A Century of Photogrammetry on Kilimanjaro

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SUMMARY

In 1912, German explorers Eduard Oehler and glaciologist Fritz Klute surveyed Kilimanjaro armed with a photogrammetric camera. This led to a 1:50,000 scale map being produced, the quality of which should be praised given the complexity of the terrain and the technical limitations of the emerging surveying technique at the time. The mapping of Kilimanjaro at a 1:50,000 scale was not repeated for another 50 years when a photogrammetric survey was conducted from aerial images captured in 1962. The rapidly changing topography associated with the glacier retreat and the fact that the slopes of Kibo attract about 40,000 climbers each year justify the need to develop a new topographic survey of this outstanding landmark, designated a UNESCO World Heritage Site in 1987. In this context, the application of the photogrammetric principles to the latest generation of very high resolution space-borne optical sensors (VHRS) offers new surveying opportunities by enabling the topographic mapping of remote and hardly accessible areas at large scale with unprecedented spatial resolution. Recent hardware and software advances now allow dense point clouds to be generated, thus making the use of VHRS stereo imagery a viable technique to complete a large topographic survey at a small pecuniary and logistical cost. Thus, 100 years after Klute and Oehler completed the first ground based photogrammetric survey of Kibo, and 50 years after the most recent aerial photogrammetric survey, this paper illustrates the potential of a space-borne photogrammetric survey technique by reporting on the last effort to map the topography of Kibo from GeoEye-1 stereo imagery, which has led to the creation of a new 50cm resolution Digital Elevation Model (DEM), namely KILISoSDEM2012.

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1. PRELUDE TO PHOTOGRAMMETRY

While on a trip down the Danube Sir Henry Wotton (1568-1639) met Johannes Kepler (1571-1630) in Linz in 1620 (Wotton, 1672: 298-302). Kepler was a mathematics teacher in what is today the capital of Upper Austria. As Wotton was impressed by a realistic drawing of a landscape found in Kepler's study, Kepler explained how he completed the drawing himself *"non tanquam pictor, sed tanquam mathematicus"* (not as an artist but as a mathematician). In a subsequent letter to Lord Francis Bacon (1561-1626), Wotton then provided one of the earliest descriptions of Kepler's *camera obscura* (Kepler, 1604: 297), a clever design of a portable camera which allowed the natural appearance of landscapes to be reproduced faithfully and objectively (Wotton, 1672, pg. 300). In his description, Wotton stressed immediately the opportunities offered by this technique to *Chorography*, i.e., the systematic description and mapping of particular regions, and the first to perceive the potential of remote sensing techniques in the surveying sciences.

More than 200 years later, Louis Daguerre (1787-1851) perfected the invention of Nicéphore Niépce (1765-1833) who succeeded in producing the world's first permanent photograph in 1825. While defending the purchase of the patent of the photographic process by the French Government in 1839, Member of Parliament and future Director of the Paris Observatory François Arago (1786-1853) alluded specifically to the benefit of the photographic process for surveyors (Arago, 1839, pg. 48).

About 10 years later, the young surveyor Aimé Laussedat (1819-1907), a Captain in the French Army Corps of Engineers, developed the mathematical principles governing "*Métrophotographie*" (Laussedat, 1899), or the process of making measurements from photographs based on the laws of perspective. Subsequent to several successes of his new technique in mapping historical monuments, Laussedat completed the first comprehensive photogrammetric survey of a township in 1861 (Laussedat, 1899: 29-21). Shortly after, Albrecht Meydenbauer (1834-1921) independently developed a similar technique in Germany that he coined "*photometrographie*".

In 1867, Meydenbauer met the geographer and explorer Otto Kersten (1839-1900) who, five years earlier, had attempted the first climb of Kibo, the highest of three peaks of Kilimanjaro. Meydenbauer presented to him the technique allowing measurements to be made from photographs as he foresaw that it could be used as a useful surveying application during expeditions (Grimm, 2007). Fascinated, Kersten proposed to rename the technique *Photogrammetry* (Albertz, 2007), thus sealing an intimate link between this science and the highest mountain of Africa and tallest freestanding mountain in the world, where a glacier named after Kersten still remains.

