Elaborating more accurate high-resolution DEMs using SfM workflow

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Abstract—**Structure-from-Motion (SfM) photogrammetry is one of the most common approaches used to elaborate high-resolution Digital Elevation Models (DEMs) nowadays. Factors that influence the final error associated to the derived DEM are: camera-to-ground distance, camera-sensor system parameters, image network geometry, matching performance, terrain type, lighting conditions and referencing methods. Here, a strategy focused on minimizing the occlusion produced by topography and determine optimal camera locations for image acquisition is presented. This methodology is based on using a viewshed analysis implemented in a Geographical Information System (GIS) to identify the best images for the SfM workflow of a specific survey-site. The suitability of the workflow presented against conventional acquisition strategies was tested using three different datasets (one terrestrial and two aerial) and analyzing differences between SfM-derived DEM produced using: 1) a dataset acquired following conventional overlap requirements (i.e. one image every 5-10º around the target for terrestrial close-range oblique SfM and 70-60% frontal and side overlap for aerial surveys), 2) a dataset overloaded with images (i.e. one image every 3-4º around the target and >95-95% frontal and side overlap for aerial surveys), and 3) images selected using the viewshed analysis. The resulting DEMs were tested against Terrestrial Laser Scanner-derived (TLS) DEMs.**

SfM results showed denser point clouds for the datasets elaborated using the viewshed analysis. Differences were particularly important for the terrestrial case indicating a stronger line-of-sight effect on the ground. Point cloud density absolute differences and no-data zones in the datasets produced using the conventional strategies resulted in larger Mean Absolute Errors (MAE) in the DEMs. DEMs produced using the viewshed criteria showed lower MAEs than the conventional dataset and similar to the dataset overloaded of images. Additionally, the processing time of the datasets that used viewshed criteria was much shorter than the datasets overloaded of images.

I. INTRODUCTION

DEMS are commonly used to represent topography in the Earth sciences and the accuracy of DEMs produced by a wide variety of techniques is usually tested. In the last years, SfM photogrammetry has become one of the most common techniques used to produce high-resolution DEMs.

SfM processing demands a great computation power because usually a large amount of images are used to feed the procedure. These images form the image network geometry which is an important factor that influences the final total error in the resulting cartographic products (i.e. point clouds, DEMs, orthophotographs, etc.). In the literature, some general guidelines about the optimal network geometry configuration are provided, but it is not yet possible to estimate *a priori* the optimal camera locations and orientations for a specific survey site. Defining optimal camera locations and orientations will require minimizing the occlusion produced by the combination of topography and camera pose. The visibility algorithms traditionally implemented in Geographical Information Systems allow to carry out this occlusion analysis.

In this work, we present a methodology based on the use of GIS-based viewshed analysis that improves the performance of SfM techniques to obtain DEMs with a higher accuracy and saving processing time. The methodology is applied to three datasets (one terrestrial oblique and two aerial datasets) that represent challenging landscapes because of their complexity and variety of forms (one rock glacier and two types of badlands).

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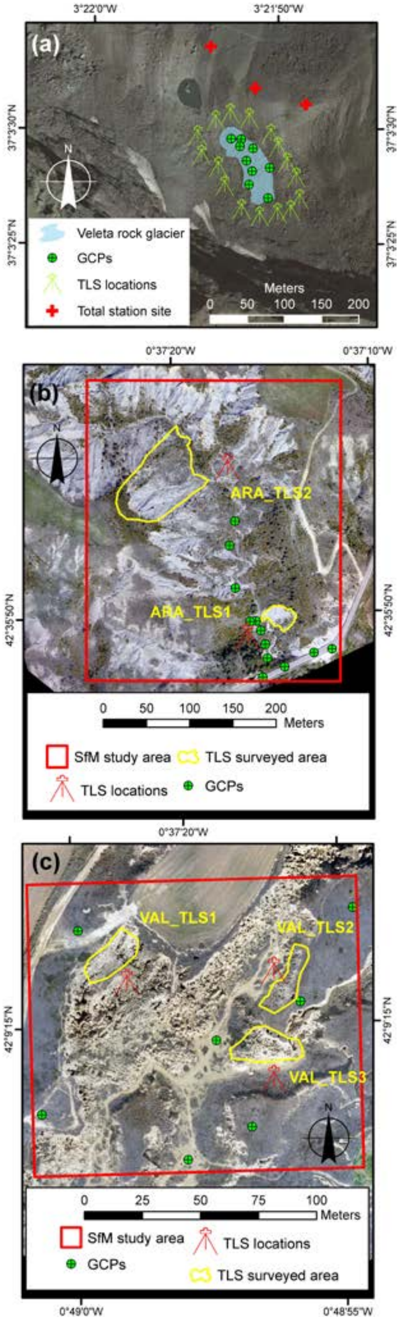

