GLACIERS CHANGE MONITORING USING OPTICAL SATELLITE IMAGERY: THE CASE OF FORNI GLACIER

Lorenza Ranaldi

Advisor: Mattia Crespi *(Geodesy and Geomatics Division, DICEA, Sapienza University of Rome, Rome, Italy; Sapienza School for Advanced Studies, Sapienza University of Rome, Rome, Italy)*
Co-advisor: Valeria Belloni *(Geodesy and Geomatics Division, DICEA, Sapienza University of Rome, Rome, Italy;)*

Sapienza University of Rome – Faculty of Civil and Industrial Engineering
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1) Introduction

The monitoring of glaciers is important to mitigate the loss of water, a fundamental resource of the Earth's ecosystem, which is indispensable not only for civil use, but also in agriculture and industry, and whose availability is now threatened due to the consequences of climate change. To deal with this issue, various techniques for analysing and studying glacial systems have been developed over time. Geodetic and remote sensing approaches have proved to be promising and reliable techniques for the study of glacier evolution, since, among the various data acquisition methodologies made available by this field, they allow to generate three-dimensional models of the Earth's surface (Digital Surface Models - DSMs). In the specific case of glaciers, when DSMs representing glacial surfaces related to different years are considered, it is possible to perform different analyses between the various models, associated with the different time periods, to assess the morphological variation of the glacier over the considered years. In general, satellite and Unmanned Aerial Vehicle (UAV) data are particularly suitable for the generation of DSMs [4], as it is possible to collect information, and thus develop subsequent analyses, reducing the need of being on the survey site, which in the case of glaciers is often difficult to access. Furthermore, optical satellite data have an important advantage over UAV data, related to the possibility of acquiring information on a large scale. Although less accurate and resolute than UAV acquisitions, such data are therefore useful to understand how the entire glacial apparatus has changed over time. In this sense, the aim of this thesis was to investigate the potential of optical satellite data for the generation of DSMs for glacier monitoring, with a focus on Forni Glacier, located in northern Italy, in the Stelvio National Park. This glacier is considered to be one of the most important in Italy, with an extension of 10.83 km2 (2012) and an altimetric variation between 2600 and 3670 metres [3]. In addition, the site is frequently visited both in summer and winter by many tourists, thus implying the need for constant monitoring to control the melting phenomenon, which has been accelerating in recent years, and the phenomena of falling of unstable ice blocks, which could cause a risk to tourists but also to the balance of the entire glacial apparatus [2].

2) Data and methods

To carry out the analyses, optical satellite stereo-images of the Forni Glacier, acquired by the Ikonos-2 satellite for the year 2009, and Pléiades-HR for the years 2013 and 2016, were selected. To generate the digital models from the optical satellite images, the photogrammetric method was implemented, which allows for the transformation of the two-dimensional data, relative to the image acquired by the satellite sensor, into a georeferenced three-dimensional data identified by the digital model, which will be representative of the investigated territory. In the case under examination, it was initially decided to investigate with the use of two different software packages, Agisoft Metashape and Catalyst, to identify the best one. A comparison carried out at the end of the analyses showed that the most accurate digital model was obtained using Agisoft Metashape (Figure 1), which was therefore chosen as the reference software for processing the data. Moreover, thanks to a collaboration between the area of Geodesy and Geomatics of Sapienza University of Roma and the Department of Environmental Sciences and Policies of the University of

Milan, DSMs generated by the UAV data collected during summer campaigns between 2014 and 2021 were used to perform a comparison with DSMs derived from optical satellite data.