2. PHOTOGRAMMETRY ON KILIMANJARO

2.1 Terrestrial photogrammetry

In 1906–07, German explorers Fritz Jaeger and Eduard Oehler conducted early mapping of Kibo from photographs but could not apply the photogrammetric principles due to the lack of a suitable camera (Jaeger, 1909, pg. 194-196). Armed with a photogrammetric camera (Figure 1), Oehler returned to Kilimanjaro in 1912 with geographer and glaciologist Fritz Klute (Klute, 1920) and spent six months on the upper slopes of Kilimanjaro. This led to a 1:50,000 scale map being produced (Figure 2), the quality of which should be praised given the complexity of the terrain and the technical limitations of the emerging surveying technique at the time.

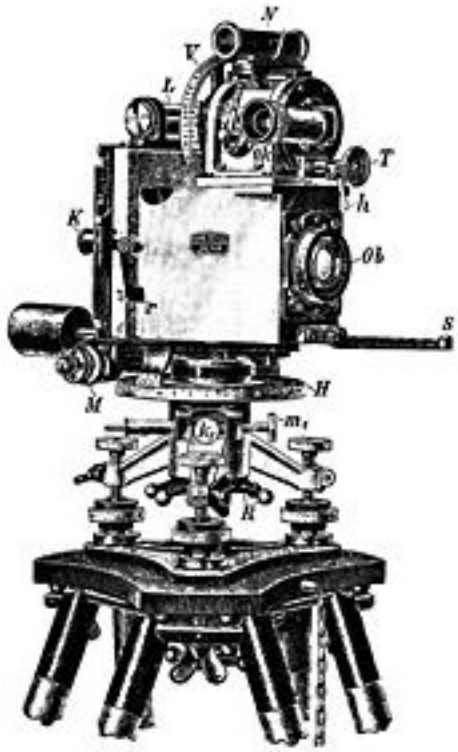

Figure 1. Field photo-theodolite, Carl Zeiss, company brochure 1908 (Schweizerisches Bundesarchiv, credit: Swiss alpine museum). Note that Klute and Oehler may have used a later model.

The map representing 50-metre contours was a vast improvement on early representations by Jeager. Although Gillman (1922) acknowledged the outstanding level of work achieved by Klute and Oehler, he regretted that only little description of the topographic work and methods was provided, thus making it almost impossible to gauge the accuracy of the map. Klute did however provide specific details in a subsequent paper (Klute, 1921). He and Oehler used a Carl Zeiss photo-theodolite, which held a photographic glass plate of 9x12cm (Figure 2). The lens was a Zeiss Ortho-Protar calibrated as having a 96.18 mm focal length,

