Multi-temporal and Multi-source Alpine Glacier Cover Classification

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***Abstract*—This work presents a multi-temporal and multi-source approach for glacier cover classification, i.e. bare soil, glacier ice, firn, and snow. The method is based on Hidden Markov Model (HMM) and Support Vector Machine (SVM) and can handle different kinds of satellite virtual constellations composed of high-resolution optical and/or SAR platforms. The proposed method is tested on a Sentinel-1 time series acquired over the Ortler Alps and the obtained classification map time series is used to extract the temporal behavior of the snowline and estimate the equilibrium line altitude (ELA) of the glaciers.**

Keywords—Glacier, Hidden Markov Model, satellite virtual constellation.

I. Introduction

Alpine glaciers play a primal role in the hydrological cycle of mountain regions and their forelands. In particular, they are responsible for the gradual release of the water flow during the advanced ablation season, when most of the snow in the catchment has already melted. Moreover, glaciers are sensitive indicators of climatic fluctuations, thus their changes in time can be referred to climate change [1].

The glacier mass balance is a key parameter for both climatological analysis and hydrological applications. It is defined as the sum of all processes which add mass to a glacier (e.g. snowfall) or remove mass from it (e.g. snow or ice melting) over one hydrological year. Remote sensing can provide relevant information about the mass balance of a glacier. One of these is the detection of the glacier cover types, from which glacier extension and snowline altitude (SLA) can be derived. The snowline is defined as the line that separates the part of the glacier covered by snow to the part of the glacier where ice or firn, i.e. snow older than one year, are present. At the end of the ablation period, the late summer snowline can be used to estimate the equilibrium line altitude (ELA), which is the line that separates the accumulation from the ablation areas and corresponds to the theoretical line where the net mass balance equals zero within a particular year [2]. Given its high correlation with the annual mass balance, the ELA is an important proxy variable for glacier mass balance estimation.

The most common approach for glacier cover mapping is based on the exploitation of the spectral information of high-resolution optical data, such as Landsat (e.g. [3]) or Sentinel-2 images [4]. Multi-temporal information is instead often neglected, probably due to the low availability of cloud-free high-resolution optical images within one ablation season (typically from June to September). However, with the launch of Senitnel-2a and with the future launch of Sentinel-2b and other upcoming optical satellite missions, an increasing number of high-resolution optical data will be available. Over certain glacierized areas of the European Alps it will be possible to have more than one high-resolution image every 3 days if Landsat-8, Sentinel-2a and Sentinel-2b are combined (Fig. 1). Moreover, by exploiting the capability of discriminating glacier facies from SAR data [5], such as the one provided by Sentinel-1, an higher temporal resolution could be achieved by combining SAR and the optical high-resolution acquisitions. This rich multi-temporal information can be explicitly exploited in order to improve the glacier classification performances.

In this work we propose an approach for glacier cover classification (i.e. bare soil, glacier ice, firn, and snow) able to exploit multi-temporal information delivered by any kind of virtual satellite constellation (i.e. optical and SAR virtual constellations, or SAR/optical virtual constellation). The method is based on Hidden Markov Model (HMM) [6] where the emission class probabilities for each acquisition are extracted

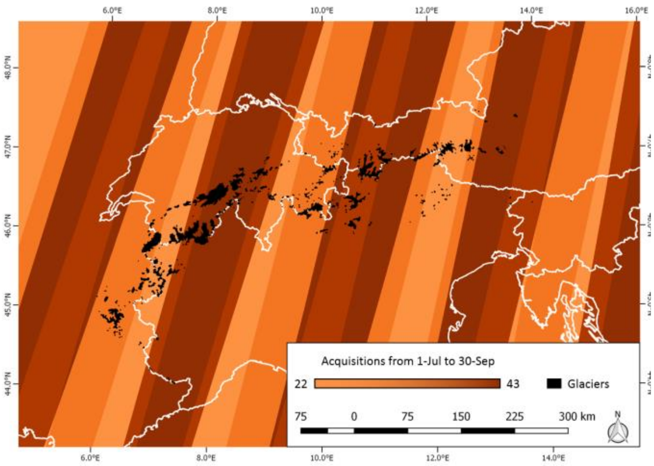


Fig. 1. Number of high-resolution optical acquisitions during one ablation season, i.e. from July 1st to September 30th, obtained by combining Landsat-8 with Sentinel-2a and Sentinel-2b. White lines show the states border and black spots indicate the alpine glacier areas as extracted from the Randolph Glacier Inventory (www.glims.org).

from the data provided by each sensor of the virtual constellation and the multi-temporal information is modeled based on a set of impossible class transitions.

