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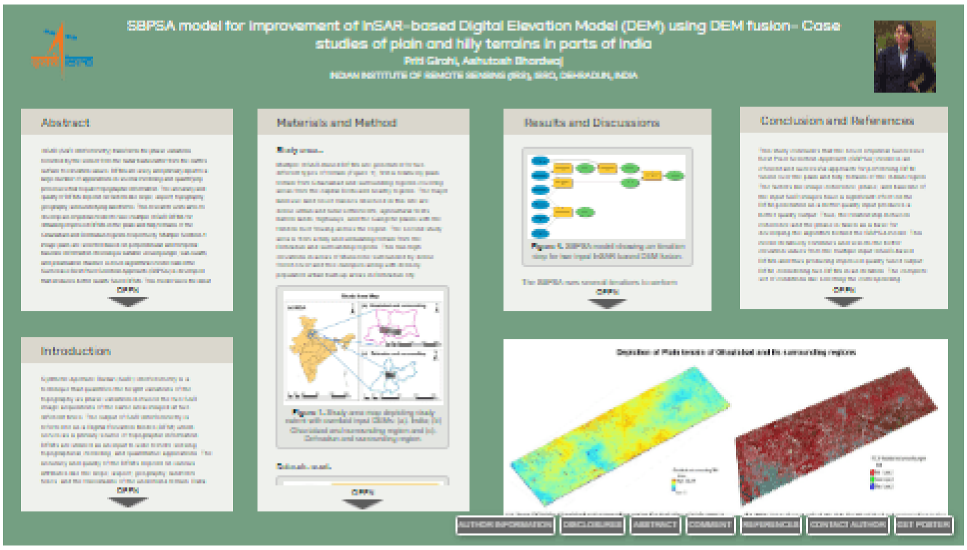
SBPSA model for improvement of InSAR-based Digital Elevation Model (DEM) using DEM fusion- Case studies of plain and hilly terrains in parts of India



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PRESENTED AT:

ABSTRACT

InSAR (SAR Interferometry) transforms the phase variations recorded by the sensor from the radar backscatter from the earth’s surface to elevation values. DEMs are a key and primary input to a large number of applications in several modeling and quantifying processes that require topographic information. The accuracy and quality of DEMs depend on factors like slope, aspect, topography, geography, and underlying landforms. This research work aims to develop an empirical model to fuse multiple InSAR DEMs for obtaining improved DEMs in the plain and hilly terrains of the Ghaziabad and Dehradun regions respectively. Multiple Sentinel-1 image pairs are selected based on perpendicular and temporal baseline information choosing a suitable viewing angle, sub-swath, and polarisation channel. A novel algorithmic model called the Successive Best Pixel Selection Approach (SBPSA) is developed that produces better quality fused DEMs. This model fuses the input InSAR DEMs firstly based on the successive comparison of the coherence value of each pixel and selecting the corresponding elevation for output which is related to a greater coherence value. Secondly, it selects those elevation values falling in the range of elevations as in toposheets of the study areas and nearest to the reference elevation values. The model runs iteratively by fusing two input InSAR DEMs and thus producing a fused output DEM in the first iteration, which is further assimilated with the consecutive input DEM in the next iteration and so on. The accuracy and quality assessment of the fused DEMs from the SBPSA model is done by estimating several statistical parameters and model performance indices. The precise ICESat-2 ATL08 photon data is used as a reference elevation for the point-based accuracy assessment of the results. The RMSE of fused DEMs reduced to 1.36m in contrast to 2.40 and 2.10m for RMSE of input DEMs in the plain region and up to 1.51m in contrast to 2.34 and 2.57m in the hilly region. The area-based improvement is shown by the histograms of the fused DEMs which have a reduced peak due to outlier removal and are concentrated within the correct range of elevations mentioned in toposheets. The percentage improvement factor (%IF) for the SBPSA model in the Ghaziabad region is 44.24% for fused DEM while in the Dehradun region about 41.28% improvement is achieved.

INTRODUCTION

Synthetic Aperture Radar (SAR) Interferometry is a technique that quantifies the height variations of the topography as phase variations between the two SAR image acquisitions of the same area imaged at two different times. The output of SAR interferometry is referred to as a Digital Elevation Model (DEM) which serves as a primary source of topographic information. DEMs are utilized as an input to wide remote sensing, topographical, modeling, and quantitative applications. The accuracy and quality of the DEMs depend on various attributes like the slope, aspect, geography, landform types, and the topography of the underlying terrain. Data fusion is a technique of combining multi-source data intelligently, to improve upon the individual inputs and produce better-quality results. DEM fusion from multi-source or multi-temporal datasets will reduce the inherent errors that may incorporate due to processing/workflow and terrain properties. A novel empirical model is designed referred to as the Successive Best Pixel Selection Approach (SBPSA) model for improving the quality of input InSAR-based DEMs over plain and hilly regions of Indian terrain. This is an algorithmic iterative model to perform a fusion of generated DEMs from a set of InSAR pairs selected on the basis of multi-baseline information and coherence values in each study site. The InSAR image pairs are selected from the Sentinel-1 A/B C-band SAR sensor by considering the perpendicular, temporal baselines, viewing angle, and image coherence for generating multiple InSAR-based DEMs for both study areas. The SBPSA model derives better elevation values in the output fused DEMs based on larger coherence values for each pixel successively from the individual input DEMs in each iteration run of the model. Further, the model selects nearest-to-truth (reference) elevation values by checking the correct range from the toposheets of each study area for obtaining the fused output DEMs. The accuracy analysis of obtained output DEMs is performed in a point-based and area-based assessment by estimating various statistical parameters and model performance indices.

MATERIALS AND METHOD

Study areas:

Multiple InSAR-based DEMs are generated for two different types of terrain (Figure 1), first a relatively plain terrain from Ghaziabad and surrounding regions covering areas from the capital Delhi and nearby regions. The major land use land cover classes observed in this site are dense urban and rural settlements, agricultural fields, barren lands, highways, and the Gangetic plains with the Hindon river flowing across the region. The second study area is from a hilly and undulating terrain from the Dehradun and surrounding regions. This has high elevations in areas of Mussoorie surrounded by dense forest cover and tree canopies along with densely populated urban built-up areas in Dehradun city.

