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Improving terrestrial photography applications on snow cover in Svalbard with satellite remote sensing imagery (PASSES 2)

Roberto Salzano[1], Kristoffer Aalstad[2], Riccardo Cerrato[1], Bartłomiej Luks[3], Rosamaria Salvatori[4], Sebastian Westermann[2]

1 Institute of Atmospheric Pollution Research, National Research Council of Italy, Fiorentino (Firenze), Italy
2 Department of Geosciences, University of Oslo, Oslo, Norway
3 Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland
4 Institute of Polar Sciences, National Research Council of Italy, Monterotondo (Roma), Italy

Corresponding author: Roberto Salzano, roberto.salzano@cnr.it
ORCID number: 0000-0002-0750-0097

Keywords: Cryosphere, snow, fractional snow-covered area, time-lapse photography

Update of chapter 10 in SESS report 2020

DOI: https://doi.org/10.5281/zenodo.5751867

1. Introduction

The dynamics of seasonal snow is a key element of changing ecosystems in Arctic regions, and the ability to monitor it requires filling the gap that exists between in situ and satellite observations (Salzano et al. 2021b). The outcomes of PASSES (Salzano et al. 2021a) gave an overview of terrestrial photography applications on the snow cover, but future actions focused on enhancing and maintaining snow observations must include data integration and assimilation while considering different platforms and spatio-temporal resolutions. The wide availability of time-lapse cameras highlighted their significant potential as a bridging point, enabling comparison of detailed descriptions of the snow cover with large-scale assessments of the snow variability obtained by satellite platforms (Aalstad et al. 2020; Gascoin et al. 2020). Time-lapse camera networks are important data sources for calibrating and validating satellite products, but guidelines about the required resolutions are needed to support creation of a regional infrastructure in the framework of the Svalbard Integrated Arctic Earth Observing System. This contribution provides: an updated and more detailed survey about terrestrial and satellite-based applications for snow cover monitoring; a comparison between different image processing algorithms; guidelines for the selection of the most appropriate spatial and temporal resolutions for terrestrial photography; and examples of the integration of data obtained by terrestrial photography with satellite remote sensing data.

2. The state of terrestrial photography applications on the snow cover

2.1. The updated survey

There are a myriad of time-lapse cameras in Svalbard that can potentially be used for assessing the evolution of the snow cover. Knowledge about available datasets, metadata descriptions, processing chains, and product specifications are all important factors for obtaining a complete overview of terrestrial photography applications in such a remote area. This overview of cameras operating in the Svalbard archipelago has been approached by searching specifically for applications on the snow cover and by collecting information about images that can be found on the web that are not solely focused on research purposes in the cryospheric domain. Compared to the previous survey (Salzano et al. 2021b) the number of cameras identified by the survey is nearly doubled. However, this updated survey considered an additional parameter related to the research topic each camera is intended to address. Most of the new cameras (88%) are in previously identified locations where the presence of research infrastructure facilitates camera installation and maintenance, whereas 12% of the newly identified cameras are outside already surveyed locations (mainly in the eastern part of the archipelago). Regarding the survey of scientific publications, an analysis was performed in Scopus using the query string (time-lapse OR camera OR photography OR webcam) AND Svalbard to search in paper titles, abstracts, and keywords. A total of 163 articles were found from which 29 used terrestrial photography, with institutes from Norway, United Kingdom, France, Italy, Sweden, United States and Poland being the most represented (Salzano et al. 2021c).

The updated survey considers a total of 106 cameras of which 84 were installed for research purposes (79%), 12 were private cameras (11%), and 10 (10%) were multi-purpose for both private (e.g., security) and research purposes. Among the cameras installed for research purposes, the main topics were snow and/or glaciers that together represent 53% of the category; the remaining cameras were dedicated to flora and fauna monitoring, weather, permafrost, and ecology in general (Figure 1). The survey shows that 46% of the cameras are still active; the rest belong to finished projects or do not report their state of activity. Most of the cameras are active for a period that spans from a month to a season (51%), followed by cameras that operate year-round (29%) and by cameras used for a limited time (less than a month, 18%).

