Documentation of Remote Archaeological Sites – A Comparison Between Long-Range Laser Scanning and UAV-Photogrammetry

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Key words: UAV,photogrammetry, terrestrial laser scanning, DTM

SUMMARY

This paper presents aninvestigation of two methods for documenting remote archaeological sites:terrestrial long-range laser scanning (LRLS), and aerial photogrammetry based on unmanned aerial vehicles (UAVs). We evaluate and compare these two methods with respect to the quality of the deriveddigital terrain model (DTM)and with respect to efficiency. The investigation is based on data collected during a field campaign attwo archaeological sites in the Peruvian Andes (Santa Maria, Cutamalla).

Both methods allowed the generation of DTMs with ground resolution of 10 cmand of digital surface models (DSM) clearly showing the objects of archeological interest such as terrace structures or brick walls. A comparison of the models reveals that the planar congruency is within1 raster cell size (10 cm)and the height differences are on the order of 20 cm (1σ). Reasons for the larger height discrepancies are the different viewing angles, the different effects of vegetation and man-made structures on the terrestrial and on the airborne measurements, anduncertainties related to the differentpost processing of the data.

UAV-photogrammetry enables one to capture the entire area with high and constant resolution from above i.e., with little or no obstacles except in case of overhanging objects. However, to keep the processing time feasible regarding software and computer capacity, thenumber of acquired images should stay below ~1000 and thus the area should not exceed approx. 1 km^2. On the other hand, LRLS is more robust with respect to meteorological conditions (e.g., wind), does not require ground control points in the observed site and can acquire data over larger areas with each static setup of the instrument. The main drawbacks of LRLS are the susceptibility to obstacles within the required line-of-sight between the instrument and the features to be scanned, and the fact that the spatial resolution decreases linearly with distance. Consequently, the acquisition from multiple stations becomes necessary which increases the effort for both fieldwork and post-processing. Finally, due to the different viewing angles LRLS is less accurate for horizontal surfaces whereas UAV-photogrammetry is less accurate for vertical ones.

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1. INTRODUCTION

The generation of digital terrain models (DTM) or digital surface models (DSM)as a basis for planning or for analysis of spatial phenomena is a typical task for surveyors. The standard methods to acquire the necessary data, especially on a regional scale,are aerial photogrammetry and airborne LiDAR.On a global scale satellite-based remote sensing techniques are usually applied.The user of the data has very limited or no control over accuracy, resolution, and measurement time (timeliness) with these systems, and cannot adapt the data collection process to specific requirements. Additionally, the cost of data collection is very high and may be prohibitive for local projects unless the required data can be retrieved from a larger data set collected anyway.

Nowadays, the demands with respect to resolution, accuracy and actuality of DTMs and DSMs are high. The modelsmust be geometrically accurate, complete and up-to-date and created at low cost. Consequently, novel methods and sensors need to be developed and investigated, allowing to better address these challenges. In this paper, two recently developedtechnologies– aerial photogrammetry based on unmanned aerial vehicles (UAV) and terrestrial long-range laser scanning (LRLS) - are compared to each other using experiences and results obtained during a project. Both technologies are based on clearly recognizable predecessors (i.e., airborne-photogrammetry[1] and airborne-LiDAR, respectively). Higher accuracy and resolution are achieved by a reduced distance between sensor and objects of interest. Furthermore, the new technologies are less expensive both in terms of investment and operation, and they can easily be applied by surveying personnel.

The investigation presented in this paper focuses (i) on the quality of the resulting models (accuracy, resolution, completeness), and (ii) on economical and practical aspects (time and suitability). The comparison is based on data acquired at two different archeological sites – Santa Mariaand Cutamalla– located in the Peruvian Andes (Figure 1, Figure 2). The surveying of these areas using UAV-photogrammetry and LRLS has been carried out in 2011 as part of the joint research project "Anden-Transekt"of the German Archaeological Institute (DAI). The two sites measure about 0.2and 0.5 km^2,respectively and feature different challenges. Santa Maria lies in a high mountain valley (approx. 2800 m a.s.l.), is structured by terraces, containsleft-overs of ancient buildings and is covered with vegetation, mainly grass, bushes and cactuses. The larger site – Cutamalla – is located at the crest of a mountain at an altitude of approx. 3300 m a.s.l. Theheight of neighbouring mountains is thereby either comparable or

[1]The term airborne-photogrammetry is generally understood to imply aircraft- or satellite-based data collection even though UAVs are also airborne objects.

lower. The area contains strongly eroded terraces and similar but fewer left-overs of ancient buildings as in Santa Maria. Due to the larger altitude, the vegetation is less dominant (i.e., smaller bushes).