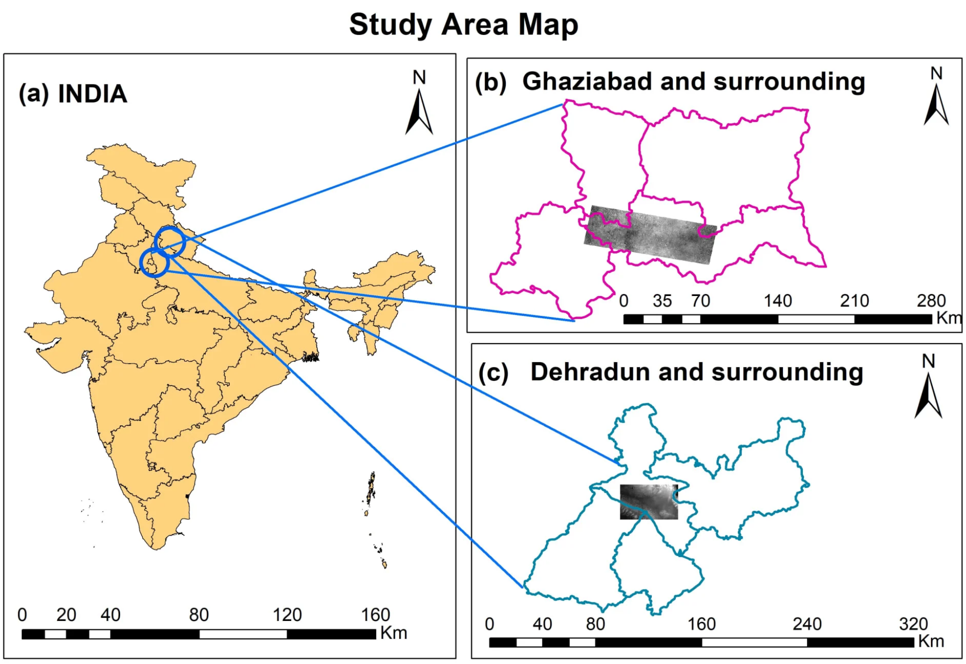

Figure 1: Study area map depicting study extent with overlaid input DEMs: (a). India; (b) Ghaziabad and surrounding region and (c). Dehradun and surrounding region.

Datasets used:

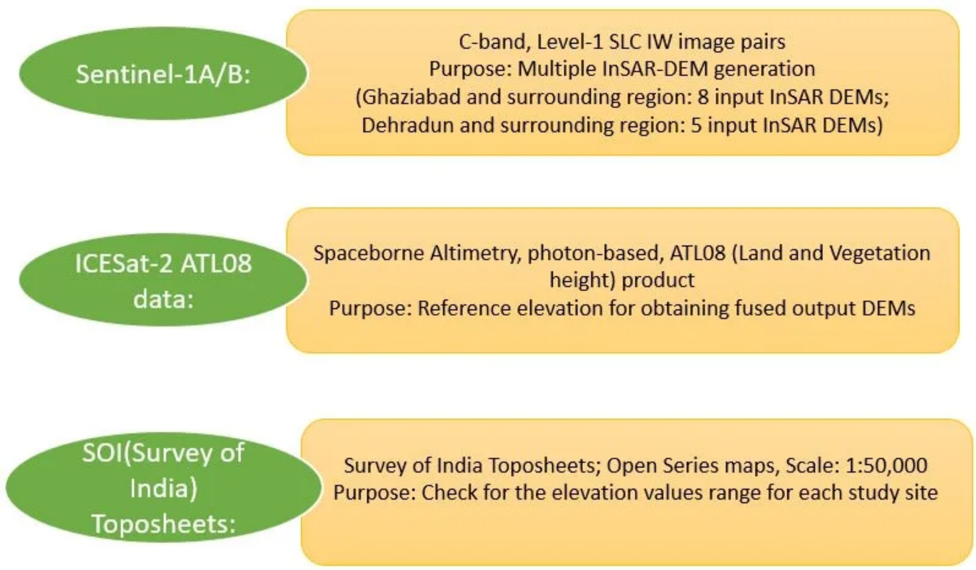

Figure 2: Datasets used, their specifications, and their purpose.

Methodology:

