*Supplementary*

# Towards a Guideline for UAV-Based Data Acquisition for Geomorphic Applications

**Dipro Sarkar [1,*], Rajiv Sinha [1] and Bodo Bookhagen [2]**

[1] Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur 208016, India; rsinha@iitk.ac.in
[2] Institute of Geosciences, University of Potsdam, 14476 Potsdam, Germany; bodo.bookhagen@uni-potsdam.de
* Correspondence: sarkar.dipro@hotmail.com or dipro@iitk.ac.in

## Section 1. Site description

*S1.1 Undulating terrain (Mandsaur, Madhya Pradesh)*

Mandsaur has an undulating terrain with an elevation range of 370-405 m and a total area of 17 km$^2$. It is situated between the longitude 75°46′29″ E - 75°48′50″ E and longitude 24°04′23″ N - 24°06′11″ N and is a barren area devoid of structures and with minimal vegetation, primarily shrubs and bushes. Few agricultural patches can be seen at Southwest side with wells. A solar power plant was to be set up at this site by NTPC, for which high precision terrain characterisation was required. For this site, we generated DTM (Figure S1a) of 8.1 cm and orthoimages (Figure S1b) with a GSD of 4.2 cm, using the guidelines described. Such high resolution and low RMSE value clearly demonstrate the efficacy of our protocol and error mitigation (Figure S1c). Smaller headwaters were even noticeable. We could also find in some reservoir structures (Figure S1d). Further, it allowed us to characterize the terrain very precisely in terms of elevation distribution, slope variability and mapping of minor drainage network which facilitated the setting up of the solar power plant at this site. Our analysis of the UAV images showed that although there is no perennial water source in this region, a few minor channels exist flowing southwest in the north-east part of the site. The general slope of the area is towards the eastern side.