Figure 1. Study areas (a: Veleta rock glacier, b: Araguás badlands and c: Valpalmas badlands) and field survey details (i.e. TLS study sites and GCPs).

II. MATERIAL AND METHODS

One terrestrial and two aerial datasets (Fig. 1 and Table I) were used to test the differences between the benchmark TLS-derived DEMs and the SfM-derived DEMs produced using 1) a dataset acquired following conventional overlap requirements (conventional: i.e. one image every 5-10º around the target for terrestrial close-range oblique SfM and 70-60% frontal and side overlap for aerial surveys), 2) a dataset overloaded with images (overloaded: i.e. one image every 3-4º around the target for terrestrial close-range oblique SfM and >95-95% frontal and side overlap for aerial surveys), and 3) images selected using the viewshed analysis (viewshed). The test against the TLS-derived DEM was carried out using a DEMs of Difference (DoD) approach. For the terrestrial case (Veleta rock glacier), the TLS data covers the whole study area, while for Araguás [1] and Valpalmas [2] badlands (due to their geographic extension) two and three sites were selected respectively.

The SfM processing was carried out using Pix4D software to obtain point clouds, DSMs, DEMs and orthomosaics for each dataset. In addition to the DoD approach, the results of the SfM processing were tested in terms of processing time, point cloud volumetric point density and georeferencing accuracy.

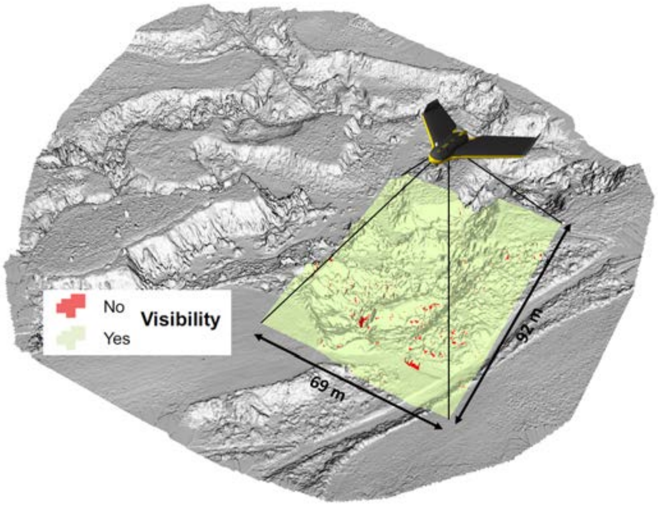

Figure 2. Viewshed analysis for the UAV location and its footprint on the ground.