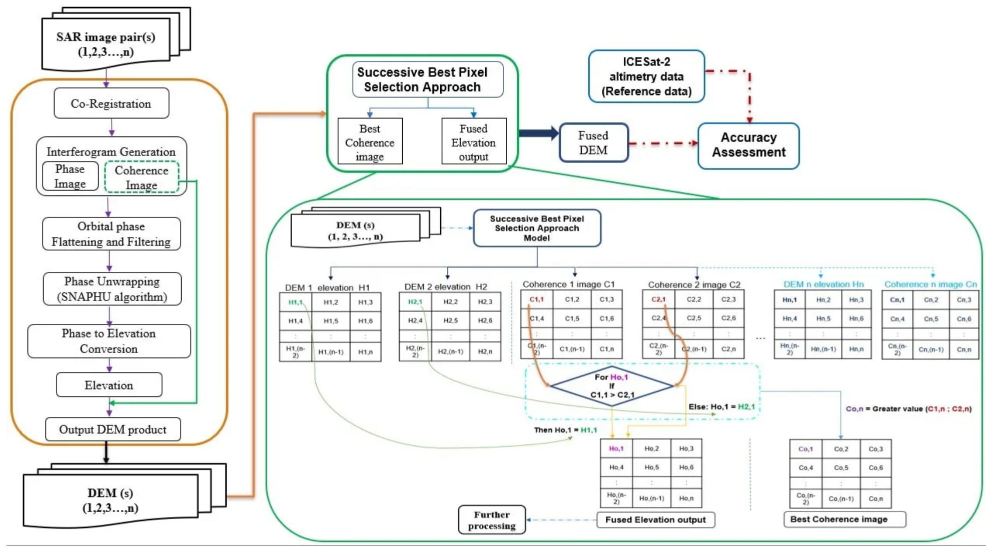

Figure 3: Processing steps of the SBPSA model

The first step in the workflow is to generate high-spatial-resolution DEMs following the SAR Interferometric process (Figure 3). Several factors are considered for the selection of Sentinel-1 InSAR image pairs, such as the wavelength (C-band is chosen), short temporal baselines (most of the image pairs have 6 or 12 days), larger perpendicular baselines (ranging from 61 to 153m for the plain region and 85 to 131m for the hilly region), same viewing angle, suitable sub-swath, polarisation channel, and image coherence, for the generation of DEMs. The ASF (Alaska Satellite Facility) Data search and baseline tools are used for the selection of the image pairs. Multiple InSAR-based DEMs are generated following the interferometric processing which includes: co-registration of the reference and secondary images, interferogram generation from the co-registered stack which contains the intensity, phase, and coherence image bands, then phase band is processed with unwrapping (SNAPHU) algorithm after removing phase from earth flattening and phase filtering, the unwrapped phase is finally converted to elevation and coherence band is added to it. The final product is terrain-corrected and output DEMs are given as input to the SBPSA model. The relationship between image coherence and phase is the base of designing this novel DEM fusion approach. The Successive Best Pixel Selection Approach is an algorithmic model that derives better elevation values from the given input DEMs based on larger coherence values for each pixel in the DEM. Each individual input DEM has a coherence and an elevation image, that is, each pixel contains a coherence and corresponding elevation value. The designed algorithm runs for each successive pixel, compares the coherence values, and selects the elevation that corresponds to a larger coherence value. This generates “Derived elevation” and “Best Coherence” images as outputs. Further, the range of elevation values as observed from the toposheets of the study areas is checked for each derived elevation image. Finally, the absolute and nearest-to-truth (reference) elevation values are selected to generate the fused output DEMs. The DEM fusion is performed by the model for combining and selecting the better elevation values in the fused output DEMs. The results of fusion are tested and validated using precise spaceborne altimetry ICESat-2 (Ice, Cloud, and Land Elevation Satellite) ATL08 (Land and Vegetation height) product as reference elevation for point-based accuracy assessment for the near-ground points (where the height error is in the range of -5 to 2.5m between the DEM and reference elevations). The area-based improvement overall in the study area is depicted in the histograms of the input and fused output DEMs.

RESULTS AND DISCUSSIONS

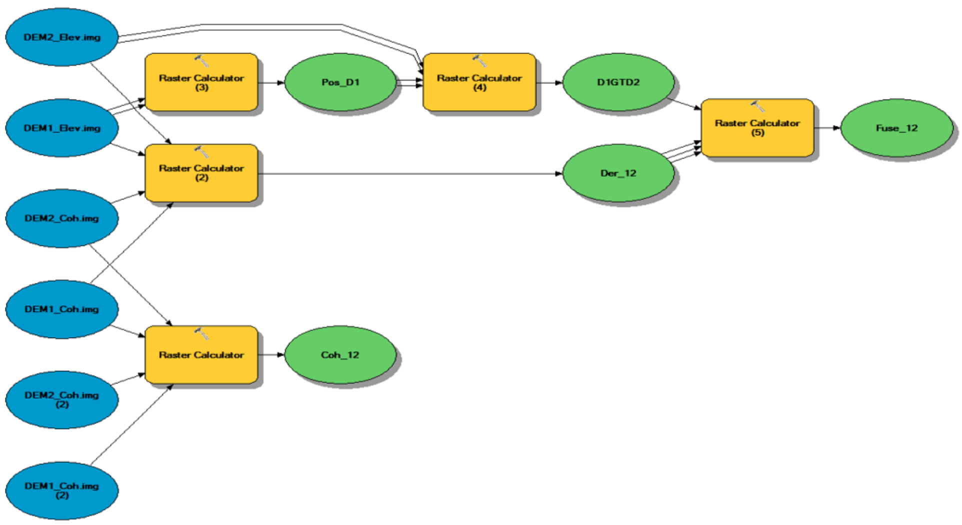

Figure 4: SBPSA model showing an iteration step for two input InSAR-based DEM fusion.

The SBPSA runs several iterations to perform DEM fusion by combining and selecting the better elevation values from two input InSAR DEMs in one step. A single iteration step of the designed SBPSA model is shown in Figure 4. Several conditions/criteria of the algorithm are implemented using raster calculators. Each iteration of the model fuses two input DEMs (referred to as input DEM1 and input DEM2 in the slides figure) and thus producing a fused output DEM in each run. The elevation values at the ICESat-2 footprint locations are extracted for the point-based accuracy assessment. The statistics are calculated (Figures 5 & 6) for each of the fused output DEMs considering the near-ground points, such as the mean error (ME), mean absolute error (MAE), root mean square error (RMSE), and linear error at 90th percentile (LE90) along with model performance indices such as Refined index of agreement (dr), Nash & Sutcliffe coefficient of efficiency (E), Legates & McCabe's coefficient of efficiency (E1) and the percentage improvement factor (%IF), for a complete accuracy analysis. The results infer that the RMSE for each of the fused outputs is less in each iteration as compared to the input DEMs and the maximum percentage improvement achieved in the fused DEM over the input DEMs, using the SBPSA fusion model is 44.24% for the plain terrain. The overall area-based improvement is depicted by the histograms where the peaks of the histograms have flattened and reduced due to the removal of outliers. The histograms of each successive fused DEM have concentrated within the correct range of elevations as observed in the toposheets of the plain Ghaziabad study area.

