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# Historical 3D Topographic Reconstruction of the Iwaki Volcano using Structure from Motion from Uncalibrated Aerial Photographs

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## Abstract

The acquisition of topographic data is crucial for earth sciences, especially for the monitoring of topography that may change drastically in a short-time such as volcanoes. Precise topographic data are usually acquired using Lidar technologies, both airborne and terrestrial, but this method tends to be very costly both financially and in term of time for data processing. The present article present therefore an alternative technique, which has been only described once in a earth-sciences article: Structure from Motion (SfM) combined with Multiple View Stereophotogrammetry (MVS). SfM-MVS is a technique developed in computer vision that allows the calculation at the same time of both the position of the camera and the reconstruction of the 3D of a scene, and then recreate a 3D mesh of the topography. The present article is testing the technique at the Iwaki volcano in Northern Honshu in Japan, using a series of historical aerial photographs taken in 1965, 1985 and 1994. This has allowed the reconstruction of the topography and the drawing of orthophotographs, but comparison with data provided by topographic data have shown that the accuracy of the topographic results tends to reduce at the external limits of the volcanoes, most certainly because of the lack of images to accurately calculate the elevation. In order to confirm the validity of the technique and to show that the lack of accuracy is linked to the character of the data, a laboratory experiment using a decimeter scale sample was conducted. The results of this experiments showed excellent and accurate results with 3D points characterized by a correlation coefficient  $R^2$  or 0.9985 between the calculated and the measured data. This demonstrates the possibility of such technique, not only in earth sciences, but also archaeology, space exploration, etc.

## Introduction

Topographic data and its modeling are essential in geomorphology and earth sciences, providing evidences of past- and present geomorphologic activity (e.g. Tarolli et al., 2012), which lead to a measured understanding of the morphology of the landscape (e.g. Gomez, 2012). The use of topographic data in geomorphology is either qualitative or quantitative. Traditionally, the first one has been linked to the characterization of forms in the landscape, whereas the second has been more linked to different morphological analysis and the production of data that feeds numerical models. Recently, however, with the increasing importance of computer geosciences, quantitative analysis has been dominating topographic data usage from at least the late 20th century and the beginning of the 21st century. This dichotomy is also on the verge of disappearing, because of the development of very accurate topography acquisition systems, such as TLS (Terrestrial Laser Scanner) or ALS (Airborne Laser Scanner) for instance.

The acquisition of accurate topographic data with a dense cloud of points is best realized using one of these two technique - ALS or TLS. They are still, however, very expensive – operation or acquisition of apparel – and the data processing is very much time-consuming. In order to overcome these two limitations, the author has investigated alternative methods and the closest low-cost and low-processing possibility available is 'Structure from Motion' (SfM), term coined by Ullman in 1979 - or sometimes called 'Structure and Motion' (SaM) . SfM "is the simultaneous recovery of 3D structure and pose from image correspondences" (p. 307 in Szelinski, 2011).

SfM provides a 3D reconstruction of a scene based on uncalibrated 2D photographs which have recognizable objects in overlapping images. Using traditional photogrammetry, the 3D is built (1) thanks to a series of points appearing, each, in at least two photographs and (2) thanks to the prior knowledge of the

images projection, orientation, camera distortion and position (Robertson and Cipolla, 2009). SfM does not require any of the above parameters (although these parameters can be integrated to improve the productivity of calculation) and it allows the simultaneous computation of both the relative projection geometry and a set of 3D points using corresponding image features in series of photographs (Fisher et al., 2005; Quan, 2010; Szeliski, 2011).

