Generation of state of the art very high resolution DSM over hilly terrain using Cartosat-2 multi-view data, its comparison and evaluation – A case study near Alwar region

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Abstract: High resolution Digital surface models (DSMs) are prime requirement for many applications such as disaster management, strategic usage, infrastructure planning and many more. Prime objective of this study is to generate high resolution and accurate DSM using Cartosat-2 multi-view, multi-date data and to evaluate its accuracies with respect to ground truth. In this study, multi-view and multi-date data from Cartosat-2 mission is used and a high resolution DSM is generated using the approach of satellite photogrammetry. Generated DSM is then compared with all other recent DSM datasets available in open space as well as with very recently generated CartoDEM V3R1 DSM. Carto2 DSM is generated at grid interval of less than 1 meter and it has vertical accuracy of < 2m as evaluated with reference Ground Control Points (GCPs). In this paper, we are discussing the methodology to generate high resolution DSM, its comparison with other available DSMs, its evaluation and accuracy with reference GCPs.

Keywords: Digital surface models, Cartosat-2, Carto-1DEM, SRTM, ASTER, ALOS.

1. Introduction

Digital Surface Models (DSM)/ Digital Elevation Models (DEM) represent surface of the Earth. There are different methods of generating DSM like satellite photogrammetry, radargrammetry, laser scanning and aerial photogrammetry. In this technical paper, across track satellite data of Cartosat-2 mission and satellite photogrammetry approach is used to generate DSM of hilly area nearby Alwar, India. Other space agencies are also in the business of generating accurate DSMs from space borne systems such as Shuttle Radar Topography Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Global DEM from India using CartoSat-1 and ALOS World 3D (AW3D c JAXA) DEM. Cartosat-2 (C2) satellite provides high resolution panchromatic data using step & stare technique with three different modes of imaging capability viz. paint brush, spot and multi-view. It is a highly agile satellite which acquires data with fine spatial resolution of 0.8m with 10-bit radiometric resolution. Generation of High Resolution(HR) DSM is one of the major requirements for cartographic applications. For this case study, a multi-date (from multi orbits) data set is selected near Alwar region. An exercise is performed to generate Carto2 DEM with stereo images.

High resolution and accurate DSM provides accurate shape of surface of the Earth and such high resolution data is required in many applications such as infrastructure planning, disaster management, city planning, 3D visualization, strategic usage and change detection. Ideally, stereo images acquired from two different view angles are required for satellite photogrammetry. Multi-view images acquired at two different times of same area with a fair amount of overlap can also be used as stereo images for the purpose of generation of DEM. Earlier, DEM generation using multi-view imageries from different satellite sensors has been attempted by many researchers across the globe. Krishnan et. al, 2008 demonstrated generation of DEM from high resolution multi-view data using Cartosat 2 data without the usage of GCPs (Krishnan et al, 2008). Nasir et. al. (2015) used Pleiades Tri stereo-pair to generate high resolution DEM and compared its accuracy with SRTM and ASTER DEM. (Ghuffar et al. 2018) generated DEM using multi – date images from Planet-scope satellite of PlanetLabs with an accuracy of ~4m at stable surface. (Han et al. 2020) used 0.3-meter World-view -3 multi-view data and generated DEM using three different software solutions. They have also compared DEM with LiDAR ground truth and obtained best RMSE of 1.4 m and worst RMSE of 1.9m. In very recent time, researchers have also conducted exercises to generate quality digital elevation models / evaluate the accuracies of DEM over Indian continent using the high resolution datasets. (Bhardwaj et al. 2019) conducted experiment of generation of high quality elevation models by assimilating DEM generated using Cartosat-1 stereo pair and InSAR pair (ALOS PALSAR-1) data to improve the quality of the DEM. In another work, (Agarwal et al. 2020) assessed accuracy of Cartosat-1 DEM using robust statistical measures. They evaluated the quality of Cartosat-1 DEM over 8 different sites. In a very recent study, Sandhu et al. (2021) evaluated suitability of Cartosat-2E data for large scale urban mappings. In this study, they have concluded that using high accurate GCPs, Cartosat-2E data can be utilized for large scale urban mappings.

Focus of this study is to generate high resolution and high accurate digital elevation model using Cartosat2 datasets. In this specific study, we have taken high resolution multi-view Cartosat-2, 0.8m data of two different dates and times and generated a high resolution DEM using the approach of satellite photogrammetry. Reference data i.e. precise ground control points are used for DEM processing and output product evaluation. Further, the generated high resolution DEM is compared with all open DEM datasets as well as with Cartosat-1 V3R1 DEM and aerial DEM. Vertical accuracy of the generated DEM is evaluated w.r.t. the ground control points (GCPs). In the last part of the paper, vertical accuracies of all available DSMs are assessed against reference ground data.

2. Datasets Details

Across the globe, many space agencies are providing 30m and coarser DSM as open source data. SRTM 30m, ASTER 30m and AW3D30 30m DSM products are available as open data on the web. Out of these SRTM is the oldest available dataset followed by ASTER and ALOS. ALOS-AW3D30 DSM is relatively newer to all of these. We have collected DSMs from multiple space agencies near to Alwar region as mentioned below:

SRTM: The Shuttle Radar Topography Mission (SRTM) was flown on space shuttle endeavour in Feb 2000**.** The main objective of the project was to acquire a digital elevation model of all land between 60° north latitudes and 56° south latitudes. SRTM employed two synthetic aperture radars, a C-band system (5.6 cm; C-RADAR) and an X-band system (3.1 cm) to capture the data in **11-day time** (Farr et. al, 2004). Third dimension was derived using the principles of interferometer by getting range difference between two radar images. Until 2014, the global dataset was available at a 3-arcsecond (90 meters) posting for regions outside the USA. In 2015**,** the NASA released the SRTM Version 3.0 Global 1-arcsecond (30 meters) dataset (SRTMGL1) for global community. In this research, the 1-arcsecond (approximately 30m at the equator), was used. It is available from NASA's Earth Explorer website.