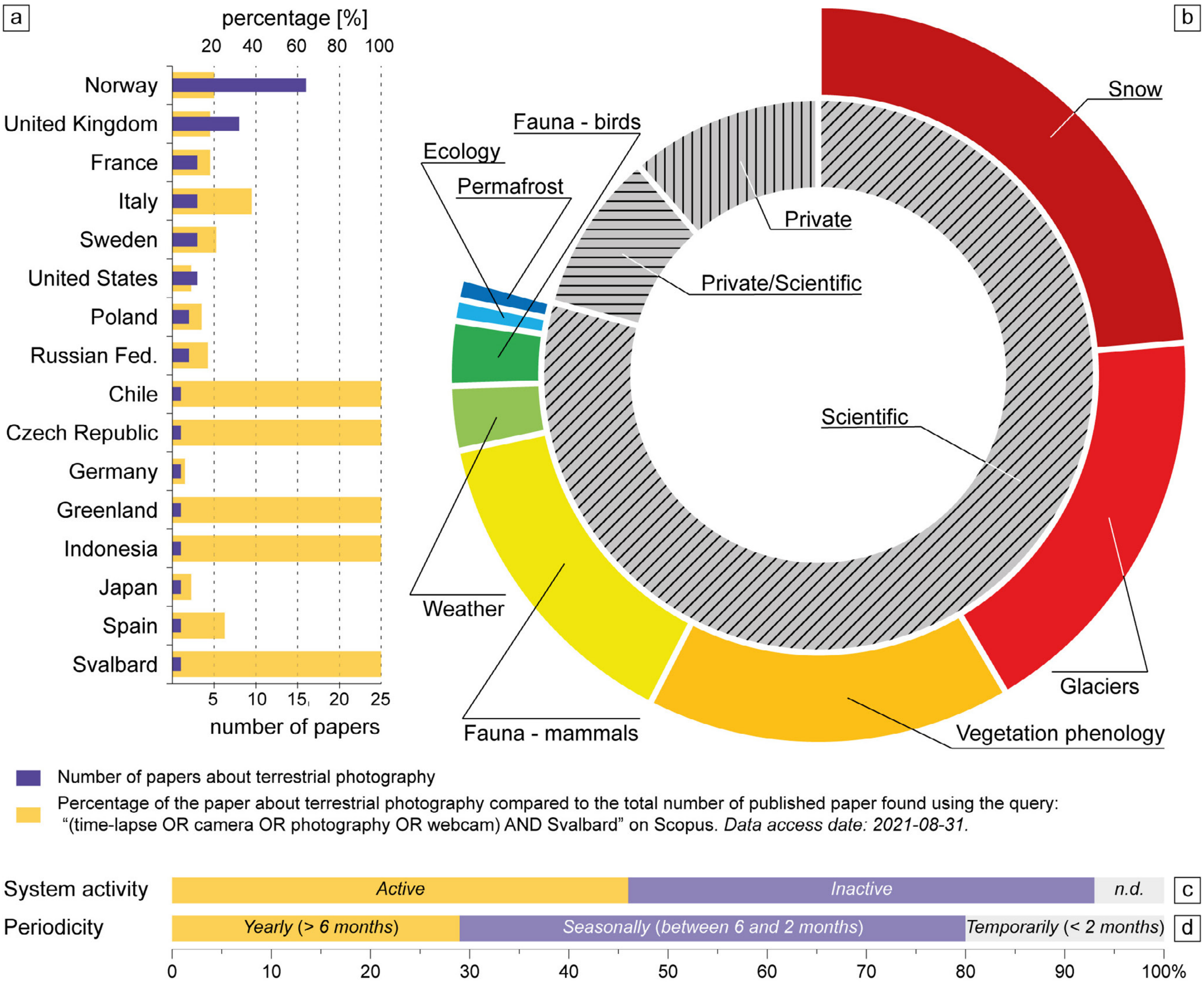

Figure 1: *(a) Number of published papers about terrestrial photography (dark bars) and percentage of these paper relative to the total number of papers published by nations on terrestrial photography applications in Svalbard (pale bars). (b) Distribution of terrestrial cameras by purpose (inner ring) and percentage of scientific topics for which a camera was installed (outer ring). State of activity of the terrestrial camera (c) and the period of the activity (d).*

2.2. Guidelines for the selection of the most appropriate spatial and temporal resolutions for terrestrial photography applications

One key recommendation of our previous SESS report (Salzano et al., 2021a) was to establish a shared protocol for terrestrial applications. Such applications support the definition of different metrics about the snow cover: the Snow-Covered Area (SCA) and the Fractional Snow-Covered Area (FSCA), also known as the Fractional Snow Cover (FSC) or Snow Cover Fraction (SCF). While SCA is a binary classification of the state of the snow cover (snow or no snow), FSCA is the areal fraction of a pixel that is covered with snow. It is challenging to estimate FSCA at the pixel level with terrestrial photography, so FSCA is usually obtained by aggregating SCA to a coarser resolution through spatial averaging. The SCA image classification algorithm considers each pixel: the SCA is strictly related to the heterogeneity within each projected surface, bearing in mind that the larger the distance from the sensor position, the larger the projected surface and, consequently, the larger the potential for mixed composition (both