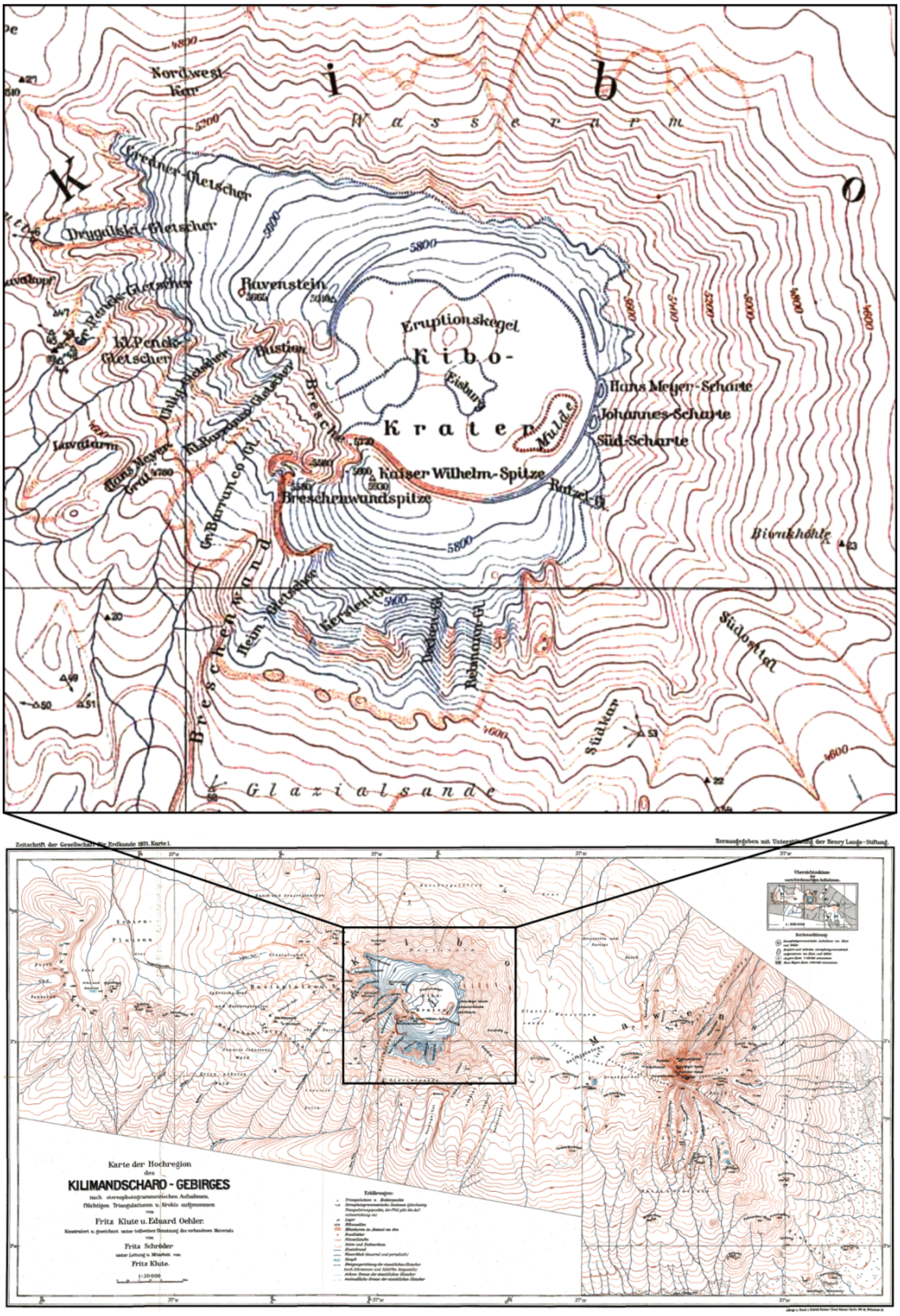

Figure 2. Reproduction of the 1:50,000 scale topographic map of Kilimanjaro derived via ground-based photogrammetry by Klute and Oehler from the 1912 surveying campaign (Klute, 1920).

providing a horizontal field of view of 64°. A notable fact is that they only had a dozen photographic plates. In order to estimate elevation at photographic stations, the geographers relied on two aneroid barometers, one pressure hypsometer with several thermometers, and one psychrometer. All instruments were tested before and after the expedition. Klute (1921) eventually provided an estimated height at Uhuru Peak of 5930 m from his photogrammetric survey (Figure 1), although Gillman (1923) estimated that this figure was tarnished by the fact that the altitudes of the photogrammetric stations were determined on the basis of uncertain barometric measurements, rather than trigonometrically.

Recently, terrestrial photogrammetry has proved to be still a useful technique on Kilimanjaro, permitting the retreat patterns of ice cliffs on the plateau of Kilimanjaro to be characterized (Winkler *et al.*, 2010).

2.2 Aerial photogrammetry

The mapping of Kibo, Kilimanjaro at a scale of 1:50,000 from an aerial survey was conducted from images captured in January 1962, following a survey in March 1958 of its surroundings (Directorate of Overseas Surveys, 1964; Young & Hastenrath, 1987; Shirima, S., pers. com., September 25, 2013). Until 1958, topographic mapping was conducted by the Directorate of Overseas Surveys using aerial photographs captured by the Royal Air Force. Imagery for Kibo following independence in 1961 was captured by British company Hunting Surveys Ltd. The photogrammetric processing was completed with assistance from foreign aid programs such as the Special Commonwealth African Assistance Plan.