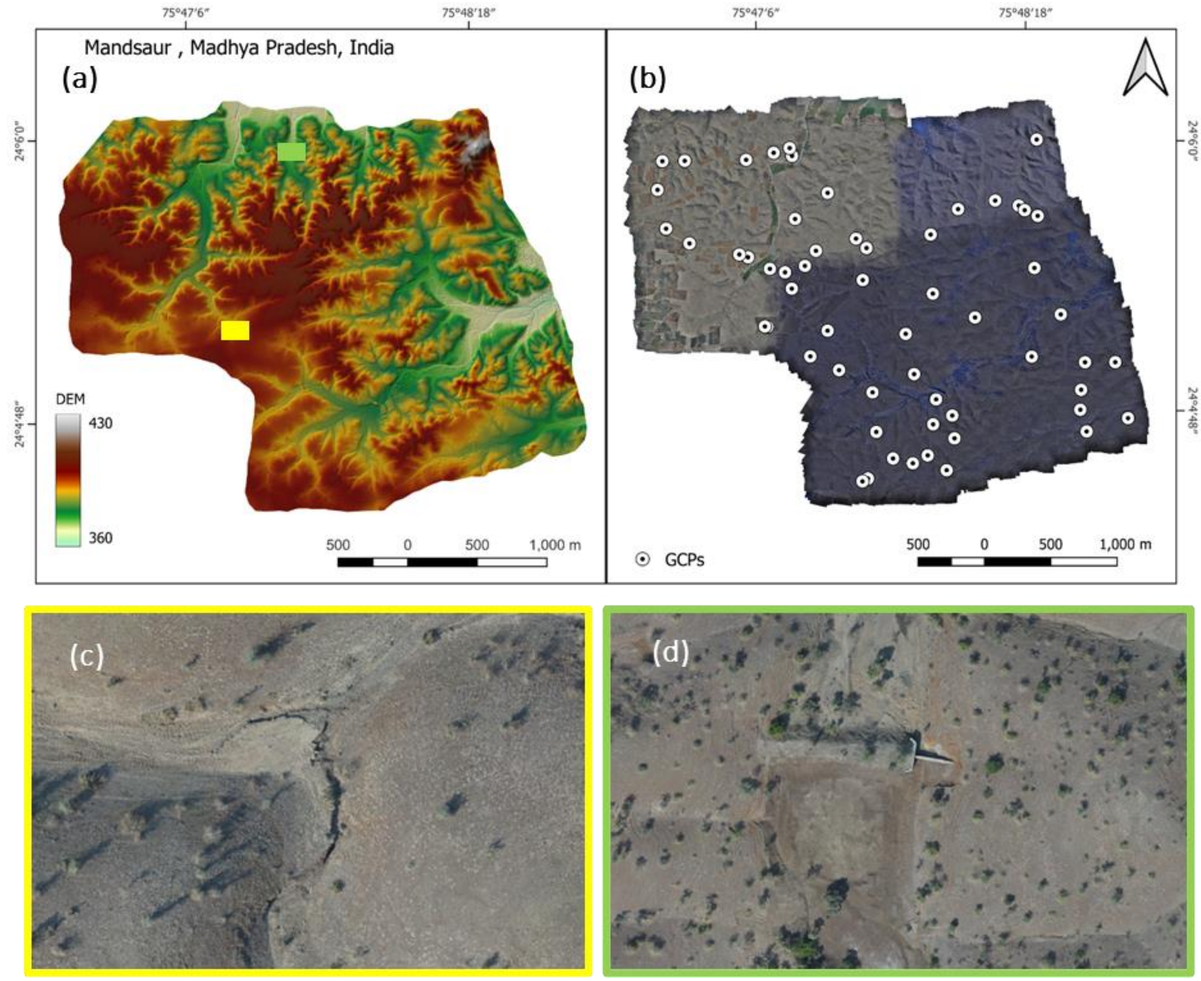


**Figure S1.** Images of Mandsaur study area. (a) DTM of Mandsaur area after all corrections, the green and yellow patched areas are shown in RGB (b) Orthoimage of Mandsaur area after all corrections. It also shows the positions of all the GCP captured during the field (c) Headwater of a stream. (d) A small dam on the channel.

*S1.2 Mixed terrain, predominantly agricultural and forested land (Mayurbhanj, Orissa)*

Mayurbhanj is the largest of all study sites, with an area of 141.8 km$^2$ bounded by latitude 22°00′00″ N to 22°05′30″ N and Longitude 86°38′40″ E to 86°45′00″ E. The elevation generally varies in the range of ± 30m, with the denudation hills rising to 50 meters. The area predominantly consists of agricultural land. For this site, we generated DTM (Figure S2a) of 23.2 cm and orthoimages (Figure S2b) with a GSD of 11.6 cm, using the guidelines described. The terrain is highly modified due to large-scale agricultural practice in the region (Figure S2c). This is an agricultural area with multiple stretches of forest and settlements. The valleys between the denudation hills are encroached upon and used as agricultural lands (Figure S2d).