snow and not snow) (Figure 2). The same holds for the FSCA estimation but, in this case, the necessary aggregation of pixels motivates statistical analysis. The uncertainty in retrieving FSCA is related to the number of pixel elements included in the projected cell unit under consideration. Since the associated uncertainty could be defined as a Poisson distribution of the number of correctly classified binary pixels, it is possible to estimate the uncertainty as the square value of the number of pixels included in each cell unit. This implies that the smaller the number of projected pixels in the aggregated cell unit, the larger the related uncertainty (Figure 2). Starting from the output definition and the related uncertainty while taking into account past experience, it is possible to summarise that the major elements involved in selecting the most appropriate application are: the spatial resolution (observation geometry, sensor specifications, cell size); the time resolution; and the classification algorithm selection.

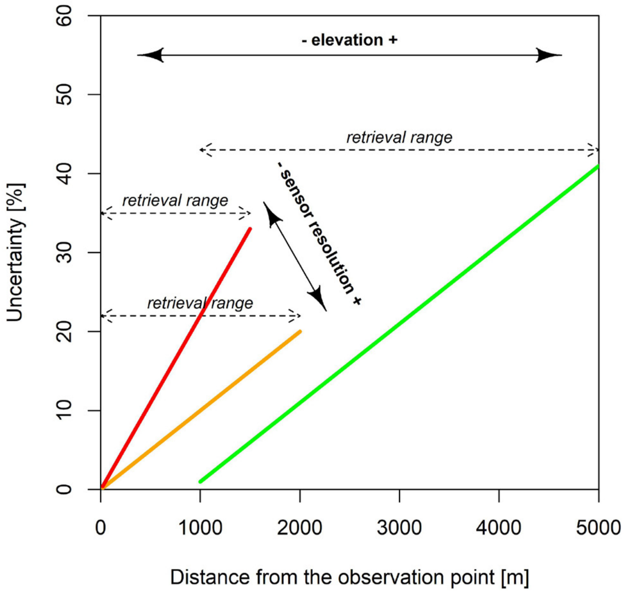

Figure 2: *Relation between distance from the observation point, the range (minimum and maximum distance) and the uncertainty of* Fractional Snow-Covered Area *(FSCA) retrievals. Coloured lines represent real experimental setup estimated considering cameras with different sensor resolutions installed at the CCTower (orange and red) and the camera located at the Zeppelin Observatory (green). Each double ended black solid arrow refers to a specific setting where the elevation of the camera location and the sensor resolution are relevant information for finding the right retrieval range.*