Statistical parameters

DEMs	ME (m)	MAE (m)	RMSE (m)	LE90 (m)
DEM 1	-0.73	1.96	2.32	3.81
DEM 2	-1.30	2.27	2.35	4.35
Fused Output 1	-0.03	1.39	**1.67**	2.75
DEM 3	-1.26	2.07	2.51	4.13
Fused Output 1	-0.57	1.73	2.14	3.51
Fused Output 2	-0.02	1.14	**1.40**	2.30
DEM 4	-0.96	2.03	2.21	3.67
Fused Output 2	-1.41	2.22	2.60	4.27
Fused Output 3	-0.30	1.37	**1.60**	2.63
DEM 5	-1.40	2.05	2.40	3.95
Fused Output 3	-0.75	1.66	2.10	3.46
Fused Output 4	-0.25	1.11	**1.36**	2.24
DEM 6	-1.22	2.05	2.48	4.07
Fused Output 4	-0.80	1.90	2.27	3.74
Fused Output 5	-0.10	1.21	**1.49**	2.46
DEM 7	-1.43	2.18	2.59	4.27
Fused output 5	-1.01	2.03	2.44	4.02
Fused output 6	-0.41	1.39	**1.74**	2.86
DEM 8	-1.33	2.10	2.51	4.12
Fused Output 6	-0.84	1.82	2.31	3.80
Fused Output 7	-0.24	1.18	**1.49**	2.45

Model performance indices

DEMs	IA(d_r)	E	E1	% IF
DEM 1 DEM 2 Fused Output 1	0.29	0.76	0.40	27.78 42.05
DEM 3 Fused Output 1 Fused Output 2	0.18	0.88	0.63	44.24 34.53
DEM 4 Fused Output 2 Fused Output 3	0.11	0.95	0.77	27.61 38.47
DEM 5 Fused Output 3 Fused Output 4	0.17	0.87	0.66	43.36 35.30
DEM 6 Fused Output 4 Fused Output 5	0.23	0.82	0.52	39.61 34.26
DEM 7 Fused output 5 Fused output 6	0.26	0.74	0.46	32.92 28.77
DEM 8 Fused Output 6 Fused Output 7	0.25	0.77	0.46	40.46 35.36

Figure 5: Point-based accuracy analysis of Fused output DEMs with ICESat-2 data by estimating statistical parameters and the model performance indices for Ghaziabad and the surrounding regions.

Similarly, for the hilly Dehradun study site, the point-based accuracy analysis shows RMSE of fused output DEMs is lesser than the RMSE of input DEMs. The maximum percentage improvement achieved in the fused output DEMs in each iteration over the fused DEMs is around 41.28%. Further, in this terrain also the SBPSA model performs DEM fusion effectively and overall area-based improvement is depicted in the histograms of the fused output and the input DEMs.

Statistical parameters

DEMs	ME (m)	MAE (m)	RMSE (m)	LE90 (m)
DEM 1	-0.96	1.95	2.31	3.80
DEM 2	-1.18	2.12	2.44	4.02
Fused Output 1	-0.28	1.29	**1.54**	2.53
DEM 3	-1.04	1.87	2.29	3.76
Fused Output 1	-1.99	2.60	2.94	4.83
Fused Output 2	-0.62	1.41	**1.73**	2.84
DEM 4	-1.14	1.95	2.34	3.85
Fused Output 2	-1.62	2.22	2.57	4.22
Fused Output 3	-0.41	1.26	**1.51**	2.48
DEM 5	-0.48	1.96	2.29	3.77
Fused Output 3	-1.21	2.21	2.54	4.19
Fused Output 4	-0.13	1.44	**1.77**	2.91

Model performance indices

DEMs	IA (d_r)	E	E1	% IF
DEM 1 DEM 2 Fused Output 1	0.014	0.9994	0.9713	33.28 36.92
DEM 3 Fused Output 1 Fused Output 2	0.016	0.9991	0.9677	24.37 41.14
DEM 4 Fused Output 2 Fused Output 3	0.016	0.9994	0.9686	35.65 41.28
DEM 5 Fused Output 3 Fused Output 4	0.013	0.9996	0.9745	22.85 30.53

Figure 6: Point-based accuracy analysis of Fused output DEMs with ICESat-2 data by estimating statistical parameters and the model performance indices for Dehradun and the surrounding regions.

CONCLUSION AND REFERENCES

This study concludes that the novel empirical Successive Best Pixel Selection Approach (SBPSA) model is an efficient and successful approach for performing DEM fusion over the plain and hilly terrains of the Indian region. The factors like image coherence, phase, and baseline of the input SAR images have a significant effect on the DEM generation as a better quality input produces a better quality output. Thus, the relationship between coherence and the phase is taken as a base for developing the algorithm behind the SBPSA model. This model iteratively combines and selects the better elevation values from the multiple input InSAR-based DEMs and thus producing improved quality fused output DEM, considering two DEMs in an iteration. The complete set of conditions like selecting the corresponding elevation value of the larger coherence values, checking for the correct range of values referred from the toposheets, and finally deriving the fused DEM elevations by selecting the nearest to reference elevation values, are tested and implemented successively on each pixel of the DEM. The SBPSA model has proven to be a successful approach for obtaining the improved fused output DEMs showing significant improvement achieved over the input DEMs in the plain majorly urban study area of Ghaziabad as well as in the hilly dense forest cover of the Dehradun study site.

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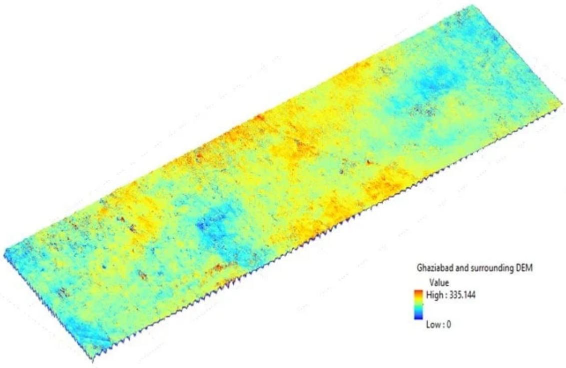
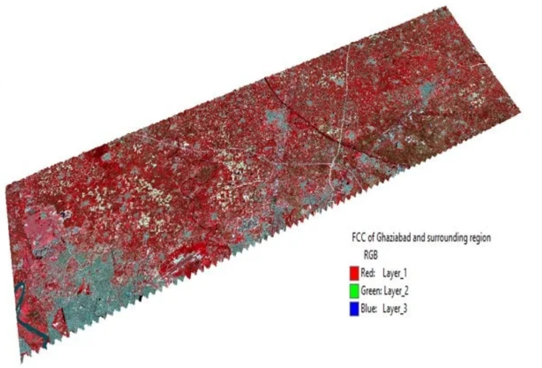
Depiction of Plain terrain of Ghaziabad and its surrounding regions