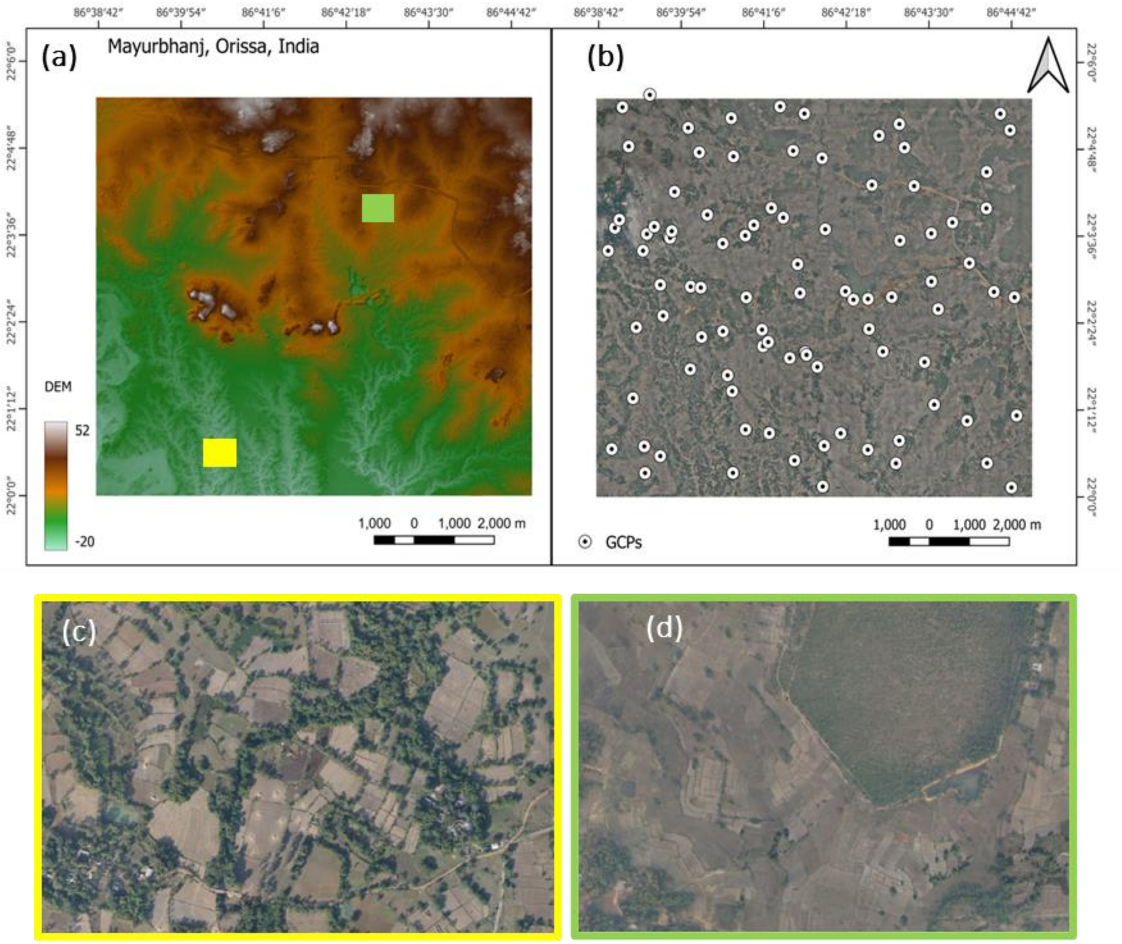


**Figure S2.** Images of Mayurbhanj study area. (a) DTM of Mayurbhanj area after all corrections, the green and yellow patched areas are shown in RGB (b) Orthoimage of Mayurbhanj area after all corrections. (c) Agricultural lands over channel areas. (d) Denudation hills with forests. The valley areas in between are converted to agricultural lands.

*S1.3 Lowland, Urbanised River basin (Sakri river basin, Kawardha, Chhattisgarh)*

The 66 $km^2$ area is highly urbanised and has multiple forest and vegetation cover. The study area is bounded by the latitudes 21′59′26″N & 22′6′24″N and longitude 81′9′30″E & 81′19′50″E. The maximum and minimum elevation in the region is 484.21 m and 230.44 m respectively. River Sakri, a tributary of Mahanadi, which originates in the reserve forest of the Chilpi Range meanders through the area. For this site, we generated DTM (Figure S3a) of 16 cm and orthoimages (Figure S3b) with a GSD of 8 cm, using the guidelines described. The general slope of the river is towards South West.

The river is highly affected by anthropogenic modifications from the locals. Multiple dams and sandbag dams plagued the river channel resulting in high siltation. This has also resulted in channel expansion, high siltation in the channel bed and undercutting of the bank.