2.2.1. The spatial resolution of time-lapse cameras

The observation geometry is strongly controlled by: the camera location (altitude), the viewing setup (orientation), the camera sensor (image resolution), and the final output representation (cell size). The optimal design is driven by the application type, and it is possible to provide some examples aimed at helping the community select the best solution for their application. The first case study is based on different setups operating in the Ny-Ålesund area, where the coastal plain has been observed for 10 years from different locations and using different perspectives for various applications (Salzano et al 2021b). This first example combines observation of the Kolhaugen site from the Zeppelin Observatory, from the Amundsen-Nobile Climate Change Tower, and from a vertical setup associated with a field spectroscopy experiment. The combination of those oblique setups gives us indications about the relation between sensor resolution, installation elevation, and uncertainties. Vertical geometries, for example, limit the field of view and provide a detailed description of the surface, but the spatial representativeness of the observed snow dynamics is poor. Oblique geometries are significantly impacted by the perspective and resolution of the sensor: installing the time-lapse camera at 20 m above ground rather than at ground level expands the observation area from tens of square metres to about 1 km^2. The aggregation of the projected pixel in the final output grid, generally based on satellite grid formats, will of course affect the final uncertainty levels, which can rise if a 10 m grid resolution is selected (Sentinel-2 for example). Conversely, the MODIS grid resolution (500 m), supports smaller uncertainty levels, although this comes at the cost of a limited number of cell units. Increasing the sensor resolution can improve the retrieval of FSCA and thus increase the quality of the terrestrial photography application. This information supports the definition of an altitude-resolution-distance relationship that can help the community find the best compromise for designing new systems.

2.2.2. The temporal resolution of terrestrial photography applications

The temporal resolution of a time-lapse camera is a user setting that should match the application requirements and consider different data processing issues. Designing a camera system to monitor snow dynamics requires several choices, and the major limitation is related to image storage: higher sensor resolutions imply larger image file size. The temporal resolution affects the required storage volume: daily acquisitions require lower storage capacity than hourly acquisitions. Cloud cover is an additional element that must be considered since the observing location could be above or below the cloud base depending on local meteorological conditions. Considering the daily revisit time of different satellites (MODIS, and Sentinel-2 MSI), the installation altitude, which may occasionally be above the cloud base, is a key parameter since cloud cover can be highly variable even on hourly timescales in Svalbard.

2.2.3. Considerations on classification algorithms

The processing of images obtained by terrestrial photography consists of two main steps: image ortho-rectification and image classification. The first task is based on the so-called monoplotting procedure, a well-established mathematical problem focused on associating pixels to ground control points. The image classification can be approached using many different methods. In Svalbard, we have identified the use of two methods: the blue thresholding (BLT) and the spectral similarity (SS). To test these methods, we considered imagery acquired in Ny-Ålesund from the Scheteligfjellet site and in Hornsund from the Fugleberget location. This analysis was aimed at comparing the BLT and the SS algorithms on the same datasets even if images were filtered to limit difficult illumination conditions and topographic effects. Both approaches were performed on 12.2-megapixel imagery acquired by sensors located at about 700 m a.s.l. on Scheteligfjellet and at 550 m a.s.l. on Fugleberget. Both datasets were sampled daily during the melting season from April to August, and contained images selected near solar noon when the solar elevation angle is highest. This comparison highlighted a good agreement between the automated approaches under consideration, and the final description of snow dynamics at daily resolution is not affected by the algorithm selection. The considered images were, in fact, screened before being classified selecting the optimal illuminating conditions. Considering the dataset obtained by a camera located at the Zeppelin Observatory (485 m a.s.l.) and operating since 2015 with a 4.9-megapixel camera, the same analysis was carried out including heterogeneous illumination conditions. This analysis showed a better performance for the SS than for the BLT method, as the latter was impacted by misclassified projected pixel associated with the projection distance. The limitations of BLT retrievals can be associated with poor illumination conditions (low sun or heavy cloud coverage) and surface roughness. While low sun can occur regularly in the early morning or in the late afternoon, surface roughness and cloud coverage are not time-dependent. While BLT can generally provide good results between 11:00 a.m. and 3:00 p.m. local time, SS can increase this time span, since it is more robust to both solar elevation and cloud cover. While hourly acquisitions required a more careful choice of classification algorithm, with SS being superior, both algorithms performed well for daily imagery.