Before analysing the glacier morphological variation, it was necessary to implement the fundamental process of coregistration of digital models. These are in fact generated from images that are processed with different accuracy. In this sense, the reconstruction of the digital model may be affected by errors, which produce a misalignment in space between the DSMs of the order of a few metres. Various procedures exist today that allow these biases to be eliminated, by estimating rototranslation or pure translation that remove the shift between models and thus allow digital systems to be coherent and superimposed in the same reference system. To perform this operation, it has to be considered an accurate DSM as a reference and a second DSM to be coregistered on the chosen reference. In particular, the alignment is carried out only on stable areas common to the two DSMs, therefore invariant in time, such as rocky areas for example, while excluding those subjects to morphological variations such as glaciers. A indicative example is shown in Figure 2, where the glacier mask is highlighted in red, and stable rocky areas outside it. In the present case, the coregistration algorithm developed by authors Nuth & Kabb of the University of Oslo [1] was used. Having the accurate DSMs generated by the UAV data available, it was first decided to align the 2016 optical satellite DSM, considered as the reference for satellite data, on the rocky areas on the DSM of the same year obtained by UAV. Subsequently, the optical satellite DSM of 2016, aligned with the most accurate UAV data, was used as a reference to align the optical satellite DSMs of 2009 and 2013 as well. The implementation of the coregistration was developed with Python language. As a result, it was possible to perform several assessments of melt conditions and glacier thickness changes, first by performing different analyses between the digital models and then by calculating melt trends for small portions of the glacier.

3) Results and future prospects

Firstly, the coregistration process allowed for a correct alignment between the models. In fact, for example, already in the first phase, shifts of about 5 metres between the satellite data and the drone data in the year 2016 were already evident, despite the fact that the two models were based on images acquired two months apart. This could have led to subsequent erroneous assessments of the glacier's morphological variation conditions, influenced precisely by such errors on the order of several metres. Instead, thanks to the coregistration algorithm, such biases were eliminated, and by applying this procedure for all models considered, it was possible to obtain the optimal condition whereby all models were placed in the same reference system with average accuracy of the order of a metre.

Subsequently, the focus was on the analysis of morphological variation. First, once the DSMs were correctly aligned with each other, it was possible to proceed with the differentiation operations between them to obtain the height variation. For example, over the period 2009-2016, thickness loss values of the order of 40 metres were recorded on the critical zone of the Forni’s tongue (Figure 2). This result is in line with the data identified by previous studies with UAV data, in which an average annual loss value of 5 m was estimated [2]; this result also underlines the consistency of analysis with the two different techniques taken into consideration. For areas located at higher altitudes, above the glacier tongue, loss values of 20-25 metres were recorded between 2600 and 2800 m.a.s.l., and about 10 metres above 3000 m.a.s.l., again in the seven reference years. These evaluations were then repeated for a shorter period of time, between 2013 and 2016, considering the areas of analysis mentioned above, once again attesting a trend of 5 m/year in the area of the Forni’s Tongue and less consistent losses for higher altitudes. Furthermore, in order to highlight the glacier losses even better, some longitudinal and transverse sections (Figure 3) were extracted from the various available optical satellite DSMs. These clearly highlighted on one hand the phenomenon of the reduction in thickness of the ice areas, where the sections presented different values, on the other hand the alignment of the rock areas due to the co-registration process when those are perfectly aligned. Subsequently, the melt trends characteristic of certain points of the glacial apparatus were estimated in order to evaluate, albeit locally, the way in which this phenomenon is evolving. For the areas of the Forni Tongue, both UAV and satellite data were used, making an estimate for the period 2009-2021 (Figure 4), while in the higher areas only satellite data were considered, as they are the only ones covering larger areas of the glacier, considering only the period 2009-2013. In each case, small areas with an extension of 10x10 pixels were taken as a reference, trying to extrapolate an average altitude value and repeating the step for the different years. In this way it was possible to construct a dataset containing the average elevation information for different areas and for different years. By graphically representing the data obtained, it was possible to clearly identify decreasing trends in elevation variation, which are however linear, indicating a strong consistency between the two data sources. In particular, it is possible to note how in all cases there is a change in the slope of the straight lines joining the first points, referring to the period 2009-2016, compared to the slope of the straight lines joining the points of the following period, up to 2021. This results in an acceleration of glacier melting. In fact, for example, for the case of the critical zone of the Forni's tongue, average variations of 3.3 m/year were estimated for the period 2009-2013, 3.8 m/year for the period 2009-2016 and 4.7 m/year for the period 2009-2021.

To conclude, it is possible to emphasise how the combination of these analyses has unfortunately highlighted the phenomenon of intensive melting of the Forni Glacier. This result was achieved thanks to the reliability demonstrated by the co-registration process of Nuth & Kaab and the information obtainable from optical satellite data. It can therefore be stated that, although optical satellite images present some limitations related to weather conditions, such as cloud cover, or inherent to revisit time, it is nevertheless possible to recognise their potential with reference to the study of glaciers and the possibility of deriving various information on the state of variation of these systems over time. In the future, the aim is to acquire additional optical satellite images to continue the investigation of the Forni Glacier. In addition, it will be possible to investigate other techniques to support the optical satellite data, such as SAR satellite systems, which can compensate for the optical satellite data when not available due to clouds.