II. Proposed Method For Glacier Cover Classification

Given a set of N states, i.e. the target classes, and a sequence of T observations, corresponding to the satellite images acquired during one ablation season by any of the sensors of the virtual constellation, the HMM is defined by the following components:

- An $N \times T$ emission probability matrix

  $$\boldsymbol{B} = \begin{bmatrix} b_{11} & \cdots & b_{1T} \\ \vdots & \ddots & \vdots \\ b_{N1} & \cdots & b_{NT} \end{bmatrix},$$

  where each element $b_{ij} = P(\boldsymbol{o}_i | s_i = q_j)$ expresses the probability of an observation $\boldsymbol{o}_i$ being generated from a state q_j;

- an $N \times N$ transition probability matrix

  $$\boldsymbol{A} = \begin{bmatrix} a_{11} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{N1} & \cdots & a_{NN} \end{bmatrix},$$

  where each $a_{ij} = P(s_t = q_j | s_{t-1} = q_i)$ represents the probability of moving from state q_i to state q_j

- an initial probability distribution over states $\boldsymbol{\pi} = \pi_1, \pi_2, \dots, \pi_N$

The most probable sequence of states $\boldsymbol{S} = s_1, s_2, \dots, s_T$ with $s_t \in Q \; \forall \, t \in \{1, \dots, T\}$ that generates the sequence of observations $\boldsymbol{O} = \boldsymbol{o}_1, \boldsymbol{o}_2, \dots, \boldsymbol{o}_T$ is found by solving the following maximization problem:

$$\boldsymbol{S} = arg\max_{\boldsymbol{S}}\{P(\boldsymbol{O}|\boldsymbol{S})\}$$

Through the Bayes theorem, each emission probability can be expressed in terms of posterior probability, which is, in general, easier to be estimated:

$$P(\boldsymbol{o}_i | q_j) = \frac{P(q_j | \boldsymbol{o}_i) P(\boldsymbol{o}_i)}{P(q_j)}$$

We propose here to estimate the posterior probability through Platt scaling on Support Vector Machine [7], by implementing a supervised classification for each kind of data acquired by satellite virtual constellation (i.e., SAR and multi-spectral).

The transition probability matrix $\boldsymbol{A}$ is the parameter that enable to exploit the multi-temporal information. For the glacier classification problem, we identified a set of impossible transitions, which cannot occur within one ablation period. These are: bare soil to glacier ice, bare soil to firn, and glacier ice to firn.

All the terms of $\boldsymbol{A}$ corresponding to impossible transitions are set to zero. All the others are computed as to set these as equiprobable. We also set the initial probability vector $\boldsymbol{\pi}$ in order to get equal initial probabilities among the target classes.

III. Results

As test case, we present the results of glacier classification considering a single satellite time series of acquisitions, i.e. the C-band SAR data acquired by Sentinel-1a. The test area considered in the example includes all the glaciers of the Ortler Alps and we consider the ablation period 2015. Three Sentinel-1 acquisition tracks cover our area of interest (Fig. 2).

We first classified each single image using an SVM based on the VV and VH Sentinel-1 polarization. In this case, no multi-temporal information is employed and we detected the 25% of the pixel time-series with at least one impossible class transition. By exploiting the membership class estimation by Platt scaling on the same SVM and by solving the multi-temporal classification problem through the proposed HMM approach, all the found impossible class transitions can be modified and solved. In this way, we can improve the classification result with respect to the classification that uses the single information. Figure 3 shows this improvement by comparing the single-time SVM classification (Fig. 3a) and the proposed integrated SVM-HMM approach (Fig. 3b) and false color composite of the Sentinel-2 image acquired during the same period (Fig. 3c).

From these maps was possible to extract the temporal behavior of the snow line altitude (SLA). This temporal detailed information was used to estimate the ELA as the maximum of SLA during one ablation period. Fig. 4 shows as an example the SLA behavior of the Careser glacier, one of the most studied glacier of the Ortler Alps, extracted by a glacier classification time series generated with Sentinel-1 data through the proposed approach.

Future tests will consider both optical only, i.e. Landsat-8 and Sentinel-2, and SAR-optical virtual constellations, i.e. Sentinel-1, Landsat-8 and Sentinel-2. These different virtual constellations will then be compared in order to assess the classification improvements that can be achieved exploiting different kind of multi-temporal and multi-source time series. The best configuration will be then tested over other mountain ranges and the estimation of ELA compared with in-situ glaciological surveys.