ASTER: Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) is a DSM from NASA and Japan's Ministry of Economy, Trade and Industry (METI). The Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) on NASA's Terra spacecraft collects in-track stereo using nadir and aft looking near infrared cameras. The "version 1" ASTER GDEM (GDEM1) was compiled from over 1.2 million scenes based DEMs covering land surfaces between 83°N and 83°S latitudes. A joint US-Japan validation team assessed the accuracy of the GDEM1. The GDEM1 was found to have an overall accuracy of around 20 meters at the 95% confidence level (Tachikawa T. et al. 2011). Improvements in the GDEM2 result from acquiring 260,000 additional scenes to improve coverage, a smaller correlation kernel to yield higher spatial resolution, and improved water masking. Data is freely available at a 1-arcsecond posting from NASA's Earth Explorer (NASA-JPL). It was compiled from over 1.5 million scenes acquired between 2000 and 2009 and released in year 2011. The RMSE accuracy of the ASTER GDEM changes with location and is influenced by the land cover type, varying from 15.1m in forested mountainous areas to 23.3m in urban areas. In this study, ASTER GDEM V2 was used and is further referred to as ASTER.

AW3D: The ALOS World 3D (AW3D c JAXA) DSM, publicly released by JAXA in **2016**, is the most recent DSM. The Japan Aerospace Exploration Agency (JAXA) generated the global digital elevation/surface model (DEM/DSM) and orthorectified image (ORI) using the archived data of the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) on board the Advanced Land Observing Satellite (ALOS), which was operated from 2006 to 2011 (Tadono et al. 2014). PRISM consisted of three panchromatic radiometers that acquired along-track stereo images. It had a spatial resolution of 2.5 m in the nadir-looking radiometer and achieved global coverage. The AW3D DSM is commercially distributed at a 5m resolution, while a 30m down sampled dataset (known as 'AW3D30') is publicly available (ALOS URL).

Cartosat-1 DEM (CartoDEM): Cartosat-1 mission was launched on May 5, 2005 with prime objective of acquiring in-track stereo images of 2.5m resolution. One of the main objective is to generate a DEM and corresponding ortho-image for the entire country to facilitate many cartographic applications. Cartosat-1 has acquired images all over India and across the globe between year 2005-2015. Cartosat-1 satellite has two panchromatic cameras with 2.5m spatial resolution, to acquire two images simultaneously, one forward looking (Fore) at +26 degrees and another rear looking (Aft) -5 degrees for near instantaneous stereo data (CartoDem Brochure). Using Cartosat-1 data over a period of (2005-2015), DEM over entire India is generated with the approach of Augmented Stereo Strip Triangulation (ASST) software developed at SAC. CartoDEM has an absolute planimetric accuracy of 15 meters and absolute vertical accuracy of 8 meters. In this exercise, we have used latest DSM of Cartosat-1 (Cartosat-1 V3R1) near Alwar region available on the (Bhuvan URL).

Cartosat-2: As such, Cartosat-2 is not a stereo mission like Cartosat-1, still stereo data can be acquired in multiple combinations of various imaging modes. Cartosat-1 provides along track stereo whereas Cartosat-2 can provide data in across track & along track. The image pair used in this exercise is acquired in across track stereo mode with B/H ratio is 0.47 over Alwar region. Cartosat-2 Orthokit products of two different dates are taken as input. Orthokit product contains meta file and RPC file along with the image. Following are the details of the dataset:

Table 1. Details of the Carto2 multi-view datasets

Sr. no	Product ID	Date of Pass	Orbit No
1.	1414051311	14MAY13	34227
2.	1418051311	18MAY13	34286

Orthokit data product Orthokit product contains a radiometrically corrected image in GeoTiff format. It also contains Rational Polynomial Coefficients (RPC) file. RPC are provided in lieu of detailed sensor and payload parameters, which helps the user to further process and geo-correct the product. The user can use these RPCs to generate a precision (or ortho-corrected) product, precise GCPs and DEM are available externally for correction.

Selected across track stereo image pair (ref Table 1) has an overlap of more than 80 percent as evident from figure 1.

Aerial DSM: Aerial survey was conducted over the same and nearby places in the year 2003-04. DSM with 25 m resolution and an accuracy better than 5 meter was generated as a result of aerial survey. This Aerial DEM is also used in the comparison.

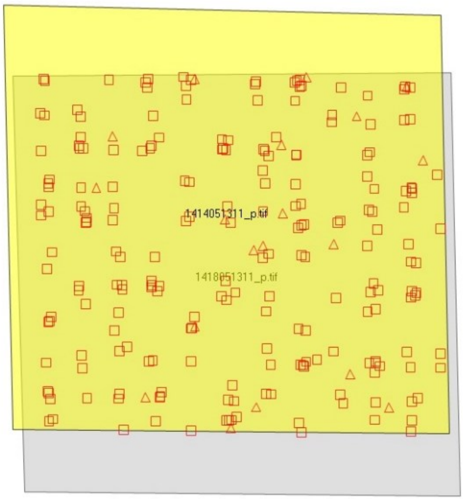


Figure 1. Overlap area from different view point acquired using Cartosat-2

Reference data: A few control points collected at relatively plain and stable areas using DGPS were used as reference in DEM generation and remaining precise control points (collected using DGPS) with accuracy less than 1m are used for evaluation purpose. For processing of stereo images, six (6) well distributed ground control points are used along with the dense tie points. Whereas, for evaluation and comparison of global DEMs with Cartosat-1 DEM, ~150 control point were used. Due to 10x10 KM area coverage in Carto-2 image, 15 nos of common control points were used for evaluation of Carto-2 and other DEMs.

3. Methodology

For DEM generation, first and foremost task is to set up the model in ERDAS (Geosystem, 2004) with the input data and reference coordinate system (WGS 84). In ERDAS, LPS software module, radiometrically corrected stereo images are added with the sensor information and RPC files, which are used in the process of interior orientation. Reference data is required to collect ground control points and ground control points are used as an input to the exterior orientation process. The work flow for DEM generation is depicted in the figure 2.

GCP identification is an important step for achieving the accurate and precise DEM. For DEM generation in this exercise, six numbers of well distributed control points are identified precisely using reference Cartosat-1 ortho image along with precise height information. Further, Tie points are generated with user defined parameters and distribution criteria.