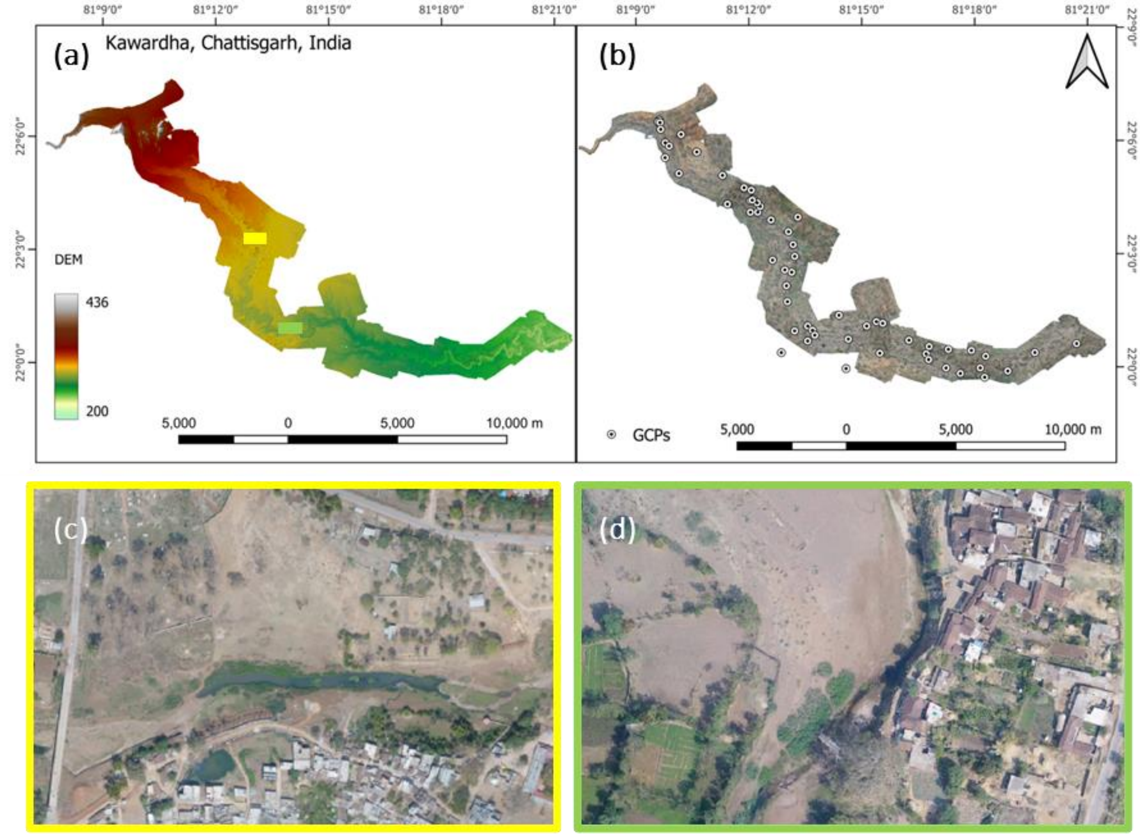


**Figure S3.** Images of Kawardha study area. (a) DTM of Kawardha area after all corrections, (b) Orthoimage of Kawardha area after all corrections. (c) Highly modified riverbed, and river space encroached upon by buildings and structures. (d) Bank cutting

*S1.4 Urbanised terrain (Anapara thermal power plant, Uttar Pradesh)*

The study area is bounded by latitude 24°12'54.82"N to 24°11'36.775"N and Longitude 82°46'20.55"E to 82°49'22.014"E. The area (approximately 4.6 $km^2$) is highly urbanized with multiple structures like multi-storied apartment complexes, buildings, industrial structures (for the thermal power plant) in South and dumping grounds in East. There were also multiple coal stacking areas. The presence of multiple and variable structures complicated the detection of ground nevertheless we provided accuracy within usable limits. As this is a thermal plant, the flight paths were regularly obstructed by the presence of cooling structures and transmission lines and special care had to be taken to avoid any collision. We also faced frequent disconnection of the UAV due to the presence of high voltage transmission lines and transformers.