2.3. Integration with satellite remote sensing

Terrestrial photography is a promising tool for cal/val of snow-related retrievals from satellite remote sensing. This is largely due to the very high spatial and temporal resolution that is obtainable using strategically placed time-lapse cameras. These cameras also allow for long temporal and large spatial coverage. As such, the sheer volume of data captured by such systems is virtually unparalleled by other terrestrial and even airborne observations targeted towards satellite cal/val. Terrestrial photography is primarily used to generate very high-resolution maps of binary snow cover which can be spatially aggregated to estimate FSCA at the resolution of the satellite products that are to be validated.

Space-borne sensors can get close to matching the combined spatiotemporal coverage and resolution of automated terrestrial photography. As a result, satellite retrievals are usually validated with higher resolution satellite retrievals. This exercise can be problematic. For example, it has been shown that high resolution retrievals on the order of tens of metres (e.g., from Landsat or Sentinel-2) may contain considerable biases if mixed pixels (subpixel variability) are not accounted for in the retrieval algorithm (Aalstad et al. 2020). These biases do not average out after spatial aggregation. This is where the resolution of terrestrial photography shines by providing a source of independent validation data for satellite retrievals, helping to support (or challenge) conclusions that are drawn higher up the validation chain.

Given this potential, there has been a growth in snow research using terrestrial photography together with satellite remote sensing. Gascoin et al. (2020) used time-lapse photography as a validation tool to retrieve FSCA, instead of binary snow cover, through a nonlinear sigmoid-based regression on the Normalised Difference Snow Index (NDSI). This approach is now used operationally to generate the FSCA product from Sentinel-2 imagery in the pan-European high-resolution snow and ice monitoring of the Copernicus Land Monitoring Service (CLMS). In Svalbard, Aalstad et al. (2018) used an automatic camera system on Scheteligfjellet near Ny-Ålesund to validate Sentinel-2 and MODIS FSCA retrievals that were then used for snow data assimilation. Subsequently, Aalstad et al. (2020) used the same camera to evaluate various FSCA retrieval techniques applied to MODIS, Sentinel-2, and Landsat 8 imagery.

The contribution of terrestrial photography to the gap reduction between in situ observations and satellite data is evidenced by Figure 3, where an area close to the Kolhaugen site (approximately 100x100 m^2) supports the description of the 2020 snowmelt season with different observation data. The impact of mixed pixels is highlighted in terms of snow depletion curve, and it suggests focusing the attention on this issue for assessing the spatial distribution of the snow cover on the ground.