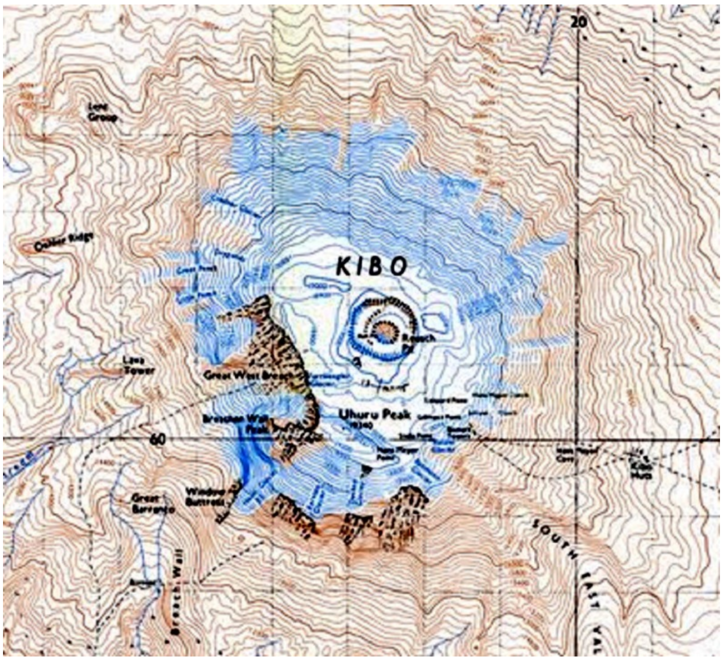

Figure 4. Subset of Kilimanjaro, East Africa (Tanganyika) Series Y742, Sheet 56/2, D.O.S. 422 1964, Edition 1, Scale 1:50,000 (Directorate of Overseas Surveys, 1964).

2.3 Space-borne technologies

2.3.1 Radargrammetry

The principles of photogrammetry have been extended to other forms of imagery, including imagery from active systems such as side looking RAdio Detection and Ranging (RADAR). Stereo imaging from Synthetic Aperture Radar (SAR) has thus been implemented successfully on-board the Space Shuttle in 2000 to yield the global and widely used Shuttle Radar Topography Mission (SRTM) DEM at 30-90m resolution (Farr *et al.,* 2007). This process is known as *radargrammetry* and has provided an updated topographic dataset for Kilimanjaro (Figure 4). Nonethless, the 90m resolution on Kibo and relatively large void areas in steep terrain, compromise the benefit of SRTM towards a new large scale mapping of the volcano. A large improvement in this technology is expected with the capabilities provided by the dual satellites mission TerraSAR-X/TanDEM-X from the German Aerospace Center (DLR), which will deliver a global DEM at about 10m spatial resolution and less than 5m relative vertical accuracy (Wessel *et al.* 2013).