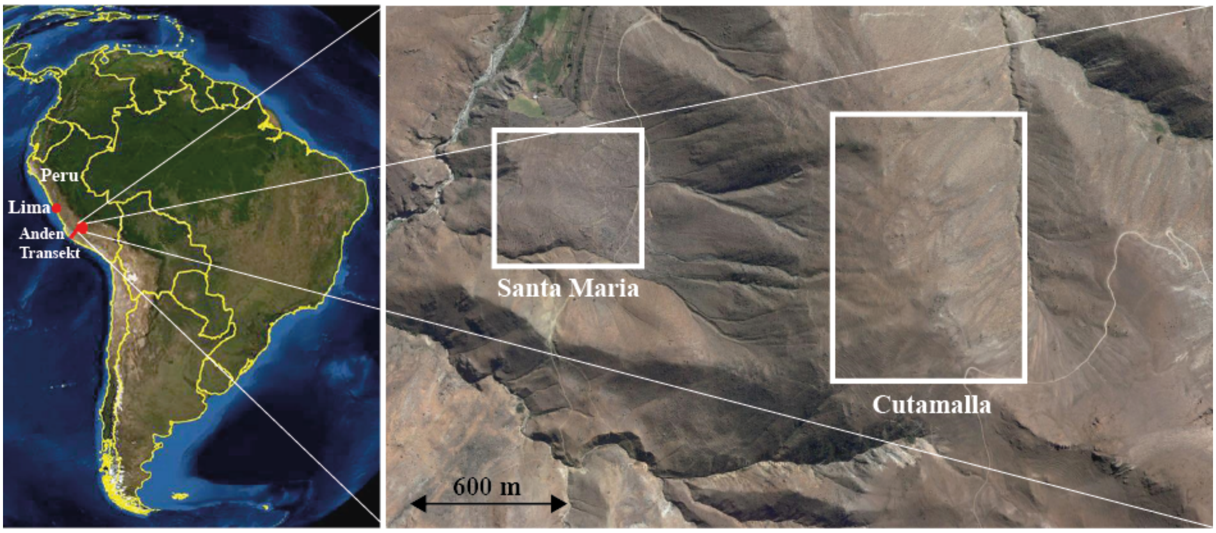

Figure 1: Overview of the investigated archaeological sites in the Peruvian Andes. Cutamalla is on the crest of a hill; Santa Maria is located in the adjacent valley.

Figure 2: The hill crest of Cutamalla (left);Santa Maria (brighter part in the middle) as seen from the opposite valley slope (right).

2. APPLIED SENSORS

2.1 Unmanned Aerial Vehicles

In the past the development of UAVs was primarily driven by military purpose, e.g. surveying of hostile territories. During the last few years the use of UAVs combined with cameras for civil applications (e.g., in geomatics)has largely increased (Remondino et al., 2011). As proposed by Eisenbeiss (2008), we refer to the combination of UAVs and digital cameras as UAV-photogrammetry. Eisenbeiss (2008) definesUAV-photogrammetry as a platform for photogrammetric acquisitions, which can be carried out remotely controlled, in semiautonomous or autonomous mode. UAVs enable flying close to the ground (typically less than 150 m above ground) and thus acquiring images with a ground pixel size of a few centimeters. Additionally, UAV-photogrammetry is applicablealso in particularly narrow spaces where conventional airborne approaches would be too dangerous or not feasible at all.

Compared to conventional aerial photogrammetry, a campaign with UAVsresults in a lot more images per unit area and thus causes higher computational effort during data processing. However, the benefit is full control over data collection parameters and high spatial resolution. Another difference regards the used cameras. As a consequence of the relatively low payload, UAVs are usually combined with non-metric cameras. The intrinsic instabilities of such cameras, aggravated by frequent takeoffs and landings (limited flight time due to batteries)and by in-flight vibrations, cause the interior orientation of the camera to change during the campaign. A solution to solve this is to do a self-calibrationduring the bundle block adjustment, as described e.g. in Kraus (1982).

In this campaign, two Falcon 8 UAVs (Figure 3, left)each equipped with a Sony NEX 5 digital compact camera, a L1-GPS antenna and a MEMS IMUwere used to obtain the images. The Falcon 8 is a multi-rotor system developed and distributed by Ascending Technologies. The system allows using a flight plan with predefined location for each image to be taken. The UAV then flies from waypoint to waypoint using (non-differential) L1-GPS and automatically controls camera tilt and system heading according to the flight plan while triggering the camera.

Figure 3: A Falcon 8 UAV as distributed by Ascending Technologies (left)[2]. An image of the site Santa Maria acquired with a ground pixel size of 2.5 cm, taken from 60 m above ground (right).

2.2 Terrestrial Long-Range Laser Scanner

LRLS is a LiDAR-based method, with which distances between a static sensor and surfaces of interest are measured using the time-of-flight principle. In combination with the recorded horizontal and vertical angles of the deflected laser beam local 3D coordinates of the measured surface points are derived. The result of a single acquisition is a point cloud, i.e., a

[2] The system in the image is equipped with a different camera than the ones used in Santa Maria and Cutamalla.

discrete representation of the surfaces facing the scanner. The angular increments between the sampled points are constant such that the point density (number of points per unit area) decreases quadratically with distance from the sensor.

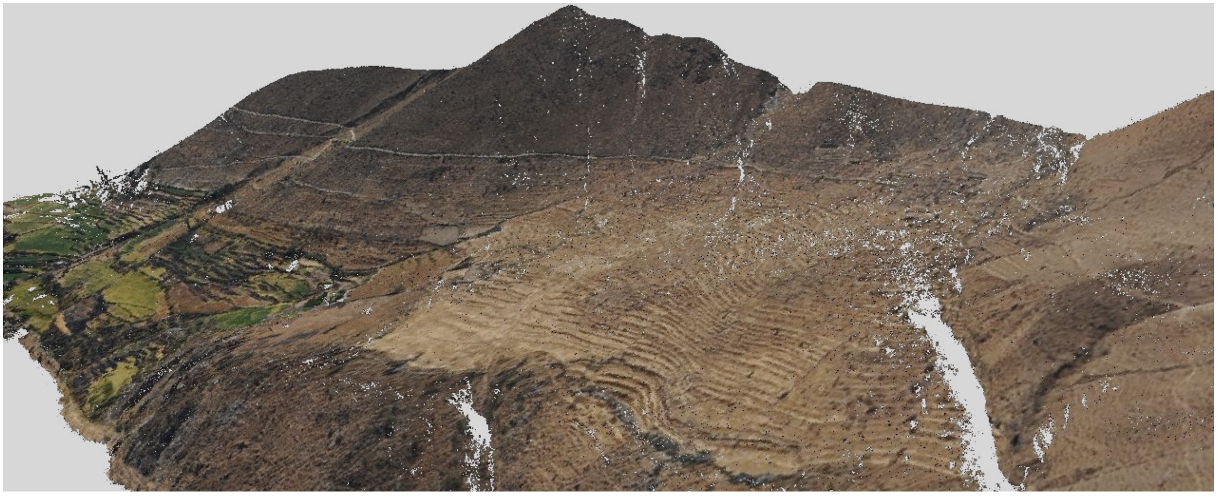

Figure 4: Colored point cloud of a single scan of the archaeological site Santa Maria acquired from a position at the counter slope of the valley (colors from digital image; occluded areas are light grey)

