within a pixel. Extreme geometric distortion along the north-facing (dilation) and south-facing (compression) slopes of E-W valleys are prevalent in high Himalayan region on Cartosat-1 images which creates problems during the process of image matching. Thus, during DEM editing process, mass points which were off the ground have been edited or densified by adding new mass points in the stereo environment. Local image enhancement functions were applied for manually improving the mass points’ concentration in the shadow regions. Breaklines (hard and soft) were added to define the locations of abrupt surface change and maintain the linear features and polygon edges. The RMSE errors using 11 checkpoints were obtained as 3.3 m, 3.5 m and 7.8 m in along-track, across-track and height, respectively. Visual assessment of data quality has been carried out with comparison of ortho-image draped over DEM and the field photograph of random sites. It is suggested here that multi-image combinations e.g., stereo-triplets (combination of Fore and Aft Camera with B/H ratio of nearly 1 along with a near nadir looking camera) imaging system or stereo-quadruplets (combination of Fore and near nadir, and near nadir and Aft image) may generate better quality DEMs for the high relief Himalayan region and that may reduce the efforts in DEM editing.

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