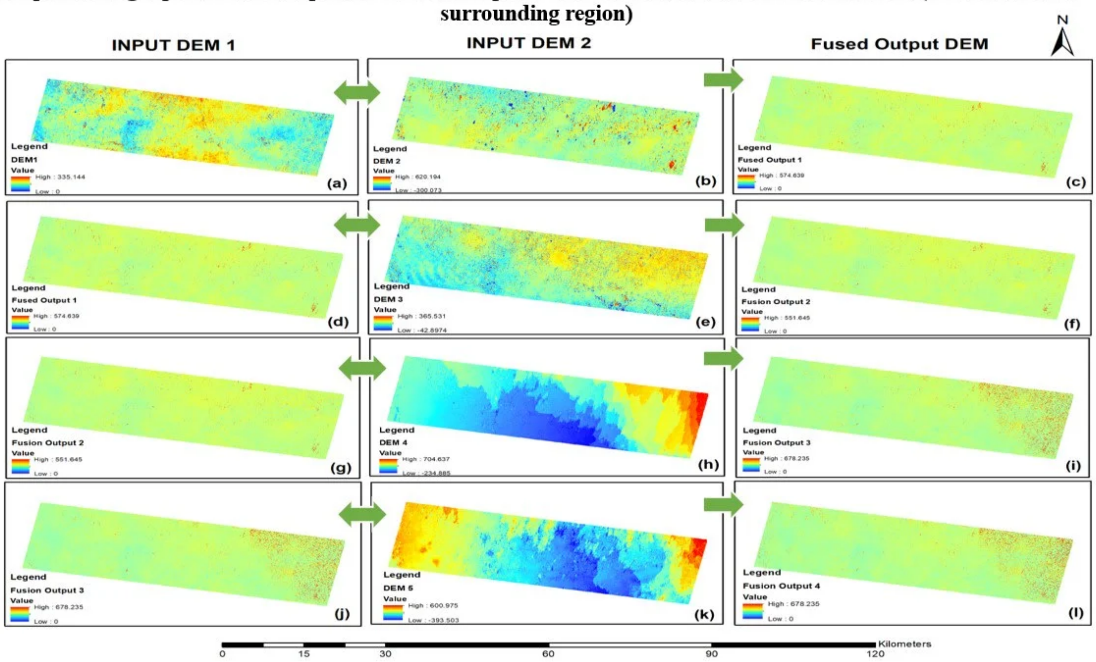


(a). Input DEM for Ghaziabad and surrounding region for depiction of plain terrain



(b). FCC image from Sentinel-2A data for Ghaziabad and surrounding region

Maps showing input DEMs and produced fused output DEMs in each iteration of SBPSA model (Ghaziabad and surrounding region)