As the name suggests, tie point binds the two images & is a point whose ground coordinates are not known, but is visually recognizable in the overlap area between two images. The tie points are generated using image matching which refers to the automatic identification and measurement of corresponding image points that are located on the overlapping area of multiple images. Well distributed and very dense tie points assure good accuracy. Triangulation is performed with well distributed control points & tie points; it means setting relation between image coordinates & ground coordinates. Triangulation results shows RMSE of 0.45 pixel with respect to given control points.

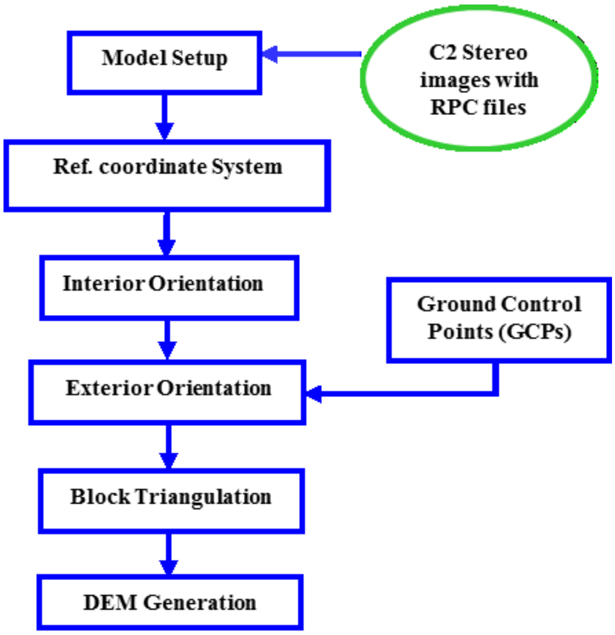


Figure 2. Work Flow of DEM generation

After triangulation, DEM with regular grid interval at 1m is generated as shown in figure 3. DEM is defined as set of well distributed regular/ irregular grid points with precise ground control points.

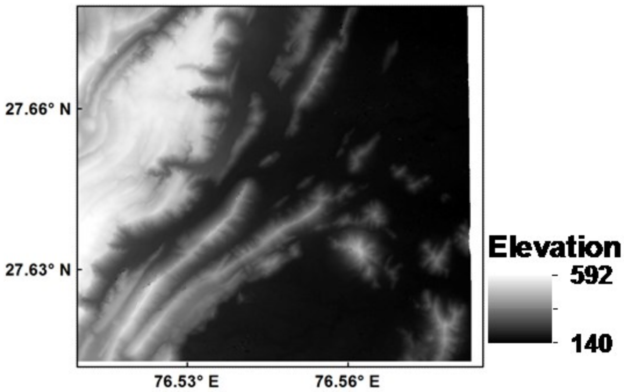


Figure 3. High resolution DEM generated using Carto2 data at grid interval of 1m

4. Results and Discussions

In this section, comparison of generated DEM is made with latest available DEMs in open source domain. As already described in section 2, data from multiple sources like SRTM-30m version-3, ASTER-30m version 2 and ALOS 30m latest DEM (AW3D30), Aerial DEM with a grid interval of 25 meter, Cartosat-1 V3R1 DEM with a resolution of 10m and Carto2 with a grid interval of 1m, 10m and 30m respectively is taken for comparison. AW3D30 and SRTM DEM are available in geoidal datum. If one straightway compares SRTM DEM with Cartosat-1 (ellipsoidal) DEM, significant differences will be observed. So, we have converted vertical datum from geoidal to ellipsoidal in the case of SRTM and ALOS for comparisons. Carto-2 DEM is also re-generated at 10m and 30m grid interval for comparisons with Cartosat-1 10m DEM and SRTM, ALOS and ASTER 30 m DEM. Further, the hill-shade views of ALOS-30m, Cartosat-1 V3R1 10m, Aerial 25m and Carto2 1m DEM are compared as per figure 6 for visual interpretations. From figure 6, the finest level of details available in 1m Carto2 DEM is visible compared to other DEMs.

In figure 4(a) and figure 5(a), differencing of resampled Carto2 30m DEM with SRTM and ALOS 30m DEM and differencing of resampled Carto2 10m DEM with CartoDEM V3R1 10m DEM, is shown. Figure-4(b) and Figure-5(b) contains the histogram profiles of the difference of respective DEMs. It can be observed that w.r.t. SRTM 30m DEM, 85% of DEM area is matching in plain areas whereas w.r.t. Carto-1 10m DEM, 95% of differences lies in +- 5 meters' heights. Difference of Carto-2 DEM w.r.t ASTER and ALOS DEM w.r.t Carto-2 DEM also depicts the similar trends of 75-80 % complete match in plain areas and about 20-25% of variations over steep hills. As notable differences are mainly observed over steep tops using all the DEMs, the most common reason of differences on the steep hills are due to hills erosions over the time. Among other differences most obvious are acquisition of the data at different times; as SRTM data was captured in early 2000s, ASTER in between year 2000-2009, ALOS in between year 2007-2011, Cartosat-1 in year between year 2005-2015 whereas Cartosat-2 multi-view data is captured in year 2013. Exact date of data capture from SRTM, ASTER, ALOS and Cartosat-1 is unknown. Better spatial resolution and radiometry of Cartosat-2 also plays significant role in bringing out the differences among DEM datasets.

Further, statistics of DEM difference is calculated by generating C2DEM at 10m for comparison with Cartosat-1 10m DEM and for comparison with SRTM/ALOS 30m DEM, C2DEM is generated at 30m grid interval. As unedited C2DEM 10m DEM is compared to Carto1 10m DEM (Table-2) using QGIS tool, overall mean error of ~4m and standard deviation (SD) of ~7m is obtained. whereas, when C2D 30m unedited DEM is compared with SRTM, ALOS and ASTER 30M DEM, overall mean error of 4 to 6 m and standard deviation of 7 to 8 m is observed, which confirms that C2D has more resemblance with Cartosat-1 10m DEM. Further, Cartosat-2 DEM is compared with reference ground control points.

Table 2. Results of comparisons of Cartosat-2 DEM with Cartosat-1 DEM at 10m and SRTM/ALOS/ASTER DEM at 30meters.