To generate DTMs from the two archaeological sites Santa Maria and Cutamalla with means of LRLS a Riegl VZ-1000 has been applied. This instrument allowsmeasuring surfaces in distances up to 1400 m. Like airborne LiDAR instruments, the VZ-1000can record the full waveform of the received signals. It internally classifies each of the stored measurements into one of 4 categories; single, first, intermediate and last pulses. As specified by the manufacturer, the scanner range measurement accuracy is8 mm at a distance of 100 m (under optimal conditions). An inclination sensor, a digital compass and an L1 GPS receiver are integrated into the instrument to provide coarse values of position and orientation. In the scope of this project, a Nikon D700 digital camera has been mounted on top of the scanner, to record color information. The colored point cloud of a scan of Santa Maria taken from the valley's counter slope is shown in Figure 4.

3. MODEL GENERATION

The workflows to generate digital terrain models from the raw data are quite different for UAV-photogrammetry and LRLS. Thus, in the following, we look at them separately.

3.1 UAV-photogrammetry

To reconstruct a terrain from multiple images one has to ensure that all points of interest on the surface arevisible in at least two images. When dealing with UAVs, our experience shows that it is preferable to use an overlap of 75% between any pair of adjacent images. The reasonsfor the rather large overlap are the sensitivity of the UAVs to wind and the limited accuracy of pseudo-range-based standalone GNSS of the UAV. Both facts reduce the chance that each image is actually taken at precisely the intended position. An overlap of 75% in both directions allows creating a complete model even if some images are missing or taken atsignificantly deviating positions.

In the present project, the areaswere covered with 240 (Santa Maria) and790 (Cutamalla) images taken at an altitude of 60 m above ground. This resulted in a ground sampling distance of 2.5 cm. The images were georeferenced usingmanually distributed targets which servedas ground control points (GCP) andwere measured usingdifferential carrier-phase-based GNSS. For Santa Maria 12 GCP and for Cutamalla 20 GCP were used to reference the images(crossesin Figure 5). In addition, for each image, the position and orientation of the camera as recorded onboard the UAV were used as initial values for the orientation of the images during the bundle block adjustment.

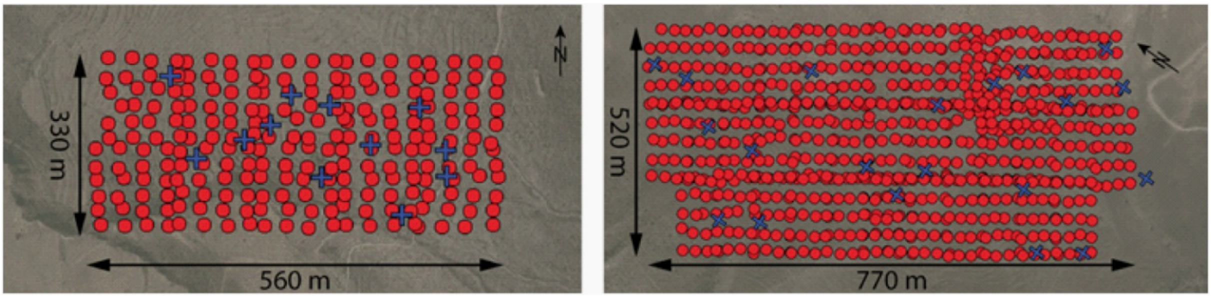

Figure 5: Positions of images(circles) and GCPs (crosses) at Santa Maria (left) and Cutamalla (right). Note the different scales and the irregular grid of the image positionscaused by the wind drifts and positioning inaccuracy of the UAV.

The photogrammetric processing from the images to the DTM and orthophoto was carried out usingthe software Pix4Dmapper (Pix4D) and the workflow depicted inFigure 6:

(i) The image orientation was the only step that partially required manual work: the GCPs were measured by the operator by manually clicking on the center of the target. The relative and absolute orientation was then estimated automatically by the software along with the self-calibration of the camera.The recorded positions and orientations of each image served thereby as initial values.

(ii)-(iv) The processes of point cloud densification as well as of the model and orthophoto generation were fully automated. Figure 7 and Figure 8 show the resulting DTMs and orthophotos for both areas. All models have a resolution of 5 cm.

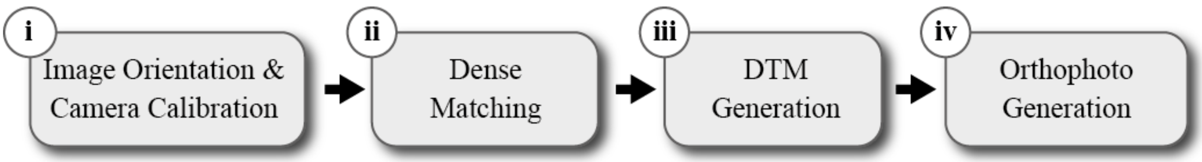

Figure 6: Applied processing steps to generate a DTM and orthophoto from the raw images.