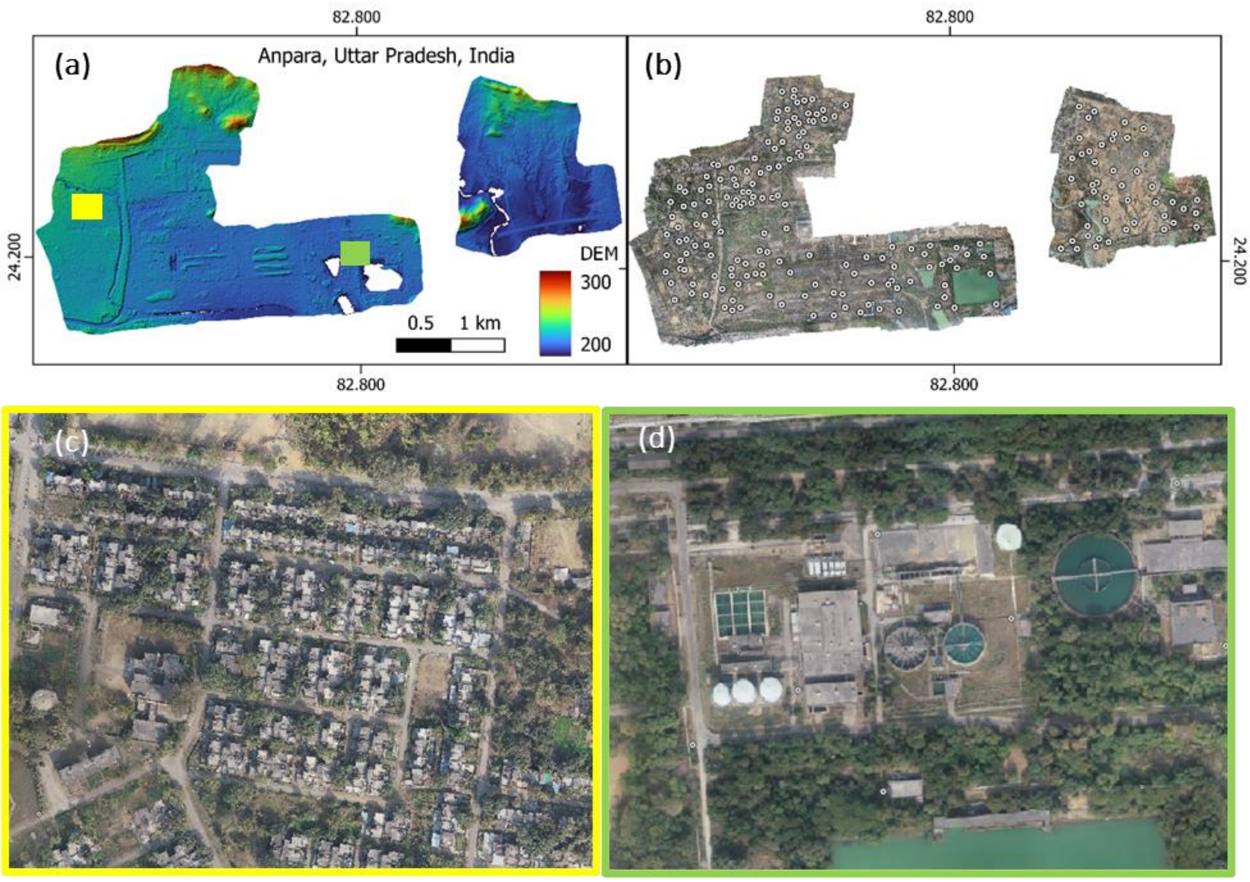


**Figure S4.** Images of Anpara study area. (a) DTM of Anpara area after all corrections, the green and yellow patched areas are shown in RGB (b) Orthoimage of Anpara area after all corrections. (c) Presence of multiple structures has altered the actual terrain. (d) presence of multiple waterbodies makes noise removal highly essential but also adds complexity.

## Section 2. Calculation of the optimum resolution for Bundle Adjustment and generation of the dense point cloud

The quality of the dense point cloud depends on the image resolution and alignment accuracy. Multiple resampling parameters are provided in photogrammetry software to fine tune between processing time and point-cloud quality. In this study, we have used the Mayurbhanj (2) study area, comprising 8729 images at an original resolution of 16MP. All the images were aligned at 100% resolution. While generating the dense point cloud, we used super scaled and downscaled version of images at 200%, 100%, 50%, 25% and 12.5% of the original image resolution. The complete data was processed in a single chunk. Time of processing and point count were compared (Figure S5). The network of two workstations with similar configuration includes, two Intel Xeon E5 2650 v3 processors running at 2.30GHz, 256GB of DDR4 RAM clocked at 1666MHz, a 256GB SATA Samsung 870 SSD, and two AMD Radeon Fury X graphics cards.