S. No	Data Set	Min	Max	Mean error	S.D.
1	C2DEM / (SRTM/ ALOS/ASTER) – 30m	**-58m**	**38.3m**	**4-6m**	**7-8m**
2	C2DEM/ Carto1 – 10m	**-59m**	**39m**	**~4m**	**~7m**

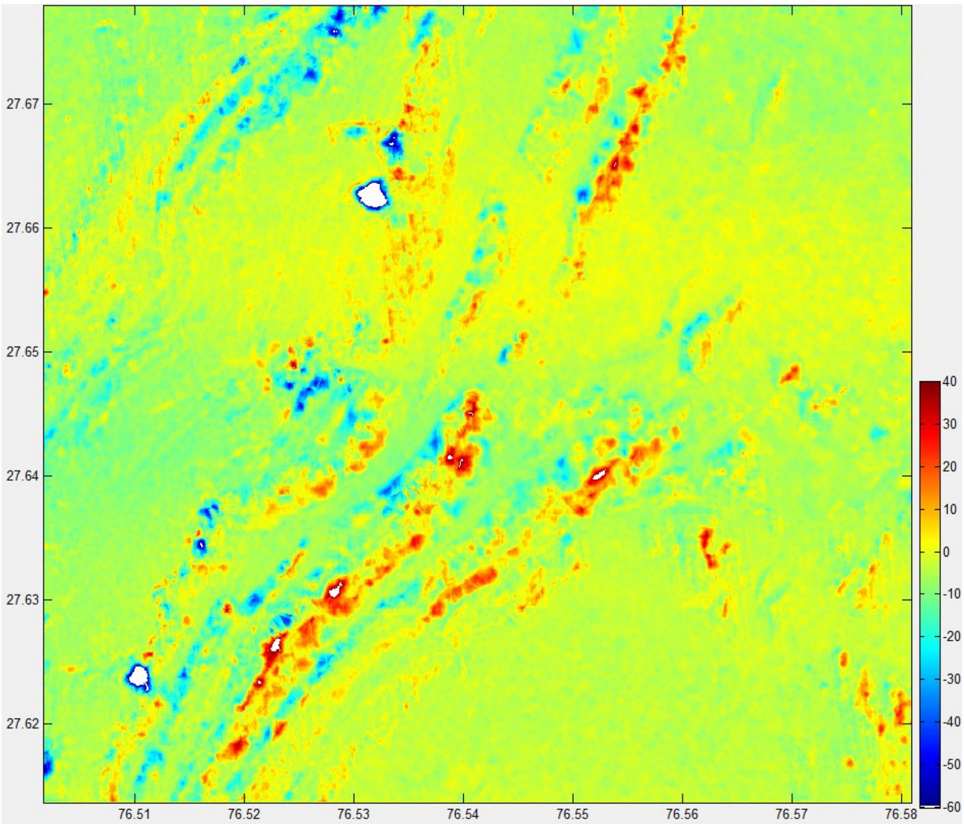


Figure 4(a). Difference of Carto2 DEM 10m with Carto1 10m DEM

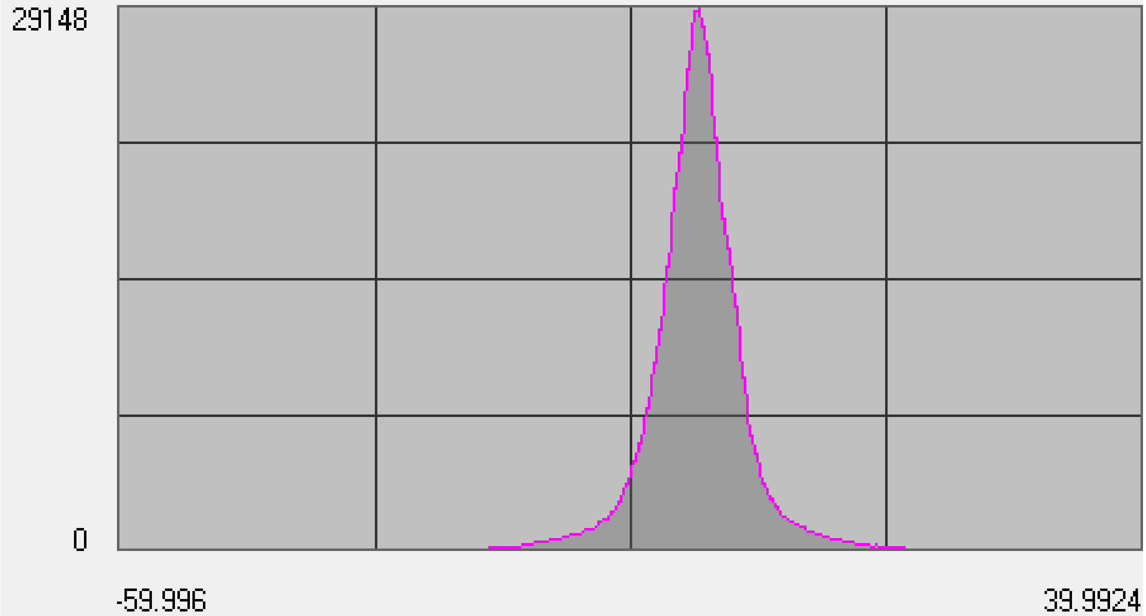