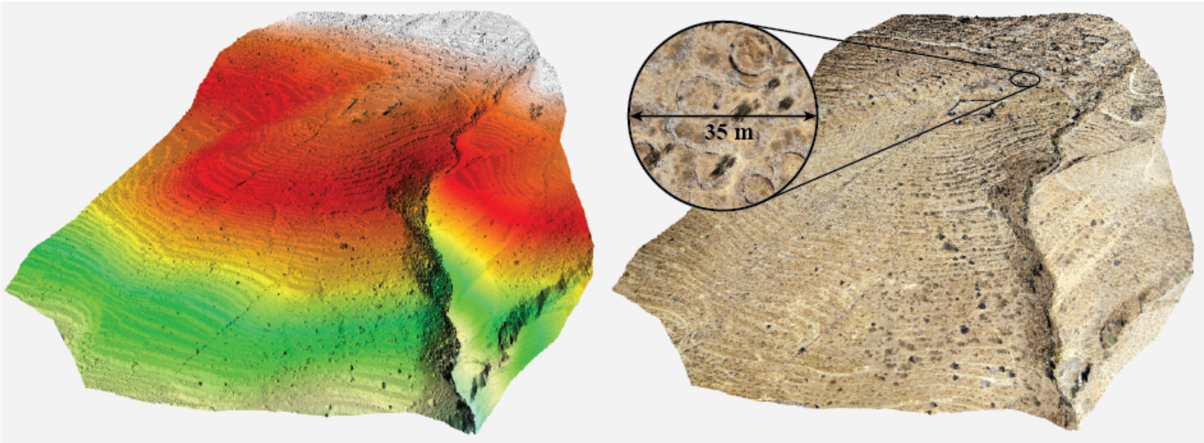

Figure 7: UAV-based DSM for Santa Maria visualized as a 3D shaded relief (left). The corresponding orthophoto mapped onto the DSM (right).

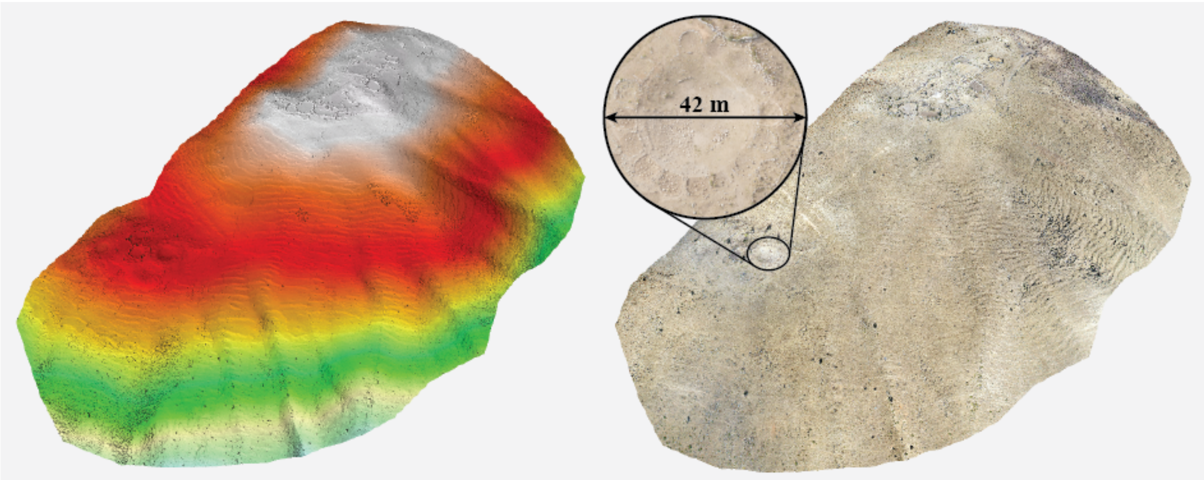

Figure 8: UAV-based DSM for Cutamalla visualized as a 3D shaded relief (left). Corresponding orthophoto mapped onto the DSM (right).

3.2 Long-Range Laser Scanning

To model the terrain or surface of a complex environment on the basis of terrestrial LRLS data, acquisitions from several stations with different viewing angles are necessary. This reduces the amount of shadows in the model, which are caused by the fact, that only objects in the direct line-of-sight of the scanner are observed. To include all major site structures in the scene (e.g., man-made structures, terraces), we aimed at a model resolution of approximately 10 cm. The angular resolution of each scan was thus set individually at each station depending on the estimated distance between the sensor and the farthest object surfaces. To ensure an accurate global referencing, well distributed instrument positions (7 in Santa Maria, 8 in Cutamalla) were additionally measured using a high-end GNSS receiver (Trimble R8) and carrier-phase in differential mode.

When surveying the two sites from terrestrial viewpoints, different challenges arose. Santa

Maria could be observed from sites located higher up the mountain slopes, which allowed covering the entire area with few instrument setups and at a fairly favorable viewing angle. Due to a lot of vegetation and man-made structures, which increases the amount of shadows, additional scans were taken from within the site itself. In total 11 scanner setups were used to cover Santa Maria and to achieve the desired model resolution. Suitable positions to scan Cutamalla could only be found on the mountain crest itself and on the surrounding hills, which have the same or lower height. Visibility of the surface to be mapped was therefore less favorable both in terms of angle of incidence and line-of-sight obstructions. We acquired 31 scans to cover Cutamalla.

Figure 9shows the workflow from the raw LRLS point clouds to the resulting DTM and DSM.Despite the availability of color information through the digital camera, no orthophoto was generated using LRLS data because of the large illumination changes across different scan positions (e.g., due to changing weather conditions).The images acquired by the camera mounted on the scanner were only used for better visualization of the point clouds.All steps were carried out using the software RiScan Pro (Riegl) with the sole exception of the raster interpolation (iv), which was done in ArcMap (esri). The resulting models of Santa Maria and Cutamalla can be seen in Figure 10.