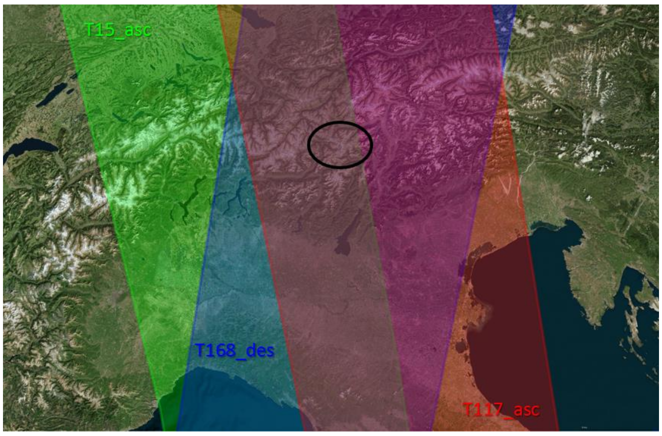
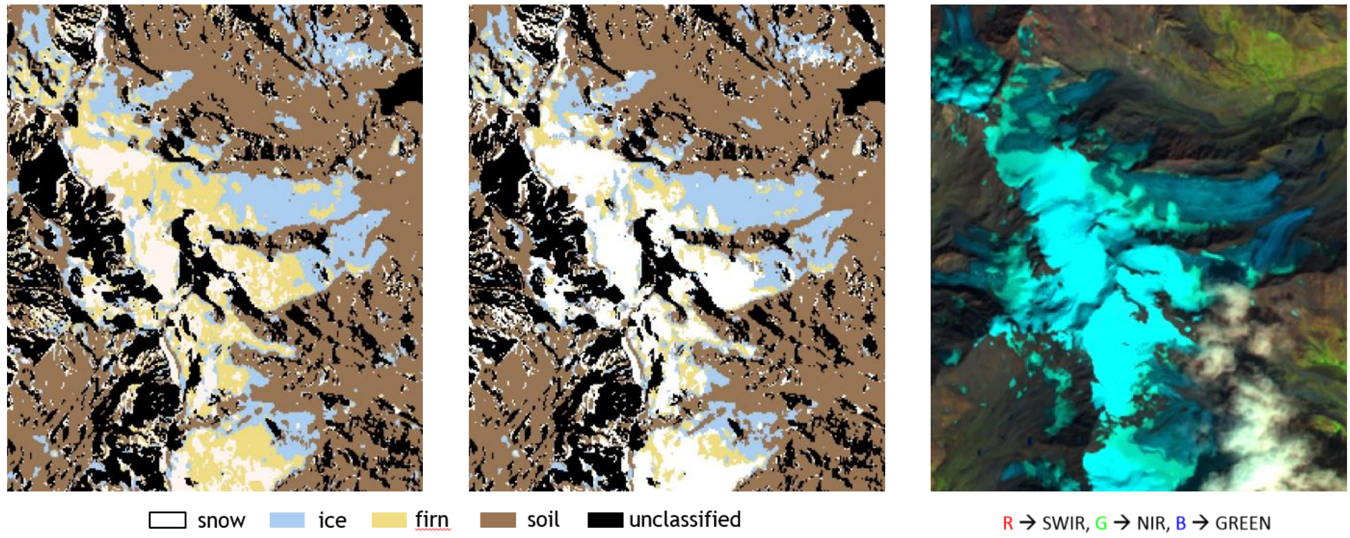


Fig. 2. Sentinel-1 acquisition tracks covering the Ortler Alps (circled in black).



a) b) c)

Fig. 3. Classification maps of the 2nd of September 2015 obtained with a SVM classification on the single Sentinel-1 image (a) and exploiting the whole Sentinel-1 time series with the proposed approach based on HMM (b). In c) the false color composite of Sentinel-2 acquired the 26th of August can be considered as reference for evaluating and comparing the classification performances.

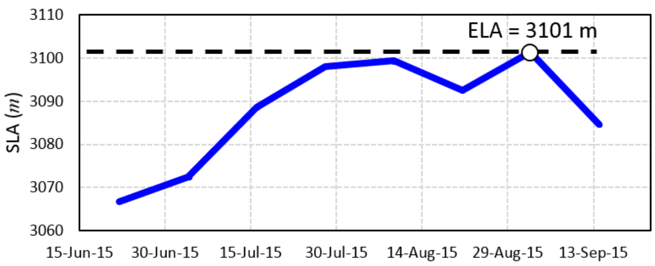


Fig. 4. SLA temporal behavior of the Careser glacier as extracted by a Sentinel-1 time series elaborated through the proposed approach.

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