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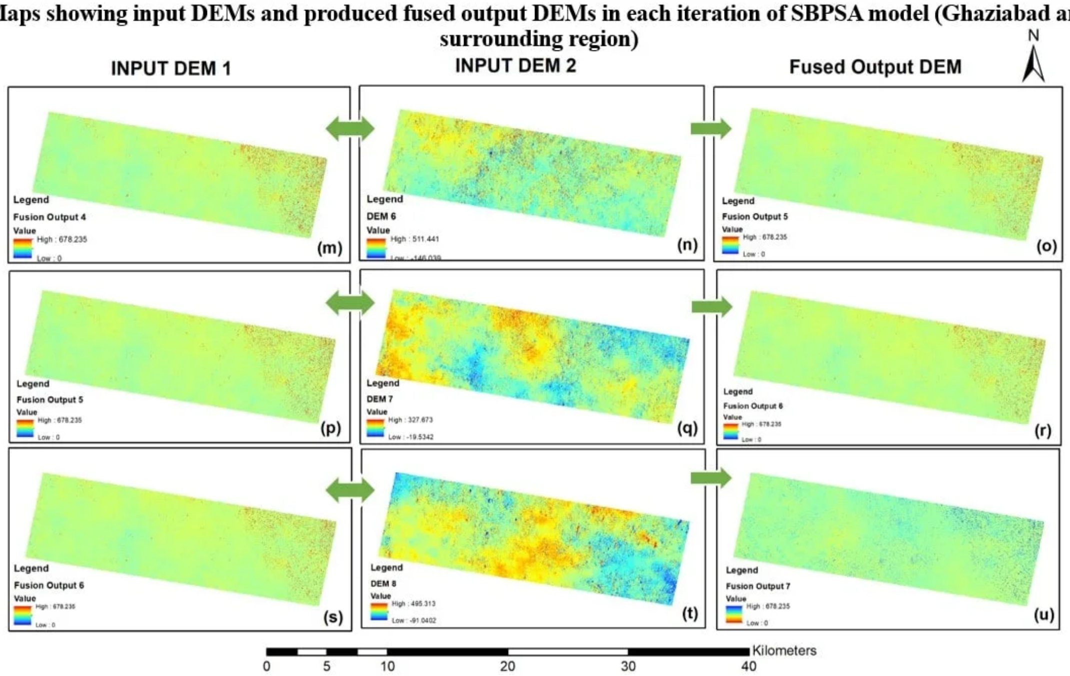
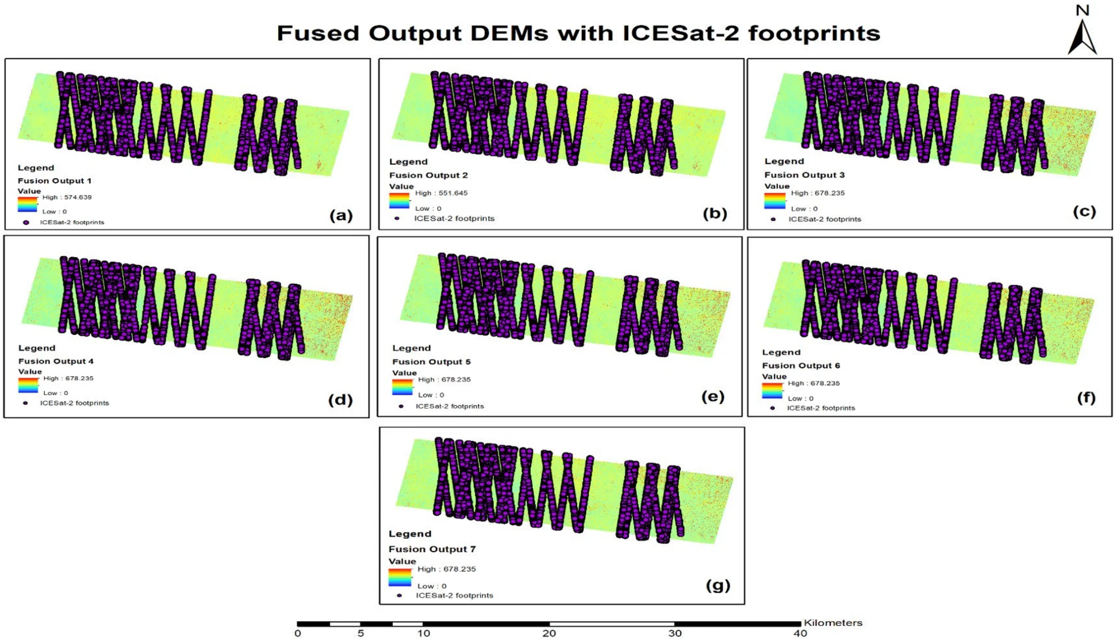
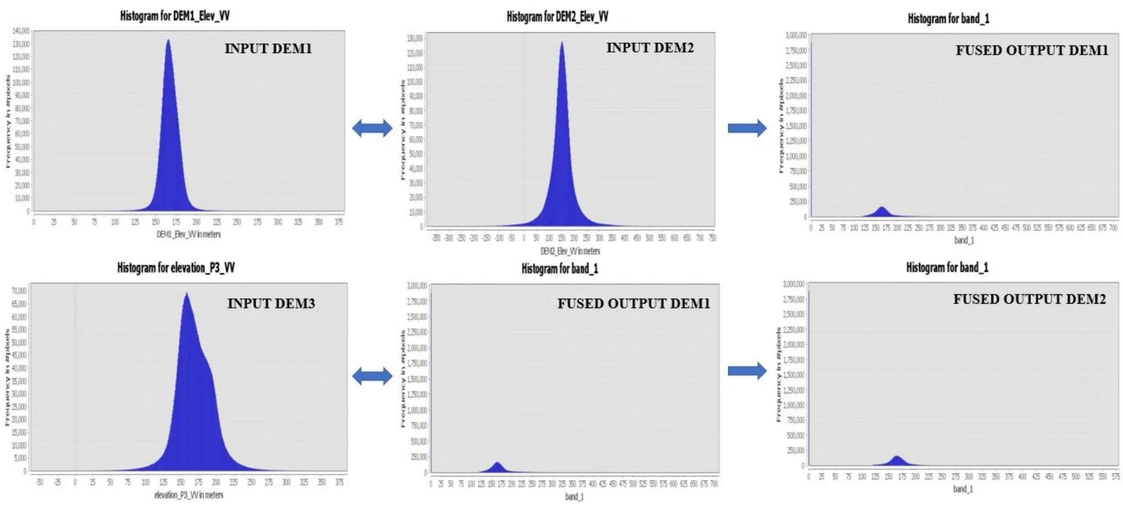


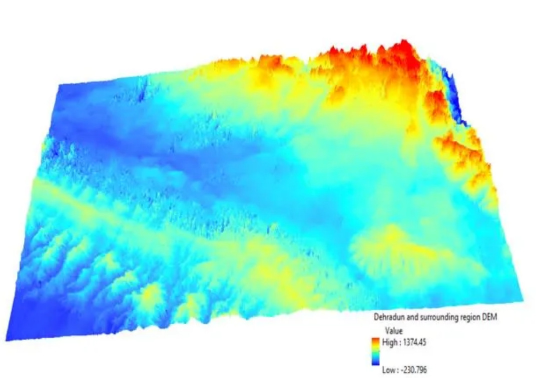
Fused Output DEMs with ICESat-2 footprints



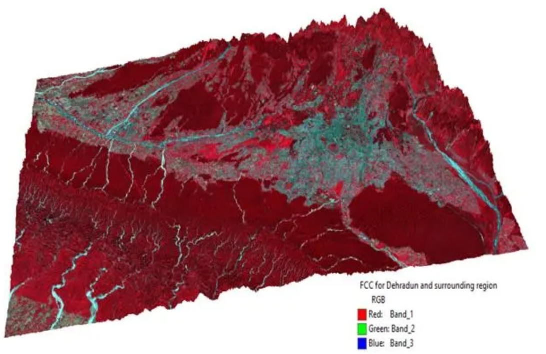
Area-based assessment: **Histograms of input and Fused output DEMs of Ghaziabad and surrounding regions**