Several SfM packages are available as desktop solutions like Bundler (Snavely, 2010, Snavely et al., 2006) or online such as Photosynth created by Microsoft (photosynth.net). Photocan-pro is a more complex package created by Agisoft that couples both SfM and multi-view stereo algorithms (MVS). This software is the most adapted for topographic reconstruction as it retrieves a set of points using SfM and then improves the construction of 3D mesh using MVS. The interest of earth-sciences towards this novel technique is evident as James and Robson (2012) have already published a pilot paper on the technique during the preparation of the present paper. The authors also recognize that the tandem SfM-MVS offers the best approach to reconstruct 3D scenes from still 2D images. Indeed, the retrieved digital surface model is more accurate than a reconstruction based on feature points, as it uses pixel values. "... this additional step enables the generation of detailed three-dimensional meshed models from the initially calculated sparse point clouds, hence enabling proper handling of fine details present in the scenes (p.2062 in Verhoeven et al., 2012). Since this technique can work from photographs and/or aerial photographs, the combination of both allows an accurate semi-automated creation of ortho-rectified aerial photographs, which can be accurately georectified if the location of the camera is known or with ground-control points (Turner et al., 2012).

The properties of SfM makes it therefore a powerful tool to reconstruct historical scenes for which no 3D structure or DEM is available. The fields of archaeology and

history are both the recent beneficiary of this idea (Agarzal et al., 2009; Schindler and Dellaert, 2012), which they use for the reconstruction of past-cities and buildings based on old photographs. Within this paradigm, the present contribution aims to prove that such reconstruction is also possible using old aerial photographs or photographs taken from the ground for historical topographies and the correction of historical aerial photographs.

## Study location

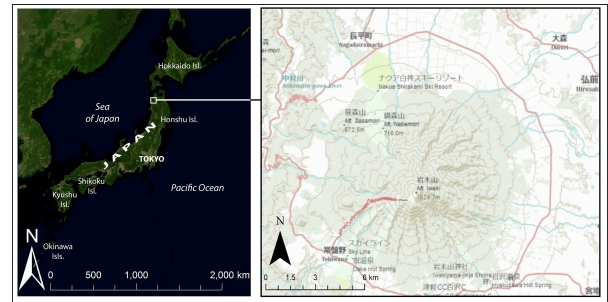
To reach this aim, the present study is set at the Mount Iwaki Volcano in the province of Aomori, Northern Honshu Island (Japan). Mount Iwaki is an andesitic stratovolcano that is 1650 m high and displays a large 2 km wide crater at its summit. Its topography is regular and has a typical conic shape, which earned it the name “Tsugaru Fuji” because of its resemblance with Fuji Volcano (Fig. 1).

The volcano rises from Miocene formation from the West to the South. Towards the East the formations are Pleistocene with some alluvial Holocene deposits. According to Kawano et al. (1961), the volcano has seen at least 3 eruptive phases until the Late Pleistocene. The first phase created large amount of volcanic breccia, which was followed by a second phase dominated by lava flow and then a third phase characterized by explosions.

The Volcano has seen its last eruption in March 1863 and at least 12 small to moderate phreatic explosions since the Edo period according to the Japanese database of active volcanoes (Geological Survey of Japan - AIST, 2012), for at least six are certain since 1597 (Kawano et al., 1961). This later explosive activity was accompanied by lahars that are oriented towards the North and with a lower extend to the South and the East. The one to the North, which almost extends to the city of Tokoshinai, has been named the “Oodaino Debris-flow deposits”, whereas the smaller one to the East named the “Tozurasawa Debris-flow deposits” (Mizuno, 1961).

This topographic structure was chosen

because of the wide range of application of SfM on active volcanoes due to their often rapid evolution during historical time and because Japan has a comprehensive of historical aerial photographs.



*Fig. 1 Location of Iwaki volcano in Northern part of Honshu Island, Japan. The topographic map of the volcano reveals the typical conic shape of the stratovolcano, which earned the volcano the nickname of Tsugaru-Fuji because of its resemblance with the most famous of Japanese volcanoes, Mount Fuji.*

## Methodology

This study differs from the one by James and Robson (2012) as it considers photographs that have been already taken, not for the sake of SfM-MVS analysis and that have a low-resolution. Therefore, to conduct this research, 87 free low-resolution (200 dpi) aerial photographs from the GSJ (Geographical Survey of Japan) have been used. All aerial photographs were taken following linear pathways, which best fit the usage of SfM for the reconstruction of objects linked to a plane, such as topographic data – in opposition to random object for which the reconstruction of both frontal and back faces are needed.