The minimum computation time was 11 hours and 50 minutes at 12.5% of their original resolution and 89 hours 20 minutes for the using 100% resolution. At 50%, the computation time is a little over 36 hours. The major increase in processing time is during the generation of depth maps for the dense point cloud. There was a marginal increase in the size of the dense point cloud until 50% of image resolution and point counts remained below 10 million. At 100%, the size of the dense point cloud exceeds 80 million points consumed 89 hours.

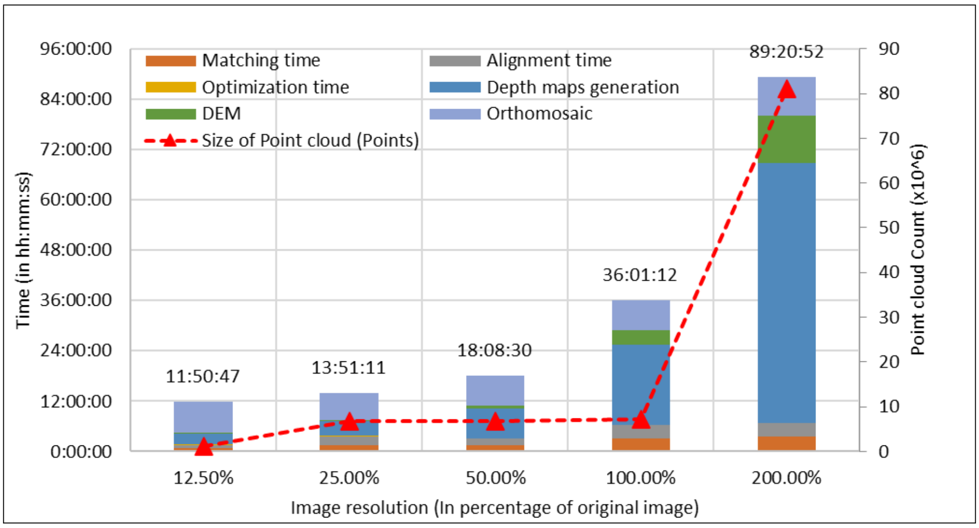


**Figure S5:** Comparison of processing time required for various stages of point cloud generation, as well as a comparison of the volume of point clouds generated at different image resolutions.

Similarly, the time required for DEM (Digital Elevation Model) generation also rose with the increased resolution. However, regardless of the quality of the dense point cloud or the DEM, generating the orthomosaic consumed 7 hours each regardless of the processed image resolution. This is because the resolution of DEM depends upon the interpolation of the point cloud, while the resolution of the orthomosaic depends upon the original images.

In Figure S6, the points in the dense point clouds were classified. It was observed that generated noise increased with image resolution, mostly related to non-perfect image alignment and camera calibration. At 100% resolution (full resolution) and at a factor two upscaling (200% resolution), more apparent noise is generated in the dense point cloud. Filtering noise from the dense point cloud can be tedious and is often an iterative, semi-automatic process. For imperfectly calibrated cameras (most field settings), using full resolution images will add more noise.

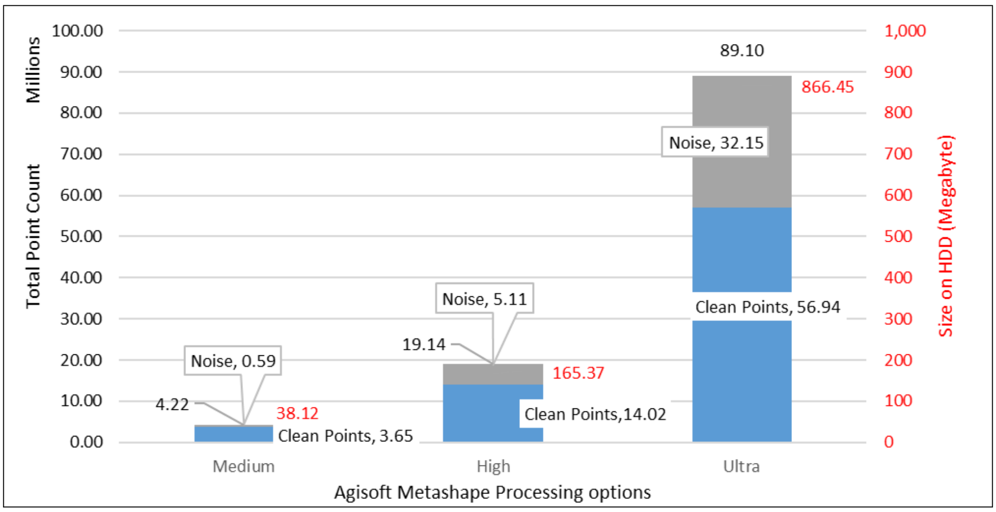

**Figure S6:** Analysis of the amount of points classified as noise and clean points at different resolution of processing.

