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# Elevation changes of Alamkouh glacier in Iran since 1955, based on remote sensing data

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ABSTRACT

To reconstruct morphometric changes in alpine glaciers, accurate and repeatable topographic surveys are required. In the present study, the elevation changes of Alamkouh glacier in Iran was evaluated by means of several multi-temporal remote sensing images with a range of high to medium nominal scales from 1955 (aerial photos), 1997 (topographic map), 2002 (Terra-ASTER) and 2010 (LiDAR). The procedures of Digital Elevation Models (DEM) extraction from aerial photos and ASTER imagery were employed by using several Ground Control Points (GCPs) which were measured by Differential Global Positioning System (DGPS) from non-glaciated areas. For assessing and correcting these DEMs to quantify Alamkouh elevation changes, first a 3-D co-registration was applied to remove the systematic shifts from the four DEMs. After the 3-D co-registration, significant biases related to elevation were found in DEMs and the existing linear relationship between the elevation differences and elevation was used to adjust the DEMs. Finally, the morphometric changes were assessed for different dates by subtracting these adjusted DEMs. The present study came across some interesting findings, including the maximum thinning rate (about $-4.5 \pm 0.32$ m/year) in high-elevated areas which fell down to about $-0.5 \pm 0.06$ m/year toward the tongue of the glacier between 1955 and 2010. The total volume loss during this period (1955–2010) is about $0.29 \pm 0.03$ km$^3$ which the highest retreat (equal to 42% of total volumetric change) occurred during 1997–2002. The estimation of cross-sectional elevation changes confirm that the maximum glacier surface lowering has taken place in the middle of the glacier, and this rate has decreased toward the sides due to the thicker debris covers and large colluvial debris sources along the steeper and more unstable valley rocks, which could retard the melting rate.



## 1. Introduction

Since the turn of the century, some global recession has been noticed in glaciers (Barry, 2006). For example, in Himalaya, several studies indicate that the glaciers have receded in recent years and these alpine glaciers are also melting down remarkably quickly at the present juncture (Kadota et al., 2000; Fujita et al., 2001; Ren et al., 2006). Several studies have shown that during the past 25 years, these glaciers have undergone a dramatic decline. These analyses reveal a 22% loss of glacial area in the entire Alps, from 1985 through 1999, which is about seven times faster than the loss experienced in the period of 1973–1985 (Petri et al., 2010). However, these results do not imply a synchronous behavior of all glaciers around the world, because there can be local differences among glaciers and even in some cases glaciers not only experience no recession but show some advancement as well. Moreover, it should be noted that although glaciers changes could be evaluated by calculating their planimetric variations, but this two-dimensional analysis cannot give comprehensive information about the severity of glacier changes. On the other hand, analyzing the morphometric changes of glacier is the most important parameters to monitor as it is a key to glacier volume and glacier mass balance studies. Besides detecting the effect of climate change on glaciers, linking between surface elevation change, volume change and mass balance change (which is the critical challenge in glaciology) is another application of Digital Elevation Models and elevation changes analysis in glaciology (e.g. Abdalati et al., 2002; Arnold et al., 2006; Bamber et al., 2004). Also hazards assessments due to rapid changes of high mountains glaciers can be performed

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with continuous monitoring based on regular morphometric observations (Kääb et al., 2005).

The topography of glaciers can be mapped using various data types such as terrestrial photography, aerial photography, digital camera data, airborne radar data, satellite radar data, ultra-high-resolution satellite imagery and laser scanner data. Generally, surface elevation data and monitoring surface change (particularly of glaciers) are collected based on two different techniques: RADAR[1] based methods and Optical/LiDAR based techniques. In Radar based techniques DEM[2] could be retrieved from SAR[3] images with slightly different viewing angles through interferometric processing. The SRTM[4] is the most typical of Radar based data which flown in February 2000 and provided continues elevation data using interferometric SAR (InSAR[5]) techniques (Farr et al., 2007). During the SRTM project, this technique was used to map most of the continental surfaces between 56°S and 60°N (Rabus et al., 2003). SRTM data have been used frequently to monitoring glaciers elevation changes. For example SRTM was used with ASTER[6]-DEM data to calculate the New Zealand Southern Alps glaciers during 2000–2006 (Nuth and Kääb, 2011). Based on this research, Fox and Franz Josef glacier experience slight thinning (1–2 m/year) at the highest elevations and thickening (5–10 m/year) at the glacier fronts (Table 1). SRTM data also is evaluated through comparison with SPOT-HRS and ICESat data for monitoring of glacier elevation changes in North-West Canada and South-East Alaska (Berthier and Toutin, 2008). Based on this analysis a maximum surface lowering of −42 m (about −10.5 m/year) was observed during the 2000–2004. In addition, thinning rates up to −10 m/year are observed at low altitude and confirm the ongoing wastage of glaciers in South-East Alaska.