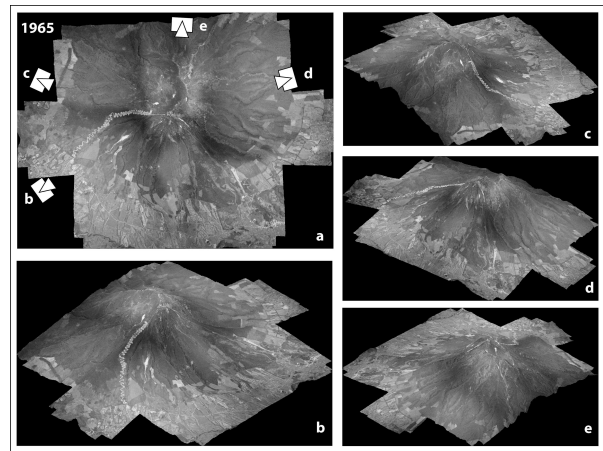
The different aerial photograph series, divided by year, were fed into the software Photoscan-Pro(r) (developed by Agisoft), in which they were first pre-processed through a mask procedure in order to exclude all non-relevant part of the photographs for the SfM and MVS (Multiple-view stereophotogrammetry) processing. Any sky-cloud or smoke and their associated shadows were also masked in order to avoid the creation of unnecessary artifacts over the topography. Then, simultaneously the photographs were aligned in 3D and a point

cloud was created using SfM. This first step took between 5 to 15 minutes with a 4 cores IE7 Intel-Mac. The second step was the reconstruction of the 3D mesh of the topography. This second step was done using MVS rather than data interpolation; the calculation time spanned between couples of hours to almost a day for meshes of 20,000 to 30,000 facets. Similar time frames were needed for the re-projection of the aerial photographs over the newly created topography.

Finally, in order to assess the accuracy of the method, the author has compared the topographic data obtained by SfM-MVS and using topographic map 1/25,000 of Japan. The two compared series were divided into different scales using wavelet analysis (Gomez, 2012). This technique allows the decomposition of a signal into a set of approximations, which is hierarchically organized in a combination of different scales. Wavelet analyses use a short-term duration wave as a kernel function in an integral transform. There are several types of wavelet, which are named after their inventors (e.g. Morlet wavelet, Meyer wavelet). Based on the shape of the series/function that needs to be analyzed, the appropriate mother wavelet is scaled and translated (daughter wavelet), allowing the detection of the different frequencies of a signal at different time (Torrence and Compo 1998; Schneider and Farge 2006). Wavelet is a well-fitted tool for separating spectral components of the topography (i.e. working on the different scales of a single object), because it gives both the spatial and the spectral resolution. For the present study, the author has used a 'dmey' – discrete meyer – function in matlab, the signal has been decomposed into 7 scales of wavelets (d1, d2, d3, etc.), such as the 'd7' level is the closest to the original signal, and 'd1' is only representing large features with low rates of change. This decomposition is used to determine (if any) the variations between the two datasets (topographic data-based DEM and SfM-MVS based DEM). The following section presents those results.

## Results

From the uncalibrated, non-georeferenced aerial photographs, SfM has proven to be an effective algorithm for the reconstruction of the topography of Iwaki Volcano (Fig. 1). For all the years, the algorithm of SfM-MVS of Photoscan-pro. For y.1965 (Fig. 2), it calculated 11,745 points, and 12,657 and 18,342 3D points for y.1985 and y.1994 respectively (Figure 3 and 4) for a maximum horizontal surface of 144 km<sup>2</sup>, giving an a maximum of ~127 points/ km<sup>2</sup> and a minimum of ~81 points/ km<sup>2</sup>.