Figure 4(b). Histogram of difference of Carto2 DEM 10m with Carto1 10m DEM

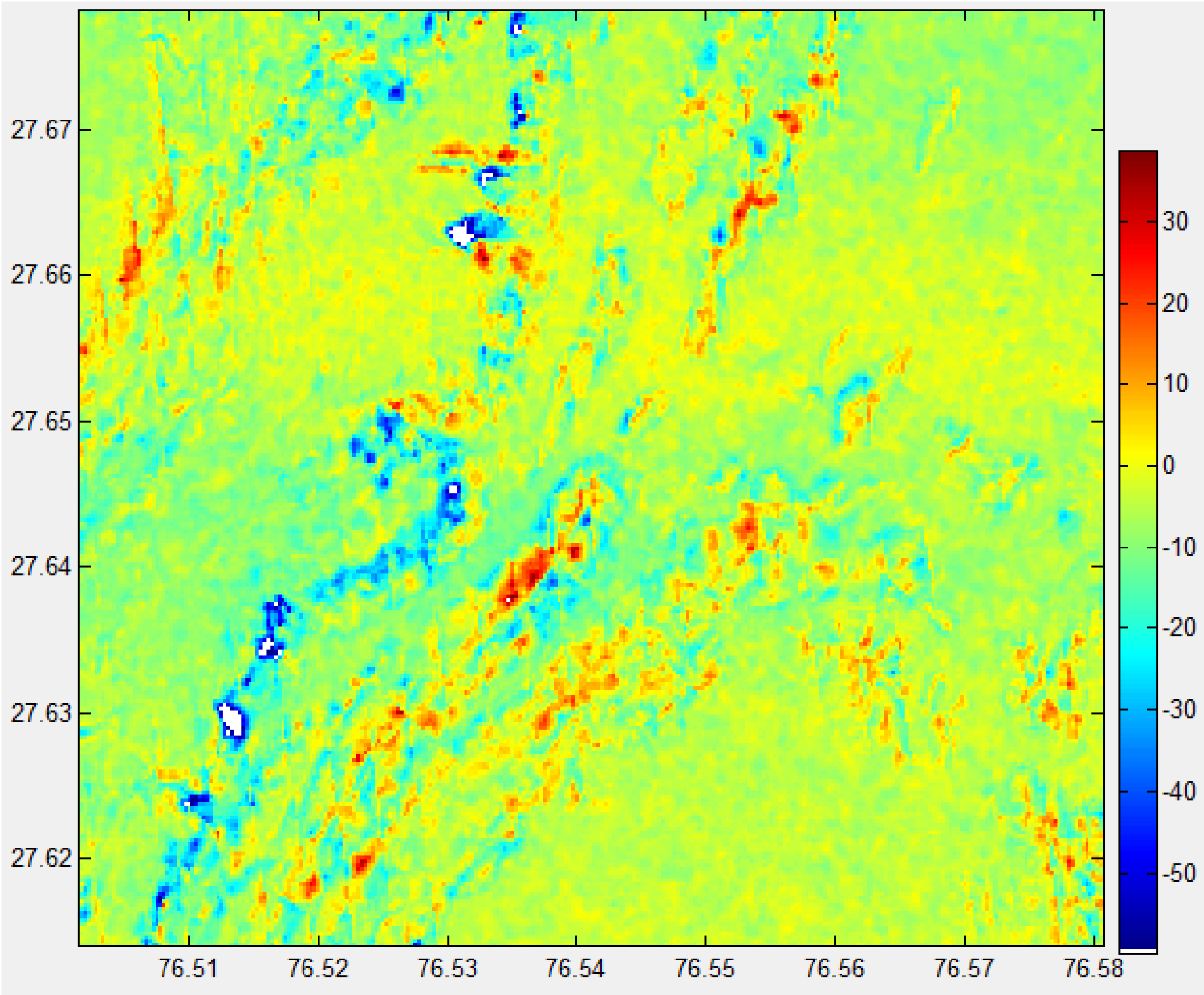


Figure 5(a). Difference of Carto2 DEM 30m with SRTM 30m DEM

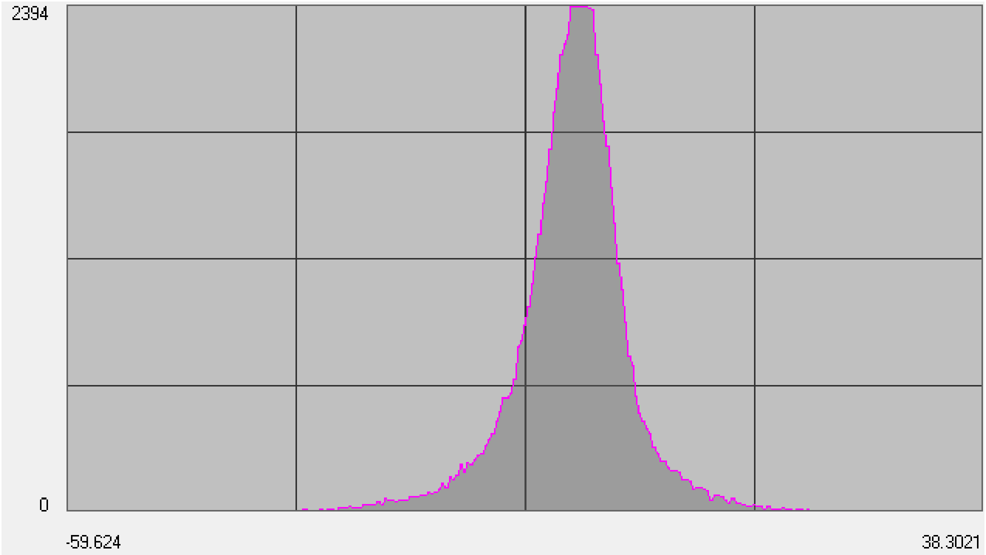
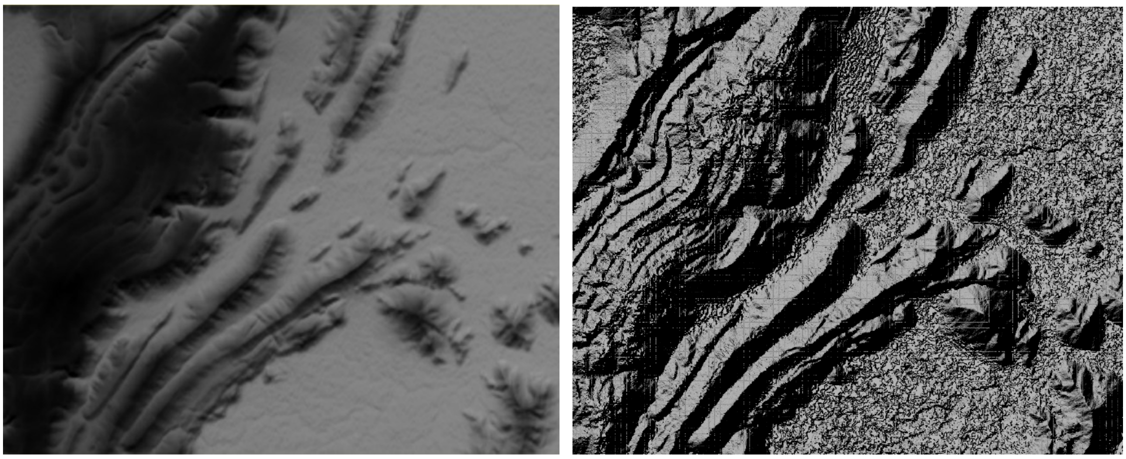
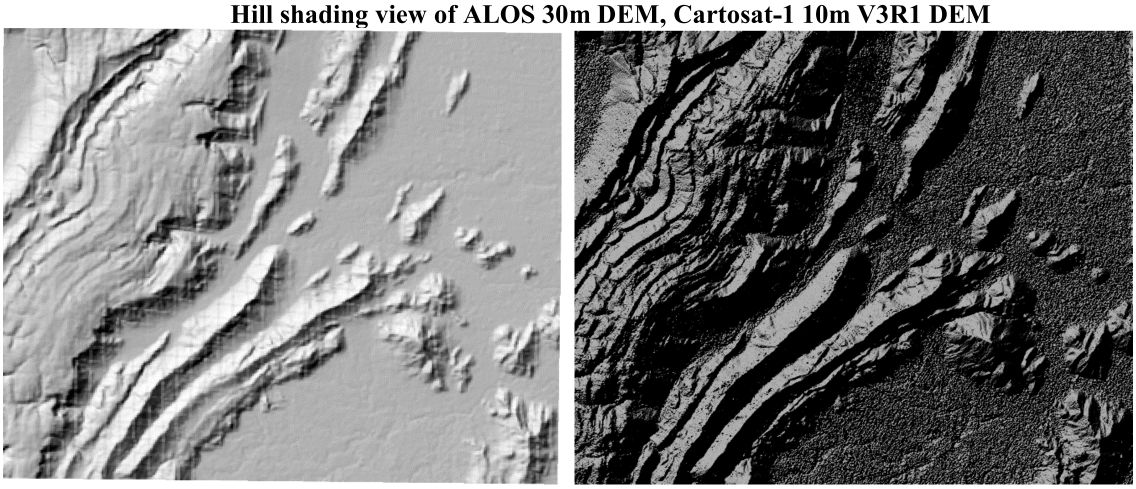