The viewshed analysis estimates the locations from which a specific location can be seen (Fig. 2). The analysis was performed using the observer point tool implemented in ArcGIS software. Here, the DEM and external camera parameters, both

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obtained from the SfM processing of the overloaded datasets are used to feed the viewshed analysis. The DEM provides the surface for analysis, while the external camera parameters allow to limit the analysis to the footprint of the camera on the ground. Note that the analysis can also be fed by any available high-resolution DEM and with simulated camera locations in order to estimate the optimal camera pose before the field survey. The viewshed analysis produces a binary encoded map showing pixels on the DEM that can be seen relative to an image location (Fig. 2). Using these maps the camera position that can see the largest fraction of the study area for every overlap zone can be identified. Overlap zones are defined as the area that should contain at least one image to keep the overlap requirements for SfM (e.g. one image every 5º-10º around the target for terrestrial datasets and 70-60% frontal and side overlap for aerial datasets). Note that the method presented here is used as a tool to filter the overloaded dataset in order to produce the viewshed dataset but it could be also applied to simulate optimal camera positions.

TABLE I. CHARACTERISTICS OF THE FIELD SURVEYS.

	Study area		
	Veleta rock glacier	***Araguás badland***	***Valpalmas badland***
SfM survey area (m^2)	9,907	101,838	19,950
Platform	Terrestrial	Aerial	Aerial
Sensor	DSLR Canon EOS 5D	Sony WX220	Sony WX220
Benchmark	TLS whole study area	TLS for 2 sites	TLS for 3 sites

III. RESULTS AND DISCUSSION

The point clouds obtained using the viewshed analysis outperformed those obtained following conventional acquisition schemes in terms of coverage and completeness (Table II). These differences were particularly important for the terrestrial case (Veleta rock glacier) where the point cloud generated using the viewshed criteria produced 4.6 million more points than the dataset obtained using the conventional acquisition scheme. No significant statistical difference was observed in terms of structural accuracy of the models (using the RMSE obtained during the georeferencing of the SfM model). Additionally, the viewshed dataset notably reduced the processing time regarding the dataset that included all the images (overloaded: Table II).

For the specific case of the DEM, error statistics obtained for each dataset and TLS study site are presented in Table III. Most of the DEMs produced using all the images showed the lowest Mean Absolute Errors (MAEs) for all the study areas excepting ARA TLS2 site. .

TABLE II. CHARACTERISTICS OF THE RESULTING DATASETS.

FEATURE		**Study area**		
	dataset	***Veleta rock glacier***	***Araguás badland***	***Valpalmas badland***
Images (n)	Over.	95	97	171
	Conv.	44	43	85
	View.	44	43	85
Points in the cloud (n)	Over.	49.8 mill.	138.1 mill.	258.3 mill.
	Conv.	11.8 mill.	71.7 mill.	173.4 mill.
	View.	16.5 mill.	74.5 mill	175.3 mill.
Processing time	Over.	2:24:01	6:48:45	12:24:46
	Conv.	0:41:19	2:48:23	8:54:32
	View.	0:34:29	2:54:16	7:48:51
Georeferencing RMSE (m)	Over.	0.011	0.031	0.045
	Conv.	0.011	0.017	0.046
	View.	0.013	0.029	0.043

A detailed examination of each TLS site corroborated that the viewshed DEM presented lower differences when compared to the TLS-derived DEM. Fig. 3 shows two examples of the results obtained by the DoD approach (one terrestrial and one aerial). These two examples presented in Fig. 3 show that DEM viewshed concentrates more pixels in the regions close to 0 (i.e. no difference between TLS-derived DEM and SfM-derived DEM) while the DEM produced with the conventional dataset presented larger number of pixels in the higher positive and negative distances.

At this point, the key question is do we save time using the viewshed processing? For example, for Valpalmas study area the viewshed analysis of the 171 photos (carried out to select those with the highest visibility) lasted 55 minutes and the SfM processing of the Viewshed dataset lasted 496 minutes. Hence the proposed methodology lasted 551 against the 744 minutes used to process the overloaded dataset. Additionally, the point cloud produced by the viewshed analysis will also reduce processing time of subsequent processes analysis (visualization, feature extraction, object recognition, segmentation, classification, etc.) with 175.3 million of points against the 258.3 million of points in the overloaded dataset resulting point cloud.