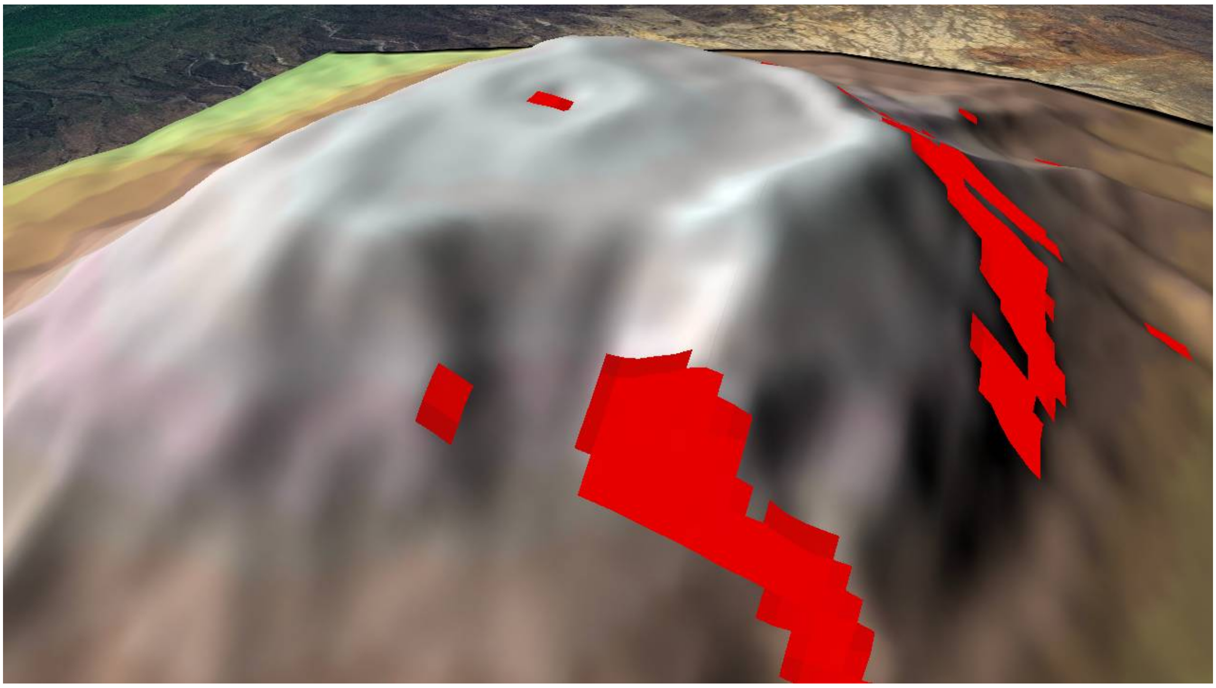

Figure 3. Subset of the Shuttle Radar Topography Mission 90m DEM (SRTM). Data voids are indicated in red.

2.3.2 Optical space-borne photogrammetry

The principles of photogrammetry have long been applied to optical satellite sensors in order to enable 3D mapping from space. For instance, sensors such as ASTER (1999-) or ALOS (2006-2011) have been specifically designed with multi-angle telescopes, allowing scenes of the earth surface to be imaged in 3D (Toutin 2002). Alternatively, platforms such as those from the SPOT program have relied on steerable vision to capture stereo images based on successive overpasses. Although no topographic mapping of Kilimanjaro seems to have been completed specifically with this technology until the work presented in this paper, the global coverage of ASTER GDEM deserves to be mentionned (Meyer *et al.*, 2011).

The photogrammetric processing of numerous stereo images enabled by the backward and nadir telescopes of ASTER supported the creation of a global DEM, namely DGEM V2. Although the nominal spatial resolution of ASTER band 3 is 15m, GDEM V2 was subsequently filtered, smoothed, and resampled to a 30m resolution. The GDEM V2 quality was assessed to have a Linear Error of 90% (LE90) of 14.5m although larger errors have affected Africa, yielding a LE90 approaching 20m. A closer inspection of GDEM V2 close to Kibo revealed numerous interpolation artefacts as well as remaining spurious elevations (Figure 4).

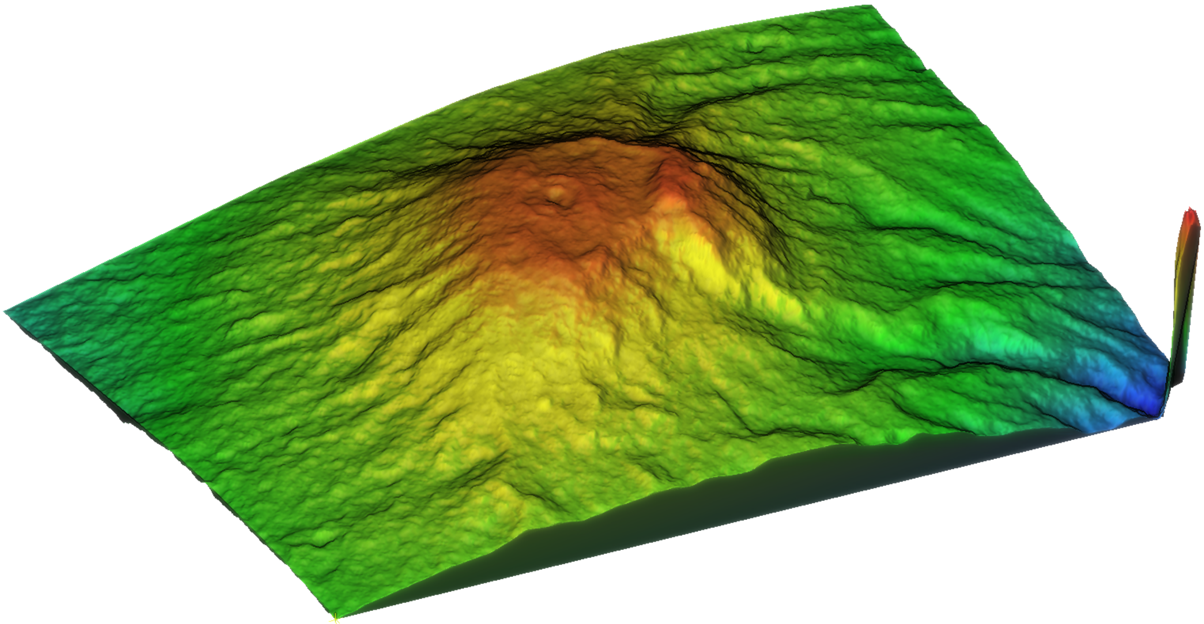

Figure 4. Subset of GDEM V2 on Kibo. Note the “granular” texture of the surface due to the interpolation, as well as the spurious elevation in the Lower Breach Wall area (high peak in the lower right), probably due to clouds in some ASTER stereo pairs.