Depiction of Hilly terrain of Dehradun and its surrounding regions

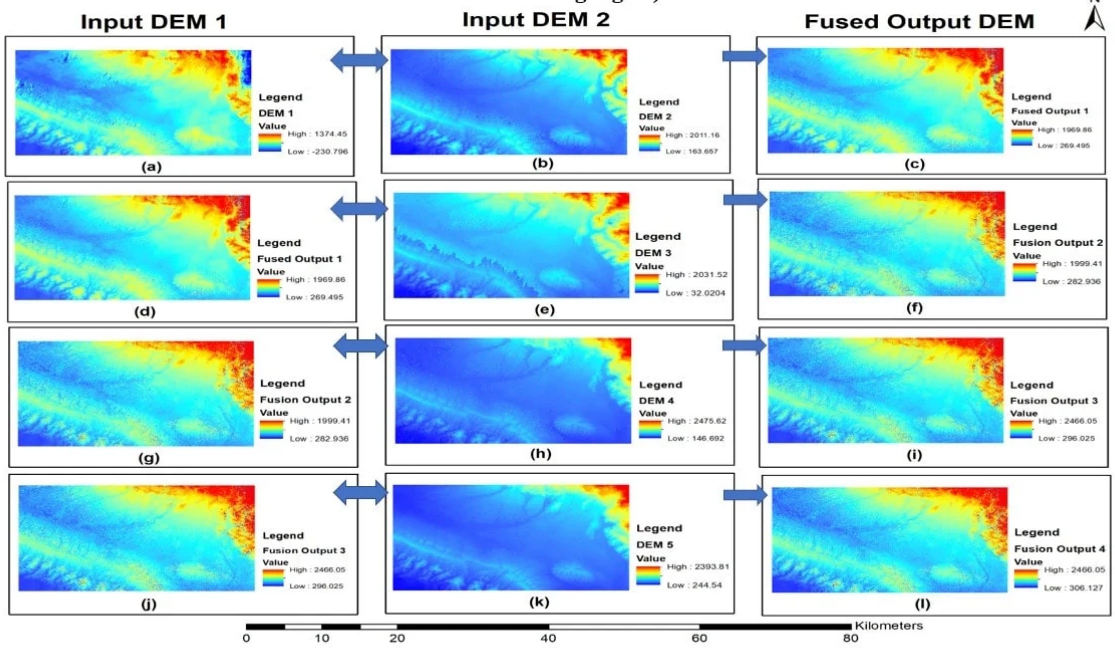


(a). Input DEM for Dehradun and surrounding region for depiction of hilly terrain

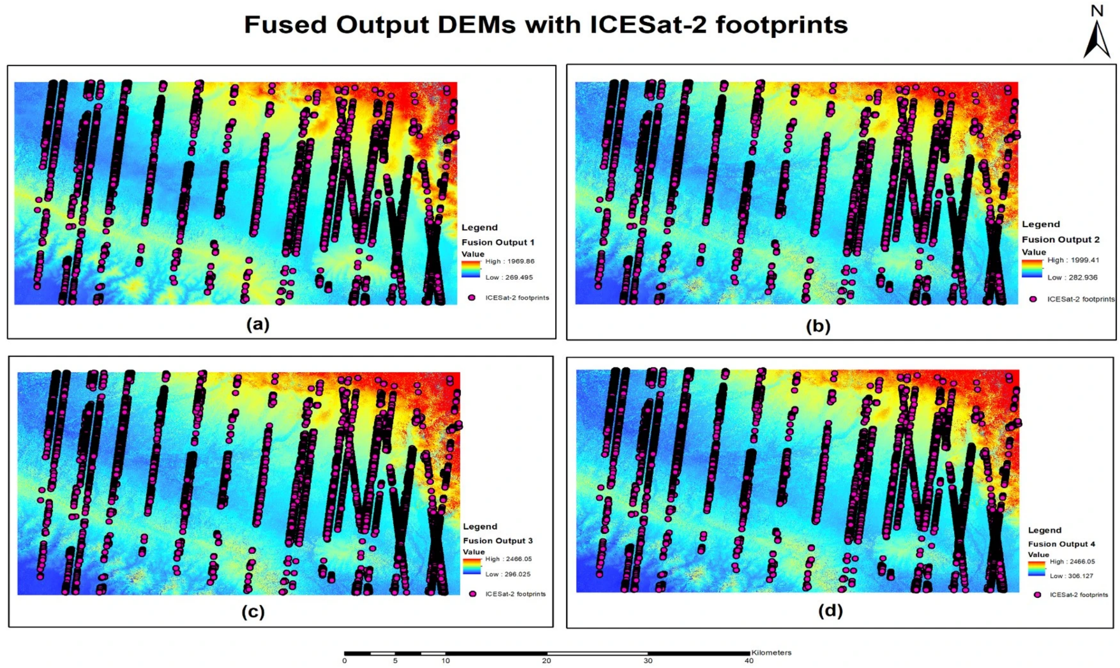


(b). FCC image from Sentinel-2A data for Dehradun and surrounding region

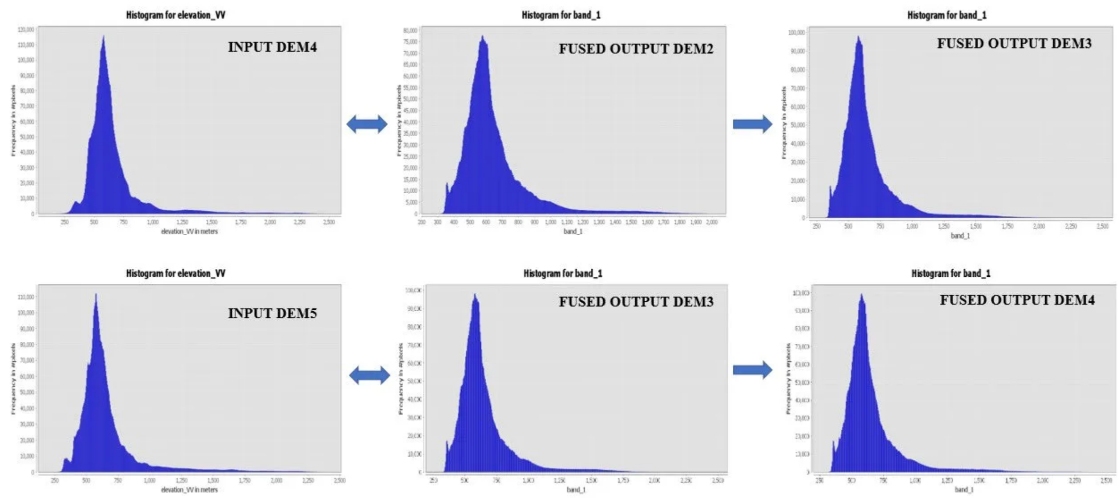
Maps showing input DEMs and produced fused output DEMs in each iteration of SBPSA model (Dehradun and surrounding region)



Fused Output DEMs with ICESat-2 footprints



Area-based assessment: **Histograms of input and Fused output DEMs for Dehradun and surrounding regions**



DISCLOSURES

The authors have no conflicts of interest to declare that are relevant to the content of this research work.