*Fig. 2 Year 1965 orthophotograph (a) and draped DEM (b,c,d,e) of Iwaki Volcano from SfM and MVS reconstruction based on aerial photographs. The orientation of the views 'b' to 'e' are given in 'a' by the 4 cameras icons.*

This difference is directly due to the quality and the resolution of the photographs: the older the lesser dpi (dots per inches). The 3D mesh calculated using MVS and draped with a mosaic of orthophotographs provides topographic surfaces of 20,000 to 30,000 facets. The recreated topography has presented the conic shape with radial valleys, typical of stratovolcanoes.

The accuracy of the obtained 3D scene and DEM has been tested against a traditional DEM created from topographic maps of the Iwaki area, at the 1/25,000 scale, using 8500 control points. Although, the SfM-MVS has offered a good approximation of the topography, the results aren't perfect with a correlation coefficient R<sup>2</sup> of 0.56. In order to comprehend this poor correlation, which does

not match the results, the dataset has been decomposed using wavelet analysis, with 7 level of discrete meyer wavelets. The combination of level 6 and 7, shows a convergence between the topographic-DEM and the SfM-MVS DEM towards the higher elevation, while data at the bottom at the volcano are more scattered (Fig 5). This tendency is confirmed while looking at the ordered deviation between SfM and the data derived from the topographic map.

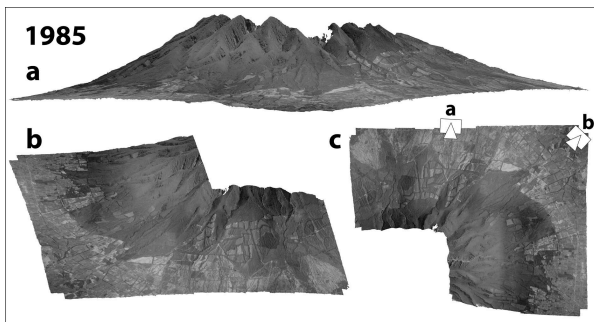


Fig. 3 Partial reconstruction of the topography of Iwaki Volcano in y.1965 with a draped DEM (a,b) and an orthophotograph (b).

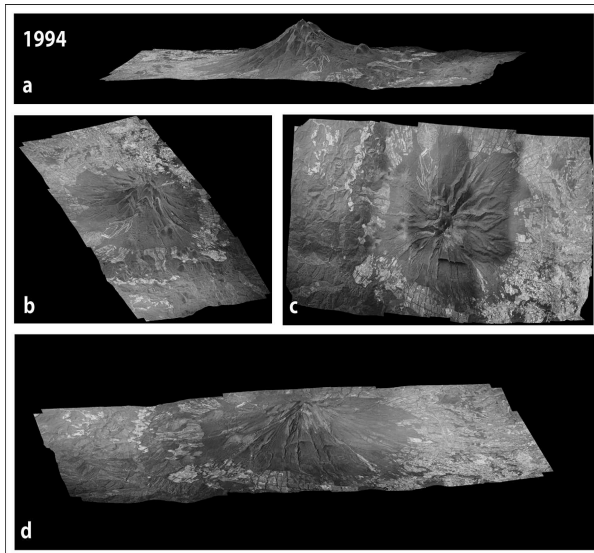


Fig. 4 Year 1994 orthophotograph (a) and draped DEM (b,c,d,e) of Iwaki Volcano from SfM and MVS reconstruction based on aerial photographs. The orientation of the views 'b' to 'e' are given in 'a' by the 4 cameras icons.

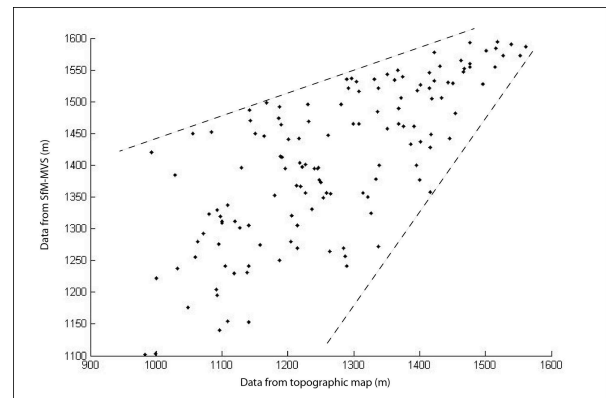


Fig. 5 Comparison between the topographic data derived from SfM and the topographic data based on 1/25,000 maps.