Despite these products, the massive volcano has not benefited from an updated large scale survey in 50 years. The rapidly changing topography associated with the glacier retreat and the fact that the slopes of Kibo attract about 40,000 climbers each year (Windsor & Rodway, 2009) certainly justified the need to develop a new topographic survey of this outstanding landmark, designated a UNESCO World Heritage Site in 1987.

In this context, the application of the photogrammetric principles to the latest generation of very high resolution space-borne optical sensors (VHRS) offers new surveying opportunities by enabling the topographic mapping of remote and hardly accessible areas at large scale with unprecedented spatial resolution. Recent hardware and software advances now allow dense point clouds to be generated, thus making the use of VHRS stereo imagery a viable technique to complete a large topographic survey at a small pecuniary and logistical cost. Exactly 100 years after Klute and Oehler completed the first ground based photogrammetric survey of Kibo, this task was completed on the basis of GeoEye-1 imagery to produce KILISoSDEM2012 (Sirguey & Cullen, 2014) for which a brief description is given below.

3. KILISoSDEM2012

3.1 Satellite imagery

The GeoEye-1 sensor belongs to the latest generation of very high spatial resolution optical sensors on the civil market. It was launched on 6 September 2008 by GeoEye Inc (now merged with Digital Globe) and supports the capture of imagery at 1.65m in four multispectral bands (MSI, visible and near infrared) and 0.41 m in the panchromatic band (PAN) although data are sold at 2m and 50cm resolution due to US government regulation.

Five stereo images were acquired between September 2012 and January 2013 over an area of about 100km^2 centred on Reusch Crater and provided almost a cloud-free coverage of the entire area. In order to provide terrain elevation data for some areas obscured by cloud, a 15m resolution stereo image from the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) acquired on 19 August 2004 was also processed.

3.2 Ground Control Points, triangulation, and DEM generation

Twenty Ground Control Points (GCPs) were collected on Kibo over 20-26 September 2012 to support the triangulation of the satellite image stereo-pairs. A single image block was formed with the 10 panchromatic images corresponding to the five stereo-pairs. Processing the multi-date acquisition of GeoEye-1 images in a single block permitted a triangulation of all images together that enabled *multiray* photogrammetric processing. This allowed every pixel in numerous image overlaps to be processed, thus yielding redundancies that could be used to increase the accuracy of the point cloud via statistical filtering, or to increase the point density. A dense point cloud (PC) was generated with the enhanced Automatic Terrain Extraction (eATE) of LPS 2013 in a *pseudo multiray* approach yielding about 270MPts, with substantial redundancy in some areas.

Blunders were removed from the PC via thinning, statistical detection, and manual editing. The final gap-filled PC accounted for about 181MPts at typically 50cm spacing, meaning that more than 40% of the final 50cm resolution raster DEM (437Mcells) was supported by measured 3D points. Finally, the meshed PC was smoothed and interpolated to a 50cm resolution raster DEM. The new KILISoSDEM2012 is illustrated in Figure 5.

3.3 Quality

The photogrammetric block and subsequent DEM were produced initially in terms of height above the WGS84 ellipsoid. Any customized adjustments to other vertical datums can therefore be easily processed subsequently to the triangulation and Digital Surface Model production. The triangulation results are shown in Table 1. Given the relatively small number of GCPs, the accuracy was independently assessed using a leave-one-out cross validation protocol (LOOCV), whereby each GCP was used as an independent check point in turn and the block re-triangulated. The residuals associated with each GCP were collected to quantify the quality of the triangulated block. The consistency between the dependent and the independent LOOCV residuals demonstrates the robustness of the triangulation.