Figure 5(b). Histogram of Carto2 DEM 10m with Carto1 10m DEM



Hill shading view of ALOS 30m DEM, Cartosat-1 10m V3R1 DEM



Hill shading view using aerial 25m DEM and Cartosat-2 (1m) DEM

Figure 6. Hill shade view of ALOS-30m, Carto1 V3R1 10m, Aerial-25m and Carto2 -1m DEM

Hence, validation of the accuracy of generated DEM with all other DEMs as well as w.r.t. reference ground control points (acquired at plain and stable areas) is carried out. In figure 7, all the available precise GCP points (~150) are overlaid on Cartosat-1 V3R1 DEM to understand the spread of GCPs in the studied area. In figure 8, profiles of SRTM 30m, ASTER 30m and AW3D 30m DEMs and reference GCP points were plotted and it is inferred that profile of all the DSM matches quite well with the available reference GCP points. Figure 9 and 10 depicts the profile plots of Aerial DEM, Carto-1 v3R1 DEM with respect to Ground control points. By looking at the plots shown in figure 8, 9 and 10, one can infer that signatures are quite matching in all the DEMs selected for comparisons and vertical accuracies of all the DEMs are quite high on hilly area near to Alwar region.

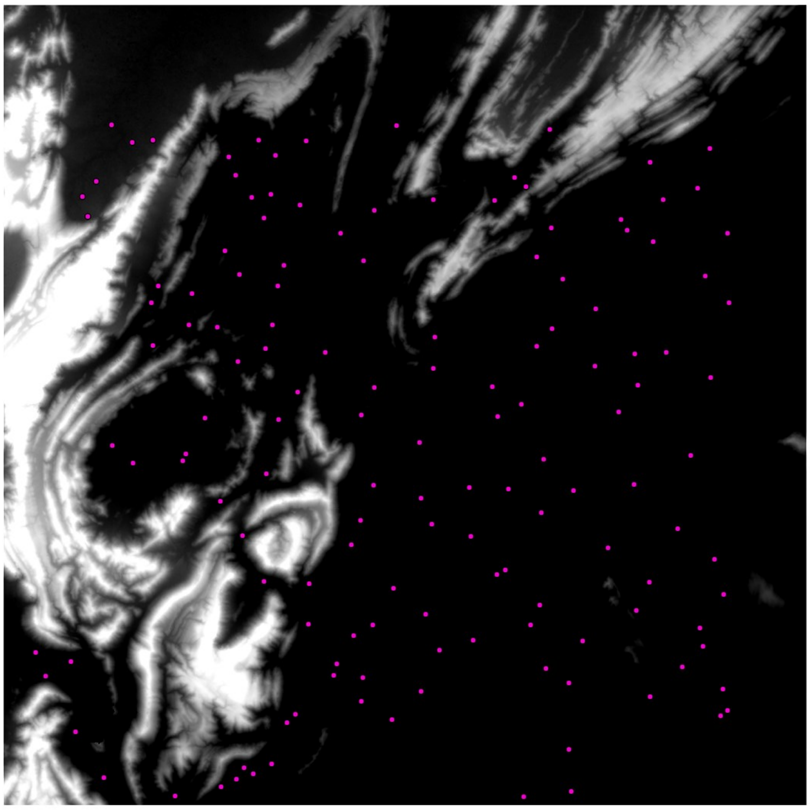


Figure 7. Distribution of precise GCPs at stable sites over the study area, overlaid on Cartosat-1 v3 DEM