The laser altimeter, or LiDAR[7] or airborne laser swath mapping (ALSM), is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target. The range of an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. The ICESat[8] mission from 2003 to 2009 created one of the most typical nearly global dataset using space-borne LiDAR technique (Zwally et al., 2002). Although present data are spatially limited to profiles of points rather than continues DEM, and arctic coverage is denser than at mid and low latitudes (due to the polar orbiting strategy of the satellite) but it has been used frequently to evaluate alpine glaciers in mid-latitudes recently. Moholdt et al. (2010) tested three methods for estimating 2003–2008 elevation changes of Svalbard glaciers from multi-temporal ICESat laser altimetry. The geodetic mass balance of Svalbard's glaciers based on ICESat data is estimated to be −4.3 m/year during 2003–2008 (Table 1).

DEMs can also be derived by optical sensors (e.g. SPOT[9]5-HRS[10], ALOS[11]-PRISM, ASTER, etc.), from acquired pairs of cross/along-track (from two different orbits) stereoscopic images (Berthier et al., 2004). However, some factors apply restrictions on the use of such stereoscopic images in studying glaciers; two such factors, inter alia, are (A) radiometric variation between the multi-date cross-track images (Toutin, 2004; Toutin and Cheng, 2002) and (B) frequent cloud cover over mountainous areas and Polar Regions. Present approach has been used frequently for reconstructing the volumetric changes of land surfaces caused by a variety of geomorphic processes, including permafrost creep (Kääb and Vollmer, 2000; Kääb, 2002; Wangensteen et al., 2006), dune migration (Brown and Arbogast, 1999), gully incision (De Rose et al., 1998; Betts et al., 2003), mass movements (Kerle, 2002; Mora et al., 2003; Hapke, 2005), volcanic deformations (Baldi et al., 2002), and glacier recession (Cox and March, 2004; Kääb et al., 2005; Rivera et al., 2005; Bolch et al., 2008; Berthier et al., 2006a; Schiefer et al., 2007).

Table 1 shows the results of some researches which performed to illustrate glacier elevation changes by using various types of remote sensing data. Schiefer et al. (2007) used historical aerial photos and photogrammetric procedures to describe terrain surface changes associated with glacier recession, moraine gully erosion and forest growth in the glacial forefield. Based on these analyses he found that during 1947–1997 the surface of Lillooet glacier (Canada) has decreased about −0.4 m/year.

Other interesting researches are the Rivera et al. (2007) and Willis et al. (2011) which have been carried out by using aerial photo-ASTER and SRTM-ASTER data respectively on Northern Patagonian glaciers complementary. Based on these results the average rate of ice lowering between the years of 1997–2001 was about −1.78 m/year. However this thinning rate has been decreased to about −0.48 m/year during the 2001–2011. Indeed, these results indicate that the rate of ice lowering during the years of 1997–2001 is 3.7 times faster than the period of 2001–2011.

The present study addresses the elevation changes of Alamkouh glacier in Iran, by combining LiDAR and Optical remote sensing data during last five decades. Therefore, we estimated the elevation changes of this glacier by using the 1955s aerial photos, 1997s topographic map, 2002s ASTER imagery and 2010s LiDAR data, to ascertain whether any elevation changes have been occurred during this period. One of the most important reasons for evaluating the volumetric changes of this case study, in comparison to its planimetric changes, is that the highly retreated small alpine glaciers such as Alamkouh is covered by the debris on the surface of the glacier (the supraglacial debris covers) and the ones on its surrounding areas (the adjacent terrain periglacial debris covers) which introduce high uncertainties in mapping the actual glacier area, and thus challenge the possibility of monitoring its planimetric changes over time.

The research will be illustrated in the following steps, first the area under study is introduced, and second the procedure of generating DEMs from aerial photos, ASTER and LiDAR data is addressed. Then, the accuracy of DEMs in non-glacial areas is evaluated against LiDAR data, and for adjustment purposes the 3D co-registration and elevation-dependent errors are taken into account. In the end, the results are reported and a discussion is provided on Alamkouh elevation changes.

## 2. The area under study

The present study has concentrated on Alamkouh glacier, which is located at the western part of the Alborz mountain range in the north of Iran, in a region called Takht-e Suleyman massif (Fig. 1). Alamkouh (Mount Alam) is the second highest peak in Iran at 4835 m above sea level. The region extends from 36.34°N to 36.40°N latitude and from 50.90°E to 51.0°E longitude. The glaciers of this massif consist of several peaks over 3000 m in elevation, connected by some high and narrow summit ridges. These glaciers are found mostly on the steep and northward-facing slopes. Bobek (1957) estimated the snow line of this glacier to be about 4000 m.

[1] Radio Detection And Ranging.
[2] Digital Elevation Model.
[3] Synthetic Aperture Radar.
[4] Shuttle Radar Topography Mission.
[5] Interferometric SAR.
[6] Advanced Spaceborne Thermal Emission and Reflection Radiometer.
[7] Light Detection and Ranging.
[8] Ice, Cloud and land Elevation Satellite.
[9] Satellite Pourl' Observation de la Terre.
[10] High Resolution Stereoscopic.
[11] Advanced Land Observing Satellite.