## Discussion

The reconstruction of topographic data from past aerial photographs with a low resolution has provided mix-results. The topographic features is being reconstructed, none of the picture has been rejected during the SfM calculation process, and the MVS procedure has successfully transformed the point cloud into a surface mesh. The scale provided by two control points seemed successful. However, the comparison between topographic data acquired from 1/25,000 topographical map and SfM derived topographic data has shown great discrepancies up to a several hundred meters difference at the base of the volcano, while to data were more accurate towards the summit of the volcano. This problem can be linked to several part of the process: (1) the quality of the images were not sufficient to reconstruct the topographical data and the convergence observed for data converging towards 1,600 m a.s.l. is only due to the numerous overlap of the aerial photographs. The points at the base, with the fewest overlap therefore provided poorer results; (2) the topographic data derived from the 1/25,000 map might be too coarse to provide a valuable comparison point. Indeed, the volcanic edifice is characterized by deeply incised valley that are often <25 m width, therefore the topographic map might not account for those data, explaining some of the very large variations. James and Robson (2012), for their study of the Piton de la Fournaise Volcano at the Reunion Islands did not meet such difficulties, although the data acquired were



not old aerial photographs but photographs taken from a micro-light aircraft with at least 24 control points location (from Figure 2 on the 6th page).

The other difference with the present study is the software package that was used: James and Robson have used a combination between the SfM application 'Bundler' with the MVS dense matcher 'PMVS2'. In order to determine if the software used in this publication is at fault, the author has conducted an experimental test at a different scale, similar to the one James and Robson (2012) have used on a hand-sample-scale volcanic bomb. This approach offers a SfM-MVS analysis at the decimeter scale, using a sample from the Waimakariri River, near Cass basin in New Zealand (Fig. 6-a). The sample was photographed 40 times on a rotary base using a Canon EOS-Kiss digital with a 50 mm focal, and the object was located 70 cm from the camera. For comparison sake, this setting resemble the setting of James and Robson (2012). Using only one measurement obtained with a caliper to scale the 3D reconstruction of the sample, the SfM-MVS gave a very accurate reconstruction of the 3D as the comparison of 20 measurements against 20 calculation using the same points gave a  $R^2$  or 0.9985. Hence, this time, the results were conclusive and the data obtained by SfM compared very well with the data obtained in the laboratory both using the caliper and immersing the sample for measuring the volume (Fig. 6).

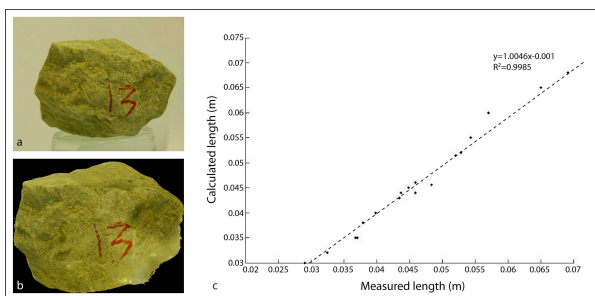


Fig. 6 Comparison at a decimeter scale for a rock sample (number 13), with a photograph of the sample (a), the reconstructed 3D image of sample 13 from a similar angle than the photograph (b), and a comparison of measurements along different axis (c). This indicates that, at a decimeter scale, using a large number of photos, the reconstruction is very accurate.

Therefore the problems encountered with the aerial photographs are certainly due to a lack of images and eventually the resolution of those ones, rather than the algorithms of the software.

## Conclusion

SfM-MVS holds great promises for the quick reconstruction of topographies and older topographic data from archives, but its accuracy is very much limited by the quality of the photographs taken. This technique is certainly going to greatly evolve for the needs of geoarcheology, archaeology, arts, but also space exploration, and vision solutions for robotic and automatic vehicles.

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