Bibliography

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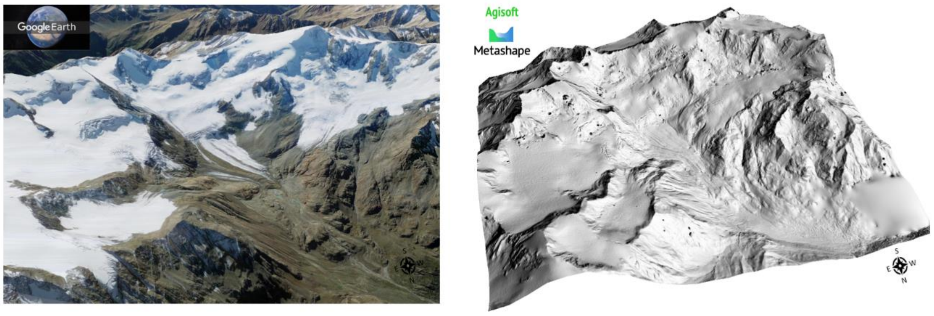
1)


Google Earth
Agisoft
Metashape
S
W
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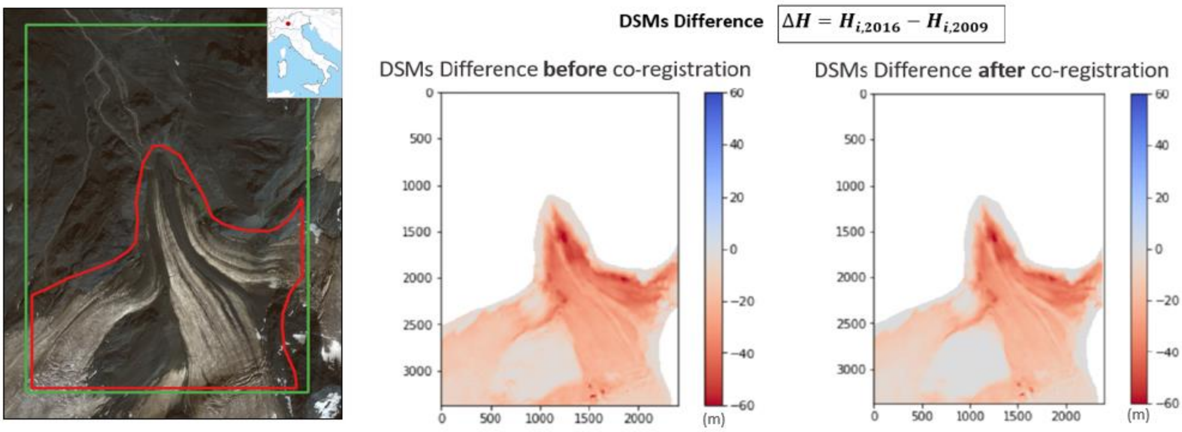
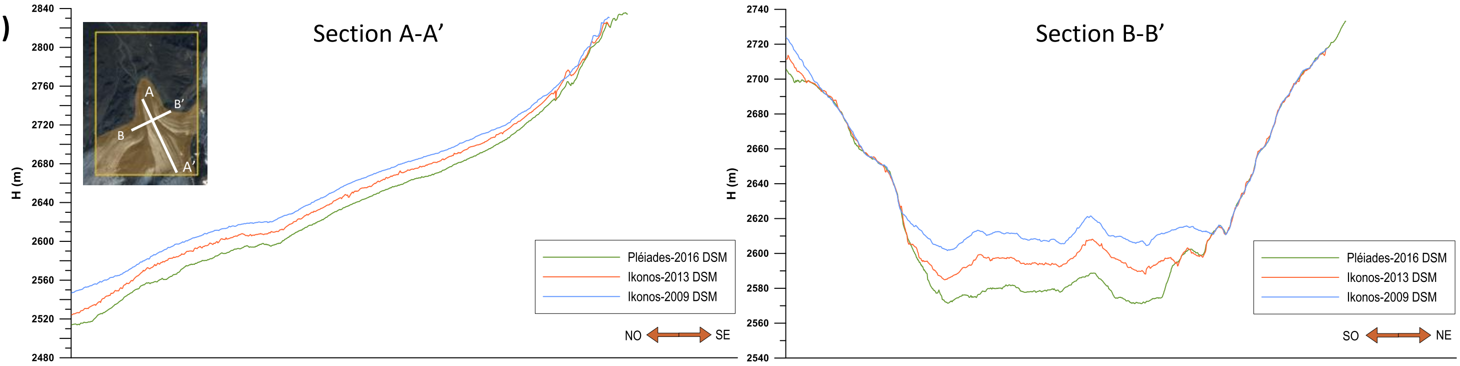
2)