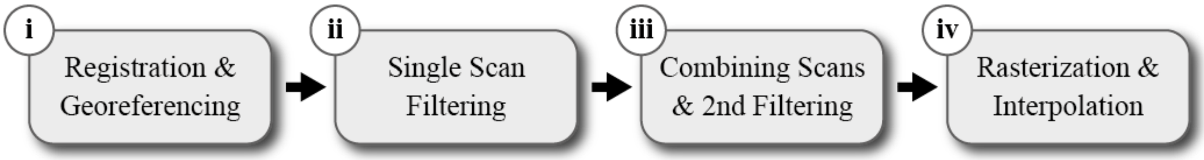

Figure 9: LRLS workflow to generate a DTM or DSM from raw laser scans.

(i) The local registration of the different scans into a common coordinate system is based on a multi-station adjustment (RiScan Pro module). This algorithm starts from coarsely registered scans (which are available here, because of the information provided by the additional sensors, see section 2.2) and is related to the iterative closest point (ICP) algorithm (Besl and McKay, 1992; Chen and Medioni, 1992). Within the multi-station adjustment, the fine registration is carried out by minimizing the Euclidean distance between corresponding planar patches, which are automatically extracted from the raw point clouds. The global registration was calculatedusing the scan positions measured separately using the high-end GNSS receiver.

(ii) Combining all scans at this stage would not have been possible because the resulting point cloud would have been too large. Thus, each scan was first filtered separately: all points outside the area of interest were deleted;then,intermediate and first pulses were deleted because they mostly correspond to sparse vegetation, which should be removed from the point cloud anyway.

(iii) The second filtering step was carried out when merging the point clouds into a single one. Anoctree filter – based on the octree structure introduced by Meagher (1982) – wasapplied to create a homogeneous point density within the new point cloud. The applied octree size (5 cm)was selected to be on the same order of magnitude as the desired final model resolution of 10 cm but somewhat smaller to better preserve details in areas where higher point density was available within the point cloud. Aterrain filter was then applied which iteratively prunes points, whose height above a smooth local surface approximation exceeds a user-defined threshold, which is comparable to the strategy described in Briese et al. (2002). At this stage, two different versions of this filter were used to generate on the one hand a DTM (strong filtering, buffer size = 0.2 m) and a DSM (soft filtering, buffer size = 1 m). In the DSM, the man-made structures and dense vegetation (e.g., cactuses) should be preserved, while the undergrowth is removed.

(iv) Each model was then rasterized, keeping only the lowest point per raster cell, as proposed by e.g., Vosselmann and Maas (2010). The lowest point is likely to be part of the terrain, and thus this step additionally removes sparse vegetation. To complete the models, missing information was interpolated using an inverse distance weighting (IDW) approach with a power of 3taking 5 neighbors into account.

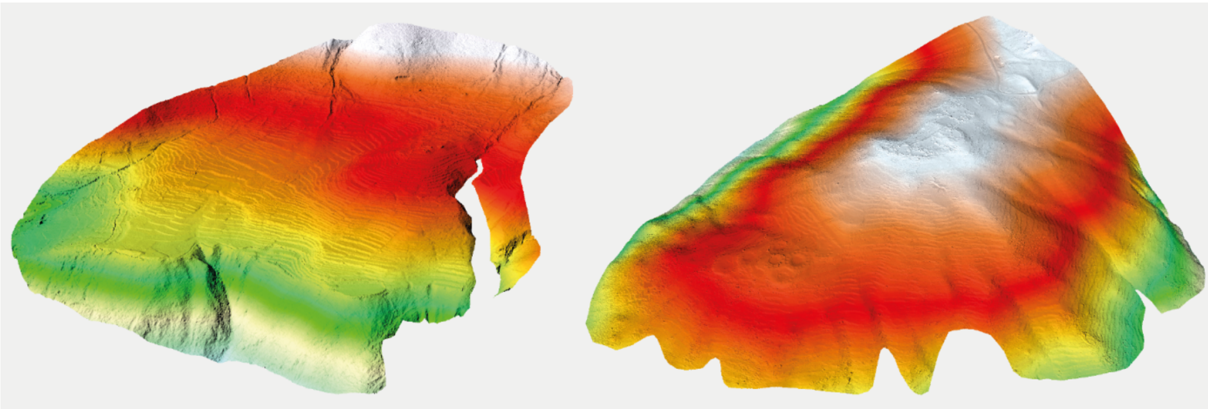

Figure 10: The DTMs of Santa Maria (left) and Cutamalla (right) visualized as 3D shaded reliefs.