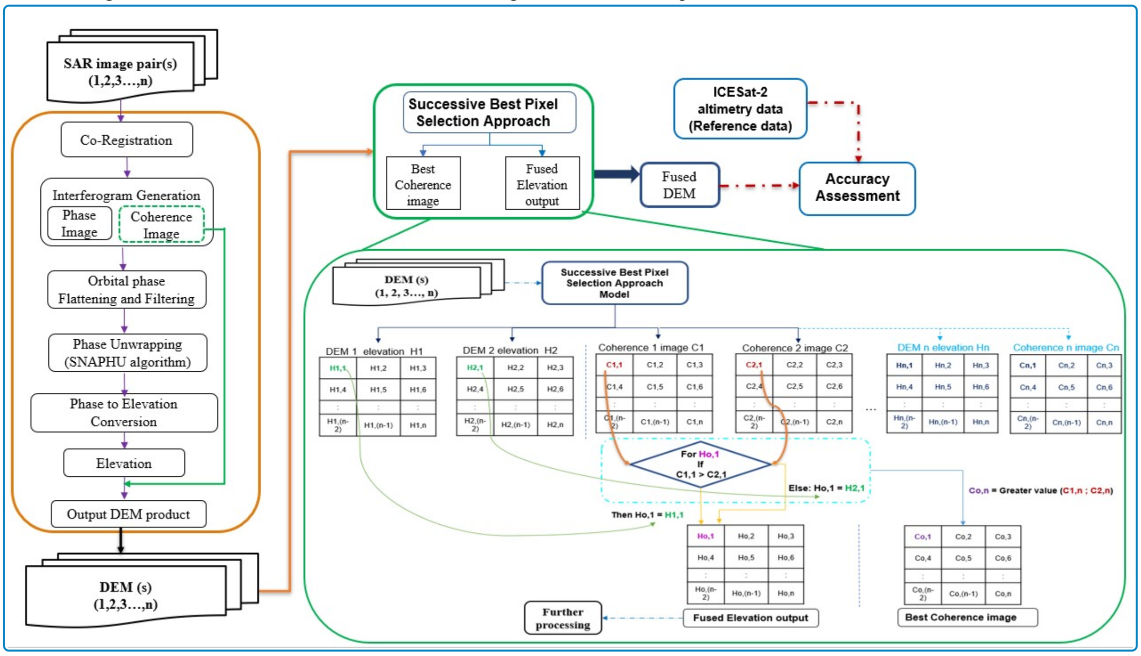
AUTHOR INFORMATION

Ashutosh Bhardwaj: Ashutosh Bhardwaj is a senior scientist in the Photogrammetry and Remote Sensing Department, GT&OP Group, of Indian Institute of Remote Sensing (Indian Space Research Organization), Dehradun, India. He has been engaged in teaching and research in topographic modeling, photogrammetry, SAR Interferometry, LiDAR and remote sensing. He has guided more than 50 graduate and postgraduate students and is currently guiding PhD students under various research programs. He has published more than 30 research papers in journal and conferences.

Priti Girohi: Ms. Priti Girohi is a young research scholar in the remote sensing and GIS domain. She was born in Ghaziabad, Uttar Pradesh in March, 1995. She graduated with B.Tech in Electronics and Communication Engineering with deep knowledge in radar systems, electronic circuits, microwave and antenna subjects. She is studying at the Indian Institute of Remote Sensing (IIRS), ISRO pursuing her Masters of Technology in Remote Sensing and GIS with a specialization in Satellite Image Analysis and Photogrammetry. Her areas of research interest include Satellite Image processing, Photogrammetry, SAR Interferometry, DEM Fusion techniques, application of machine learning and deep learning in the remote sensing domain. She worked on developing methods and models for InSAR-based DEM fusion and improvement in the diverse topography of the Indian region.

ABSTRACT

InSAR (SAR Interferometry) transforms the phase variations recorded by the sensor from the radar backscatter from the earth's surface to elevation values. DEMs are a key and primary input to a large number of applications in several modelling and quantifying processes that require topographic information. The accuracy and quality of DEMs depend on factors like slope, aspect, topography, geography and underlying landforms. This research work aims to develop an empirical model to fuse multiple InSAR DEMs for obtaining improved DEMs in the plain and hilly terrains of the Ghaziabad and Dehradun regions respectively. Multiple Sentinel-1 image pairs are selected based on perpendicular and temporal baseline information choosing a suitable viewing angle, sub-swath and polarisation channel. A novel algorithmic model called the Successive Best Pixel Selection Approach (SBPSA) is developed that produces better quality fused DEMs. This model fuses the input InSAR DEMs firstly based on the successive comparison of the coherence value of each pixel and selecting the corresponding elevation for output which is related to a greater coherence value. Secondly, it selects those elevation values falling in the range of elevations as in toposheets of the study areas and nearest to the reference elevation values. The model runs iteratively by fusing two input InSAR DEMs and thus producing a fused output DEM in the first iteration, which is further assimilated with the consecutive input DEM in the next iteration and so on. The accuracy and quality assessment of the fused DEMs from the SBPSA model is done by estimating several statistical parameters and model performance indices. The precise ICESat-2 ATL08 photon data is used as a reference elevation for the point-based accuracy assessment of the results. The RMSE of fused DEMs reduced to 1.36m in contrast to 2.40 and 2.10m for RMSE of input DEMs in the plain region and up to 1.51m in contrast to 2.34 and 2.57m in hilly region. The area-based improvement is shown by the histograms of the fused DEMs which have a reduced peak due to outlier removal and are concentrated within the correct range of elevations mentioned in toposheets. The percentage improvement factor (%IF) for SBPSA model in Ghaziabad region is 44.24% for fused DEM while in Dehradun region about 41.28% improvement is achieved.



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