Also, in Figure S6, it can be observed that the data volume of supersampling (200%) was approximately eight times compared to those of the High (100%) settings and generated 32.15 x10^6 noise points compared to 5.11 x 10^6 in High settings. The effect of increased noise in the point cloud can be visually observed in Figure S7: A, B &C. We conclude that an optimum processing resolution should be 50% of original image resolution unless an elaborative camera calibration and camera position scheme is applied.

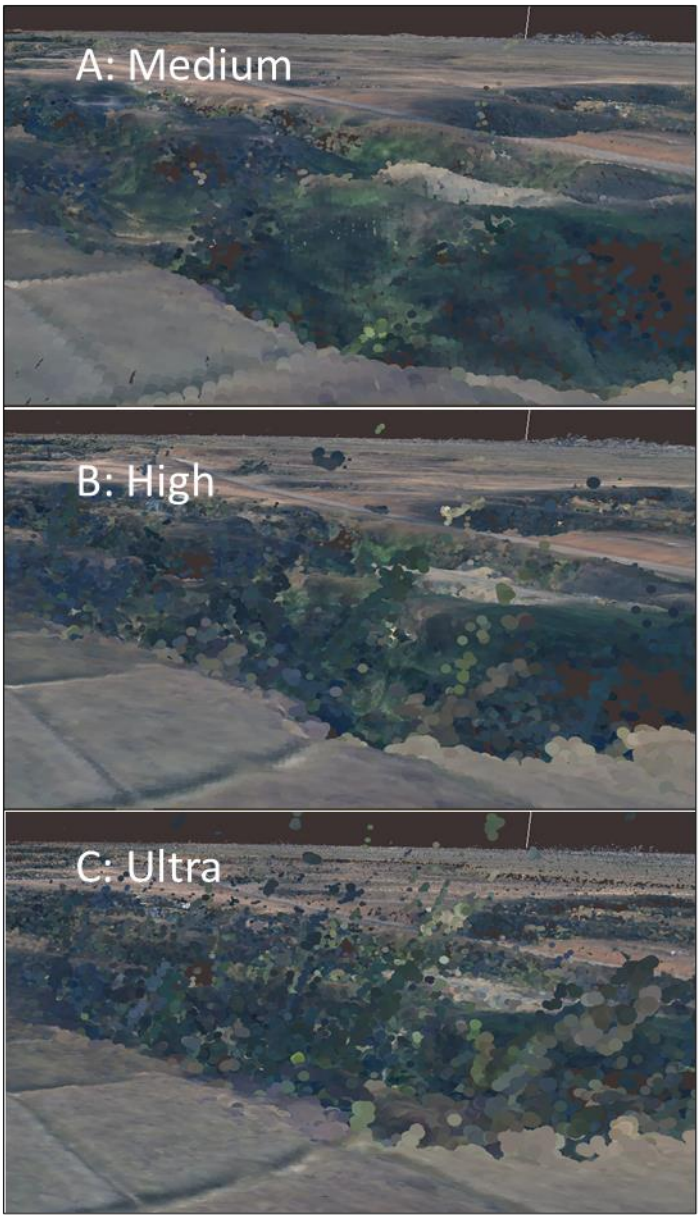


**Figure S7**: A visual examination of the differences in noise levels resulting from varying processing resolutions. Figure A was processed in 'Medium' (Downscaling ratio per side is 1:4) resolution in AMP which misses a lot of sharp edges. At 'High', Figure B, (Downscaling ratio per side is 1:2), the edges are being generated but the noise is also more. At 'Ultra' resolution, (Downscaling ratio per side is 1:1), over estimation of edges lead to higher noises.