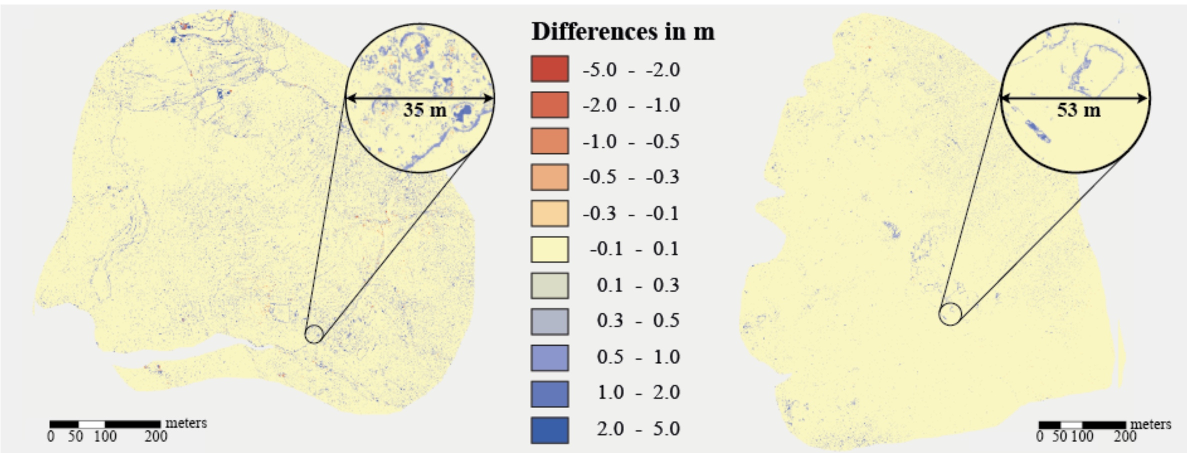

Figure 11: Vertical differences between the DSM and DTM of the two investigated sites (blue: DSM is higher; left: Santa Maria, right: Cutamalla).

Figure 11 shows the differences between the respective DTM and DSM. The differences are for most parts within a range of 10 cm. The blue lines and spots show that the DSM preserves the man-made structures (a) and still holds parts of dense vegetation (b), which was not pruned completely. Differences larger than 10 cm are much less numerous at Cutamalla, which is explained by the lower amount of vegetation and man-made structures at this site.

4. MODEL ANDSENSOR COMPARISON

In this project, the suitability of the two methods to generate complete models differed between the two sites. In Santa Maria, which could be observed from viewpoints at the surrounding higher slopes, LRLS proved to be more suited, especially considering efficiency during data acquisition. The upper part of Cutamalla, which is rather flat and is located on a mountain crest, could be better observedusing UAV-photogrammetry. In contrast, the lower part of Cutamalla is steep, increasing the effort to acquire images and at the same time making the UAV-based model generation more difficult. With LRLS on the other hand, one side of the hill could be well observed from viewpoints at neighboring hills, while for the western flank, no suitable instrument setups could be found, impeding the generation of models of the entire hill.

In the following, we compare the DSM generated from UAV-photogrammetry (further called UAV-DSM) with the two models from LRLS (i.e., LRLS-DTM, LRLS-DSM). The investigation focuses first on the quality of the derived models, and second on the efficiency of their generation. To compare models with approx. the same level of detail. The UAV-DSM was down-sampled (i.e. re-rasterized) with bilinear interpolation to a resolution of 10 cm.

A prior assessment of the accuracy (1σ) ofthe UAV-DSM with highest resolution (5 cm) is 4 cm in horizontaland 6 cm in vertical direction. The uncertainty mainlyresultsfrom the limited accuracy of the GNSS-based GCP coordinates, from the uncertaintiesofthe GCP measurements in the images and from inaccuracies introduced during the model generation steps (e.g., by smoothing). This assessment was verified using check points (artificial targets placed in the scene and measured separately also using carrier-phase-based GNSS) distributed over the two excavation sites.The mean residuals in these points were 2.9 cm for Santa Maria and 5.1 cm for Cutamalla.

For the LRLS models, accuracies(1σ) of around 6 cm horizontally and8 cm vertically were expected, again based on prior assessment.The main sources of uncertainties are the limited accuracy of the GNSS-basedGCP coordinates, the uncertainties of thelaser scanner measurements, the determination of the instrument height and again uncertainties arising during data processing (e.g. by filtering).Due to missing LRLS-GCPs, the estimated LRLS model accuracy could not be independently verified. Although, the mean residuals of the reference points during the georeferencing (7 in Santa Maria, 8 in Cutamalla) of 8 cm planar and 5 cm in height indicate that the estimations are in a reasonable range.

On the one hand, given the position accuracies of the individual models, the congruency of the models in horizontal direction should beapproximately 7 cm (1σ). Given a raster cell size of 10 cm, maximum position deviations must not exceed one cell. Based on visual comparisons at well-defined structures the estimated planar accuracies of the models could be validated. On the other hand, we will treat height differences below 10 cm as negligible in the subsequent comparisons because they are within the expected accuracy level. Differences exceeding 0.5 m will be classified as outliers.Figure 12 and Figure 13 show the height differences between the LRLS models and the UAV-DSM for the two investigated sites.

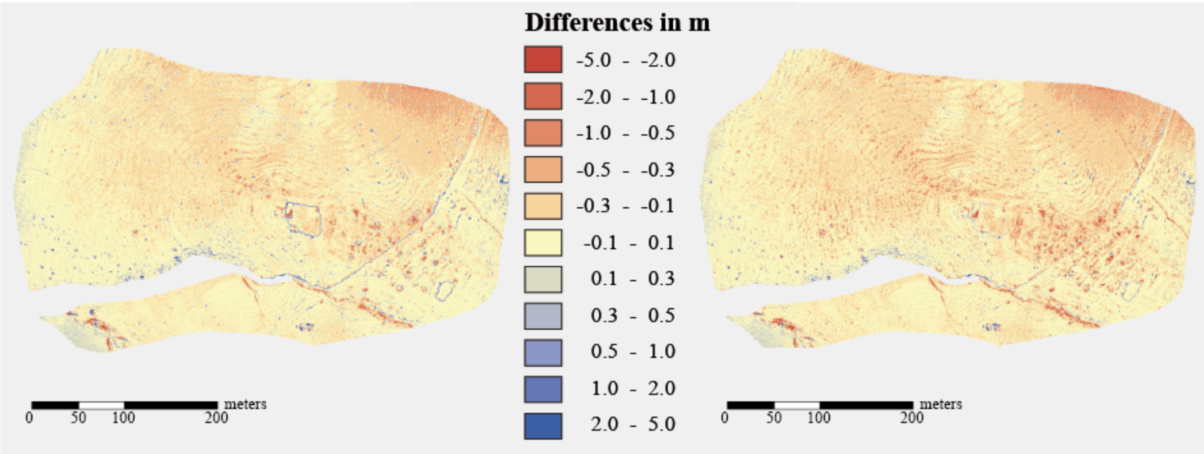

Figure 12: Comparison of the UAV-DSM with the LRLS models of Santa Maria. Left: UAV-DSM – LRLS-DTM, right: UAV-DSM – LRLS-DSM.