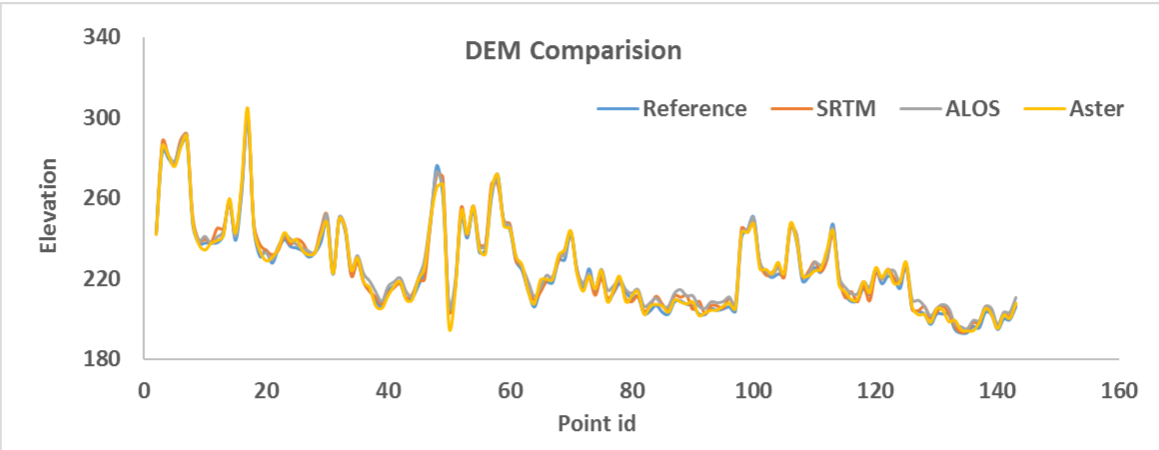


Figure 8. Plot of SRTM-30m, ASTER-30m and AW3D30m over study Area w.r.t reference GCP data

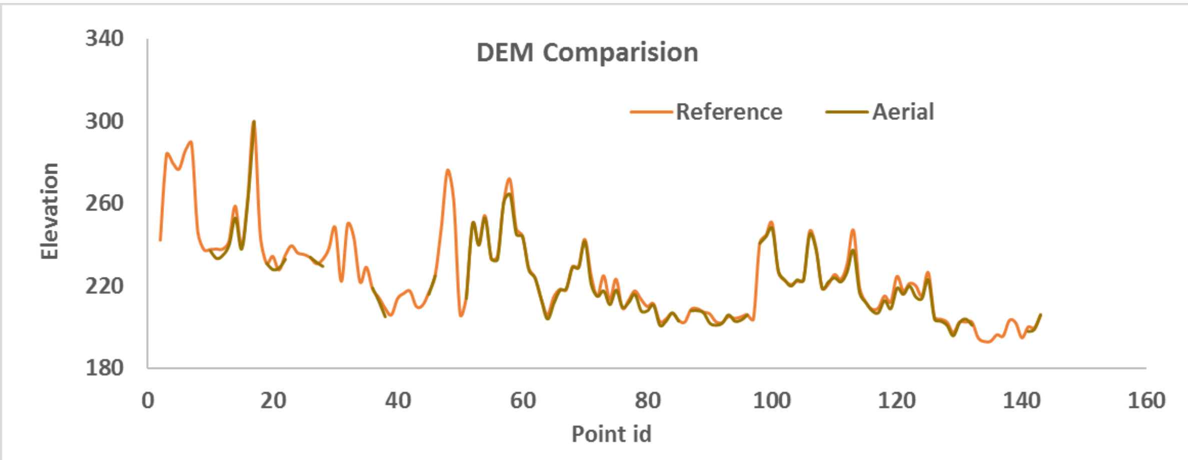


Figure 9. Plot of Aerial 25m DEM w.r.t. reference GCP data

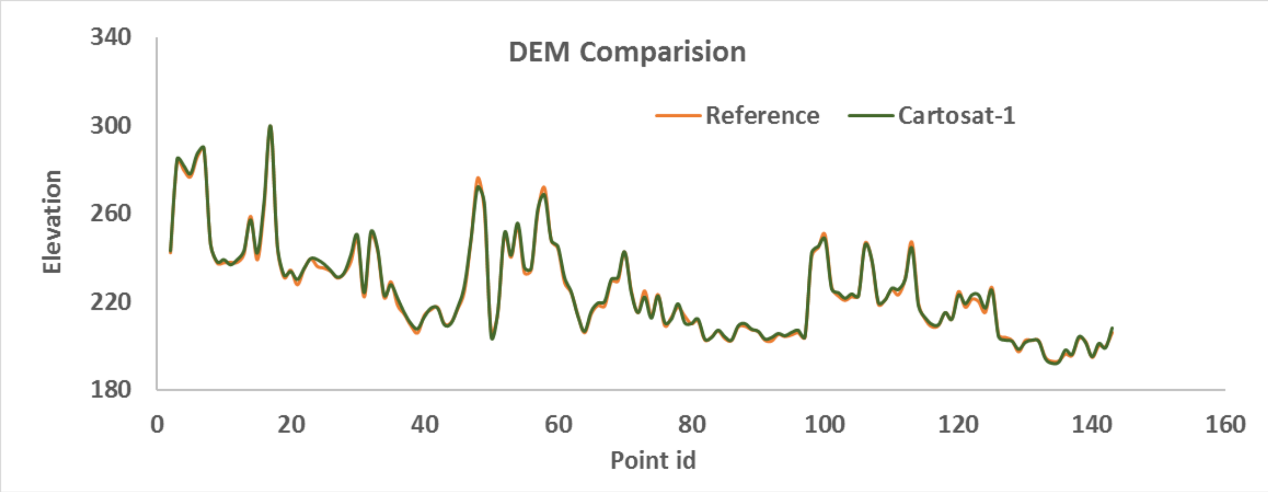


Figure 10. Plot of Cartosat-1 V3R1 w.r.t. reference GCP data

Beside qualitative, quantitative analysis on the study area using all the available data sets is also carried out as per Table-3 and Table-4. The vertical accuracy of the estimated datasets was analysed by calculating the descriptive statistics of the difference between the estimated height and the reference height. These statistics were the Root-Mean-Square Error (RMSE) and Mean Error (ME). The RMSE describes how much the estimated dataset differs from the reference dataset in terms of deviation from zero. The ME describes the bias toward underestimation (negative ME) or overestimation (positive ME) with respect to the reference dataset. In Table-3, we have compared the DEMs which covers maximum number of GCP points (150 no's). Comparison results points that **Cartosat-1 V3R1** data has better RMSE values among all. So, vertical accuracy of Cartosat-1 V3R1 is better than all other available DEMs in this region. It can be observed that vertical accuracy of Aerial DEM is also within the claimed accuracy. Accuracies of SRTM, ASTER and ALOS DEMs are quite good with RMSE values better than 3 meters. ME of Cartosat-1 V3R1 and AW3D30 is slightly underestimated whereas ASTER has the most underestimated values in comparison to other available results.