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TABLE III. DIFFERENCES BETWEEN SFM-DERIVED DEMS AND BENCHMARK DEMS PRODUCED USING THE TLS DATASETS. ALL= OVERLOADED DATASET, RAN= CONVENTIONAL DATASET, VIEW= VIEWSHED DATASET, ME=MEAN ERROR, MAE= MEAN ABSOLUTE ERROR AND SDE=STANDARD DEVIATION OF ERROR.

Table Head	**Dataset**	**ME (m)**	**MAE (m)**	**SDE (m)**
Veleta	ALL	-0.09	0.12	0.16
	RAN	-0.13	0.18	0.27
	VIEW	-0.11	0.14	0.17
Araguás	ALL_TLS1	-0.02	0.12	0.24
	RAN_TLS1	0.41	1.46	1.96
	VIEW_TLS1	0.09	0.19	0.38
	ALL_TLS2	-0.02	0.34	0.60
	RAN_TLS2	0.04	0.13	0.48
	VIEW_TLS2	0.05	0.33	1.95
Valpalmas	ALL_TLS1	0.05	0.10	0.13
	RAN_TLS1	0.09	0.15	0.19
	VIEW_TLS1	0.05	0.10	0.13
	ALL_TLS2	0.10	0.27	0.39
	RAN_TLS2	0.43	0.47	0.41
	VIEW_TLS2	0.06	0.16	0.27
	ALL_TLS3	0.18	0.27	0.38
	RAN_TLS3	0.41	0.50	0.48
	VIEW_TLS3	0.32	0.36	0.35

IV. CONCLUSIONS

According to the findings presented here, visibility analysis in SfM workflow may be helpful to elaborate more accurate DEMs while reducing processing time. Studies based on the use of SfM-derived DEM in complex topographic surfaces should note that data holes consequence of the line-of-sight effect may produce important errors in their analysis. In this context, the methodology presented here could be helpful to improve the quality of the resulting DEM.

Our future research is focused on designing specific tools for QGIS to support the data acquisition for SfM workflows.

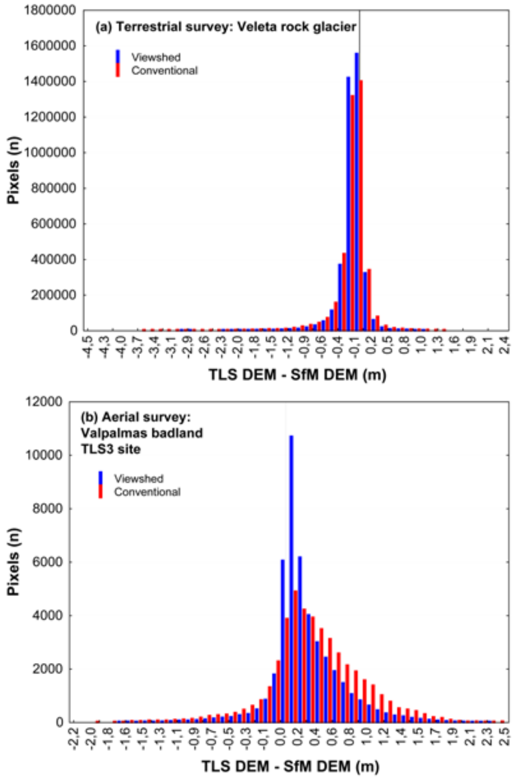

Figure 3. Differences between the TLS-derived DEMs and the SfM-derived DEMs for a) the terrestrial survey and b) the aerial survey in Valpalmas badland.

ACKNOWLEDGMENT

Álvaro Gómez Gutiérrez was the beneficiary of a Fulbright-José Castillejo postdoctoral grant (Fulbright Foundation and Spanish Ministry of Education, Culture and Sports) for carrying out the present research. Estela Nadal-Romero received a “Ramón y Cajal” postdoctoral contract (Spanish Ministry of Economy and Competitiveness). Field surveys were possible thanks to the financial support of the Spanish Ministry of Economy and Competitiveness (project CGL2014-54822-R).

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