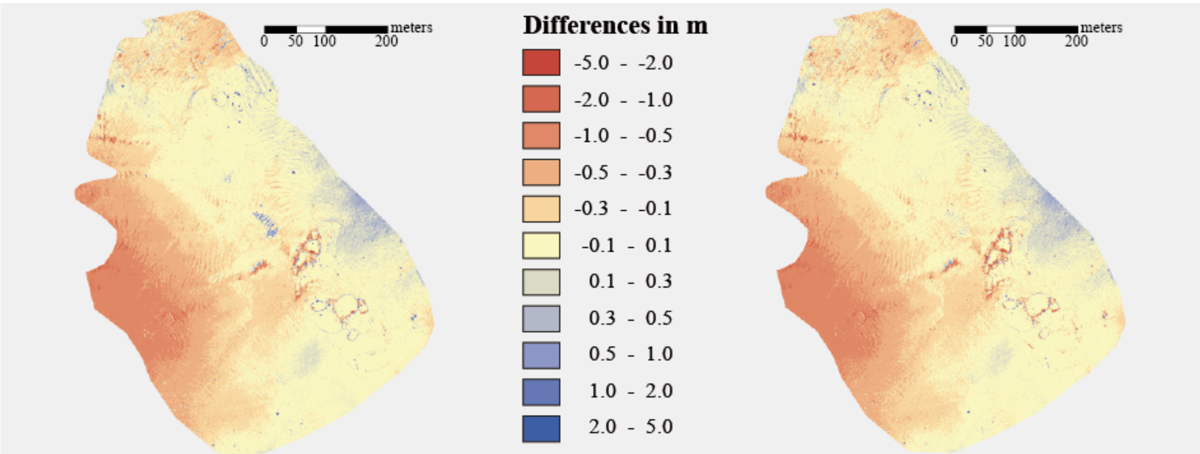

Figure 13: Comparison of the UAV-DSM with the LRLS models of Cutamalla with the larger differences at the western flank (red). Left: UAV-DSM – LRLS-DTM, right: UAV-DSM – LRLS-DSM.

Larger differences between UAV- and LRLS-based models are foundat the border of the models. These differences can be explained on the one hand by inaccuracies of the self-calibration of the camera during image orientation, which would lead to a slight bending of the model at itsedges, and on the other hand because these parts are also steeper than the rest of the model, causing additional image matching problems. In the case of Cutamalla, the area on the west side of hill is poorly covered by LRLS, which leads to data gaps that must be interpolated and could thus cause height errors. Since there is a lack of control points in this area absolute statements about model correctness are not possible.In addition, one can observe that significantheight differencesin the models of Santa Maria as well as Cutamallacan often be found near vegetation or man-made structures. In the difference image of the UAV-DSMand the LRLS-DTM almost all artificial structures correspondtopositive height differences. This means, that the strong filtering step in the generation of the LRLS-DTMmodel was able to remove these structures successfully (Figure 14, middle). Adjacent to the artificial structures and large vegetation, one can identify areas where the LRLS-DTM is higher (red). This effect is caused by data gaps in the shadows of the objects, leading to interpolation errors in the model. Errors due to missing data also occur in other areas, e.g., swales (Figure 14, left).

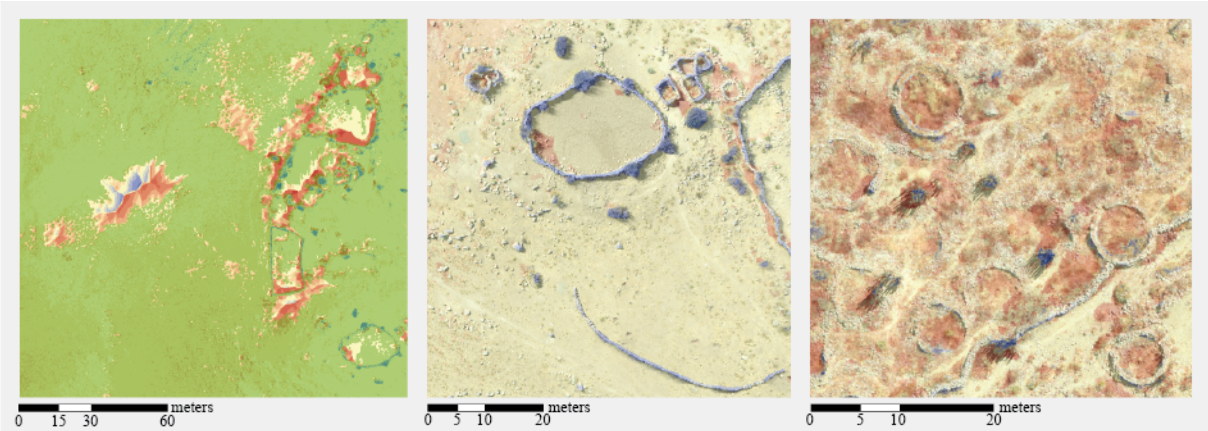

Figure 14: Zooms into the difference images. Left: Errors arising during interpolation because ofmissing data (green overlay = basic point cloud, no green color = no measured points). Middle: Deviations between UAV-DSM and LRLS-DTM in areas with man-made structures and vegetation. Right: Differences of the two DSMs in areas with vegetation and objects of interest.