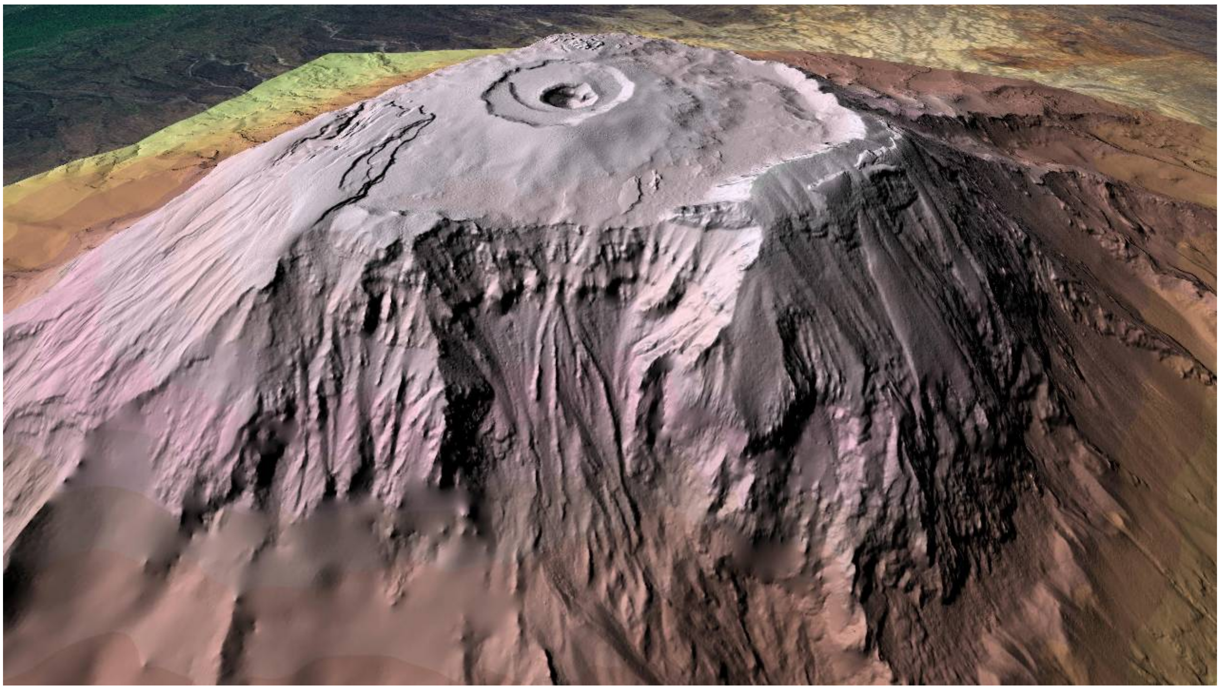

Figure 5. 3D visualisation of the colourized shaded relief of KILISoSDEM2012 DEM.

Table 1. Results of the image triangulation.

Image blocks	*Pixel size [m]*	*Image RMSE [px]*	*Residuals of the control points [m]*		
			RMS_x	RMS_y	RMS_z
GeoEye-1	0.5	0.27	0.42	0.61	1.09
		LOOCV	0.45	0.67	1.19

The propagation of Gaussian errors between the LOOCV residuals (Table 1) and the uncertainty of the GPS survey supports the accuracy specification of the final DEM product shown in Table 2. The latter exhibits a 35% and 25% improvement in planimetric (CE90) and elevation accuracy (LE90), respectively, compared to the specifications of GeoEye-1 Precision products.

Table 2. Accuracy of the final DEM product.

RMSE	*CE90*	*LE90*
0.86 m	1.31 m	2.12 m

4. CONCLUSION

Kilimanjaro holds an intimate link with the science of photogrammetry. 100 years after Klute and Oehler completed the first ground based photogrammetric survey of Kibo, and 50 years after the most recent aerial photogrammetric survey, this paper illustrates the potential of a space-borne photogrammetric survey technique. The latest effort to map the topography of Kibo used GeoEye-1 stereo imagery, which has led to the creation of a new 50cm resolution Digital Elevation Model (DEM), namely KILISoSDEM2012. Among the multiple use that can be made of this dataset, this new topography will support the characterization of the rapid demise of glaciers on Kibo (see Cullen *et al.*, 2012; Sirguey *et al.*, 2013).

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BIOGRAPHICAL NOTES

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