Table 4, contains the RMSE and Mean error results of Carto2 1m grid interval DEM compared to reference points (15 numbers). Other DEMs are also cropped w.r.t. Carto2 area and RMSE and Mean error were calculated for all the DEMs for comparisons. Results mentioned in Table-3 states that Carto2 DEM has lowest RMSE values and lowest under estimation of data. So, results obtained using Carto2 DEM are quite accurate. Further, Cartosat-1 V3R1 DEM is showing RMSE of ~2 m followed by ALOS, ASTER and SRTM. SRTM has the highest RMSE values of 3.7 meter. Underestimation results in ME are also showing the same trend as those of RMSE results.

Table 3. Comparison of Cartosat-1 v3R1 with other DEMs using maximum number of GCP points (~150)

Sr. No	Data Set	RMSE	Mean Error
1	SRTM-30m	2.82	-1.39
2	ASTER-30m	2.62	-2.46
3	AW3D30-30m	2.99	-0.88
4	Aerial-DEM 25m	2.41	1.32
5	CartoDEM V3 10m	1.40	-0.54

Table 4. Comparison of Carto2 and other DEMs w.r.t. common reference points (15 numbers)

Data Set	RMSE	Mean Error
SRTM-30m	3.67	-2.75
ASTER-30m	2.95	-1.95
AW3D30-30m	2.34	-1.94
Cartosat-1 V3R1	2.06	-1.51
Cartosat-2	1.60	-0.69

Figure 11 presents a perspective view of color coded DEM over study area for visualization purpose. Many applications like disaster management, infrastructure management can be derived using 3D surface visualization of remote sites using satellite photogrammetry. Generation of high resolution and precise DEM using multi-date and multi-view satellite imagery has many advantages like wider coverage and economical in nature as compared to other aerial photogrammetry methods. With the launch of many multi-view satellites, availability of across track stereo is also improved. DEM validation is tricky part in the whole exercise as collection of precise GCPs and evaluation points is a tedious activity.

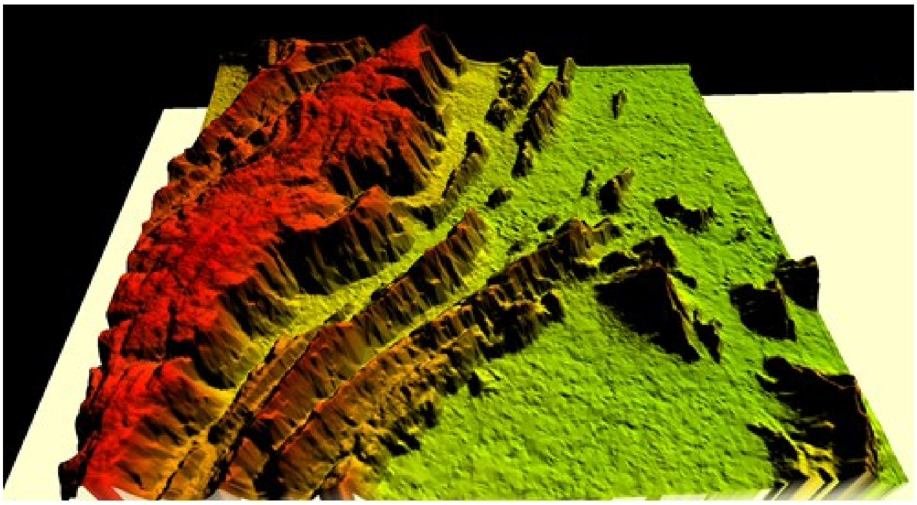


Figure 11. Perspective view of color coded DEM over the study area.

5. Conclusions

The prime objective of this study is to generate high resolution and accurate DEM using Carto2 datasets and validation of the DEM using reference points. In this paper, Carto2 multi-view multi-date data as given in table 1 is used for DEM generation using the approach of satellite photogrammetry (Figure 2). Generated DEM with grid interval of 1m (Figure 3) is compared with all latest available DEMs with a grid interval of 30m across the world. Carto-2 DEM is generated at 10m and 30m grid interval for comparisons with latest Cartosat-1 V3R1 DEM with resolution of 10 meters and SRTM/ALOS DEM with resolution of 30 meters. Hill shade views of digital elevation models are also compared visually as per Figure 5 and 6. From Figures 4 and 5, it is inferred that there are notable variations in the Carto-2 DEM from Cartosat-1 and other DEMs at steep hill tops whereas differences are close to zero at plain areas. It is also inferred that Cartosat-2 DEM is more resembled with Cartosat-1 version 3 DEM as compared to 30M DEMs. Further, Carto2 DEM results and other DEM datasets are also validated with reference ground control points and vertical accuracies are figured out for all the DEM datasets as per Figure 8, 9 and 10. By comparing all the available datasets using metrics of RMSE and ME, we concluded that obtained DEM from Cartosat2 has better vertical accuracy (<2m) (Table-3) over the plain and stable areas as well as has a very high resolution results with better level of details. It is also observed that Cartosat-1 V3R1 DEM accuracies are quite high as per Table-2 and the vertical accuracies of open source DEMs are also better than general specifications over studied area. With the launch of Cartosat-2S and Cartosat-3 satellites capable of capturing multi-view imagery, it is possible to generated precise DEM of a given area. Due to launch of high resolution satellites such as Cartosat-2 and Cartosat-2S series of satellites, there is an advantage to generate high resolution and precise DEMs all over India using multi-date across track stereo imagery.

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ALOS URL: Earth Observation Research Center

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