Height differences between the LRLS-DSM and the UAV-DSM only arise at the largest man-made structures and dense vegetation parts (i.e. cactuses), while the deviations at smaller structures and with lower vegetation remainbelow 10 cm(Figure 14, right).With respect to the LRLS-DTM and UAV-DSM comparison, smaller differences arise, which can be explained considering the method to generate the UAV-DSM. Recall, that only visible points are recorded and thus matched, which leads to a model of the surface (i.e., DSM). The UAV-based model is smoothed during generation, while the vegetation filter in the LRLS model computation removes isolatedpoints (outliers or vegetation), or keeps them at their actual height.This different behavior of the filter and the different viewing angle explains the larger discrepancies in areas which are rich in vegetation.

Apart from the visual comparison, we have carried out a statistical evaluation. For each site, the mean of the height differences, theirstandard deviation, the number of points (model grid cells) and the outlier ratio werecalculated. Due to the rather large systematic differences at the western flank of Cutamalla, these parts were excluded in the statistical analysis.

Table 1: Statistical evaluation of the differences between the UAV and LRLS models of Santa

Maria (1) and Cutamalla (2). *Note, that the mean height differences (Mean) and the corresponding 1σ standard deviations (StdDev) are calculated including the outliers.

Site	Compared models	No. compared points	Mean* in m	StdDev* in m	Outlier > 0.5 m
1	UAV - LRLS DTM	12853092	-0.07	0.18	4.6 %
	UAV - LRLS DSM	12853092	-0.11	0.22	4.6 %
2	UAV - LRLS DTM	19858840	-0.02	0.17	1.7 %
	UAV - LRLS DSM	19858840	-0.03	0.18	1.8 %

Table **1** shows, that there are no further systematic effects remaining in the Cutamalla models (i.e. mean differences are 2 to 3 cm). The cause of the systematic errors in the Santa Maria models (up to 11 cm mean difference) could not yet conclusively be verified. Additionally, the number of outliers in Santa Maria (~5%) exceeds the one in Cutamalla (~2%), probably caused by the larger amount of man-made structures and dense vegetation. The standard deviation of the height differences is approx.20 cm for all analyzed pairs of models, which is twice as high as the expected model accuracy of 10 cm. Removing all differences >0.5 m as outliers reduces the standard deviations by a few centimeters, but not down to 10 cm. An analysis of the histogram shows that the distribution of all differences is actually not normal but has significantly heavier tails, most likely due to moderate (but many) outliers next to vegetation and in obstructed areas, as discussed above. This explains why the prior assessment was valid for free areas (where the checkpoints had been placed) but overall too optimistic.

Comparing UAV-photogrammetry to LRLS regarding efficiency and effectiveness based on this project, we have to consider the following: First, the models resulting from the LRLS cover a significantly (i.e. 2 to 3 times) larger area than the ones derived from the UAV-images. Second, the resolution of the UAV-based models was with 5 cm approximately twice as high as in the LRLS models. Third, some processing steps during the LRLS model generation were carried out twice to receive a DTM and DSM model. Taking these considerations into account, it turned out that the generation of DTMs from UAV-photogrammetry and LRLS require approximately the same processing time.With the recent development of almost fully automated processing workflows, UAV-photogrammetry became competitive to LRLS, which still requires more manual interactions during the point cloud processing. In addition, the handling of large laser point clouds like the ones obtained here (single scans with up to 100 M points before filtering)still overstrains commercial software or PCs, which increases working time by introducing additional processing steps. To put it in numbers, experienced surveyors (1 for LRLS, 2 for UAV) require 1 day for the data acquisition of Santa Maria and it takes a well-trained operator 2 days for the model generation (assuming no unexpected problems occur).

5. CONCLUSION

The described investigation proved that both methods – LRLS as well as UAV-photogrammetry – are suited to generate high resolution terrain and surface models. The models fulfil the requirements of archaeological surveying, i.e. man-made structures such as terraces and brick walls can be identified in the DSM models. The planar accuracy of approximately 7 cm additionally enables the use of such models for further analyzes. The estimated height accuracy of the models of 10 cm (1σ) was not confirmed by the comparison of LRLS- and UAV-models. The standard deviations (1σ) of the height differences are around 20 cm, probably because the distribution of these differences is not normal but has significantly heavier tails. The main uncertainties in the models are located around dense vegetation and larger structures. At these positions the comparisons are showing the largest deviations, resulting from data gaps and different smoothing as well as filtering during model generation.

The two methods are comparable regarding the required processing time to generate complete models. Taking the acquisition time into account, LRLS was able to cover larger areas than UAV within the same time for field work. On the other hand,point cloudsderived from the UAV-based imageshave less gaps as well ashigherand more constant point densities. Considering the suitability regarding the different investigated sites, the following conclusions can be drawn: (a) The flat area of the hill crest of Cutamalla is better suited for airborne methods such as UAV-photogrammetry;especially due to the lack of observation points located at higher positions, the LRLS models contain large data gaps caused by obstacles (e.g., man-made structures, vegetation). (b) The observation of Santa Maria was successful with both methods. However, the many convenient terrestrial viewpoints enabled to cover a larger area with LRLS in the same time. (c) For the steep flanks of the hill crest of Cutamalla LRLS is preferable.Areas consisting of rather vertical structures are better observable from terrestrial viewpoints.The viewing angle is unfavorable when measured from above, the flight planning is more challenging, and the large height differences result in strongly varying ground pixel sizes within an aerial image and thus the automatic matching becomes more error-prone.

The investigation showed that both methods are complementary if the area to be covered contains both nearly vertical and nearly horizontal parts. Therefore, we will investigate the combination of both for the derivation of even better terrain and surface models.

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