DSMs Difference
$\Delta H = H_{i,2016} - H_{i,2009}$
DSMs Difference before co-registration
DSMs Difference after co-registration
0
500
1000
1500
2000
2500
3000
60
40
20
0
−20
−40
−60
(m)

3)


Section A-A'
Section B-B'
H (m)
A
A'
B
B'
Pléiades-2016 DSM
Ikonos-2013 DSM
Ikonos-2009 DSM
NO
SE
SO
NE
2480
2520
2560
2600
2640
2680
2720
2760
2800
2840
2540
2560
2580
2600
2620
2640
2660
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2700
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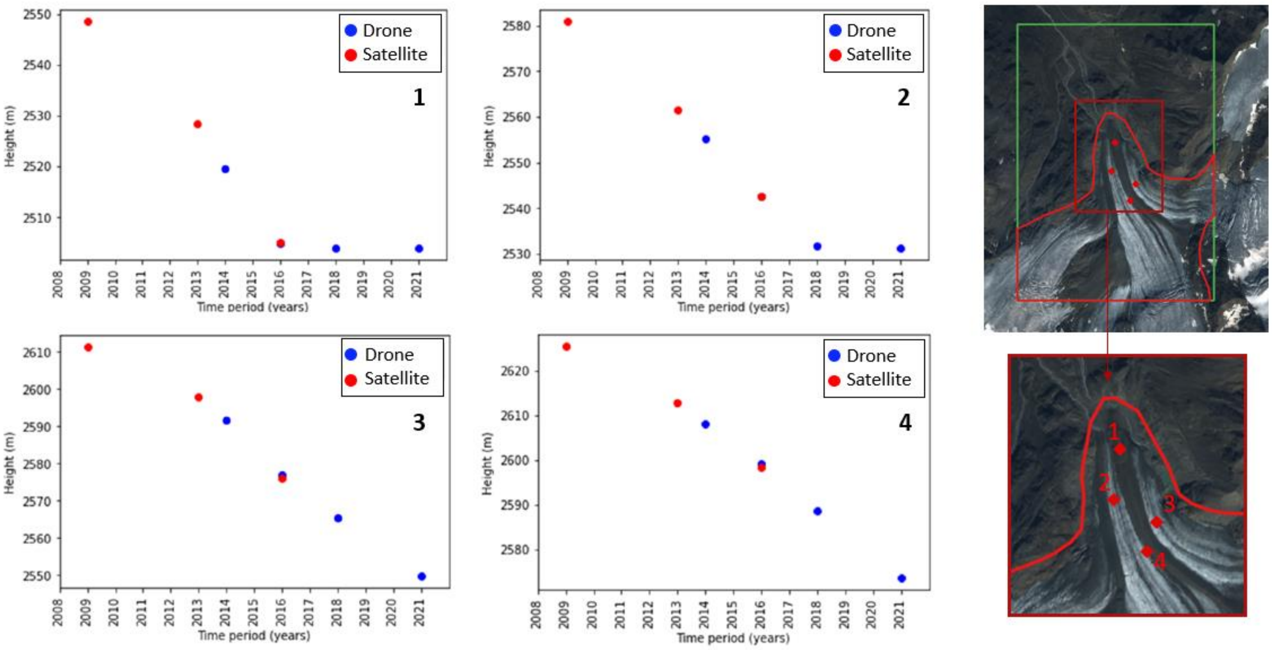
2740

4)


Drone
Satellite
1
2
3
4
Height (m)
Time period (years)
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021