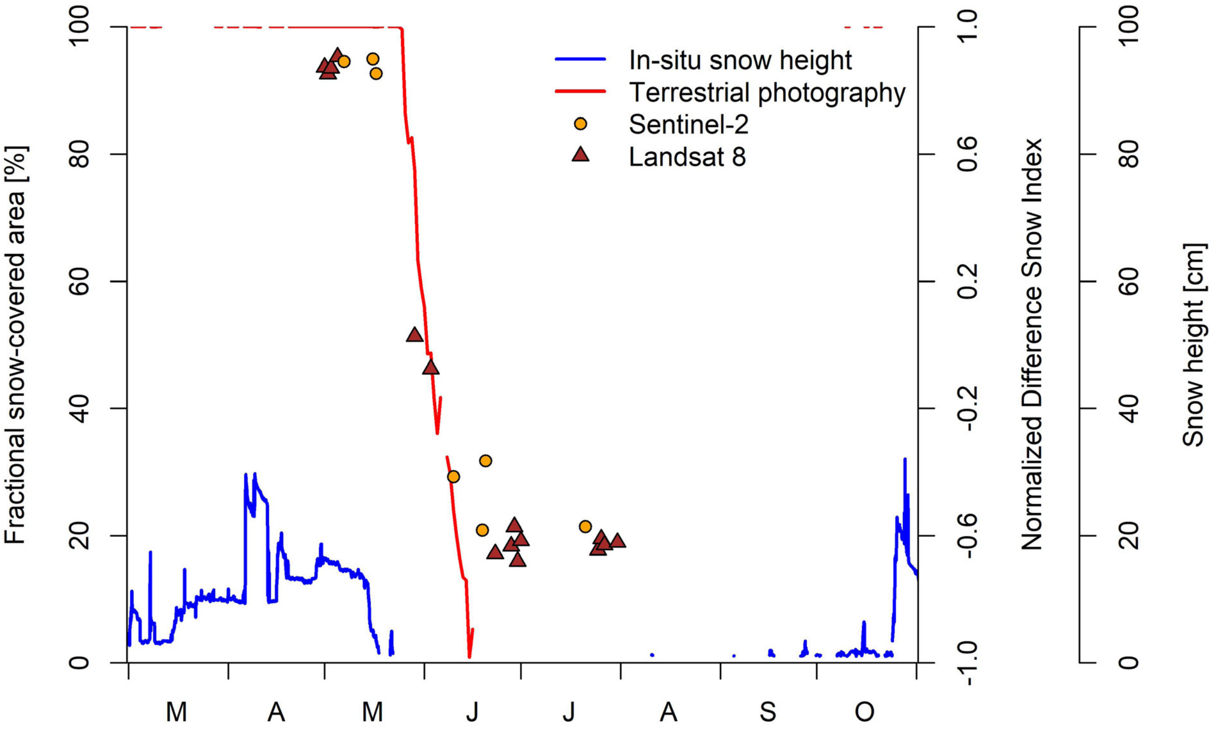

Figure 3: *Evolution of the snow cover at the Kolhaugen site (Ny-Ålesund) in 2020 combining the fractional snow-covered area (FSCA) retrieved by terrestrial photography, in situ measurements of the snow height (Mazzola et al. 2021) at the Climate Change Tower and the Normalised Difference Snow Index (NDSI) obtained by Landsat 8 and Sentinel-2 platforms.*

This was supported by the evaluation of Aalstad et al. (2020) where spectral unmixing, which explicitly accounts for mixed pixels, performed best overall. Moreover, NDSI regression, which implicitly accounts for mixed pixels, could provide nearly the same performance at a considerably lower computational cost. These results helped support the new Let-it-Snow (LIS) algorithm in Gascoin et al. (2020) and provided observation error estimates for snow data assimilation (Alonso-González et al. 2021; Fiddes et al. 2019), exemplifying the benefits that terrestrial photography can bring to snow science. LIS has yet to be tested in Svalbard, which is currently outside the pan-European operational domain of CLMS. As such, we performed an initial validation of LIS in the high-Arctic and compared it to other retrieval algorithms. For the validation, we used the Zeppelin dataset described in Salzano et al. (2021a), where images were ortho-rectified and classified using SS to yield FSCA at 10 m resolution. To avoid artefacts, we cropped the area of interest to exclude the village and airport of Ny-Ålesund. We selected camera-based FSCA maps for five days during June 2019 where cloud-free atmospherically corrected (L2A) multispectral satellite imagery from Sentinel-2A/2B was also

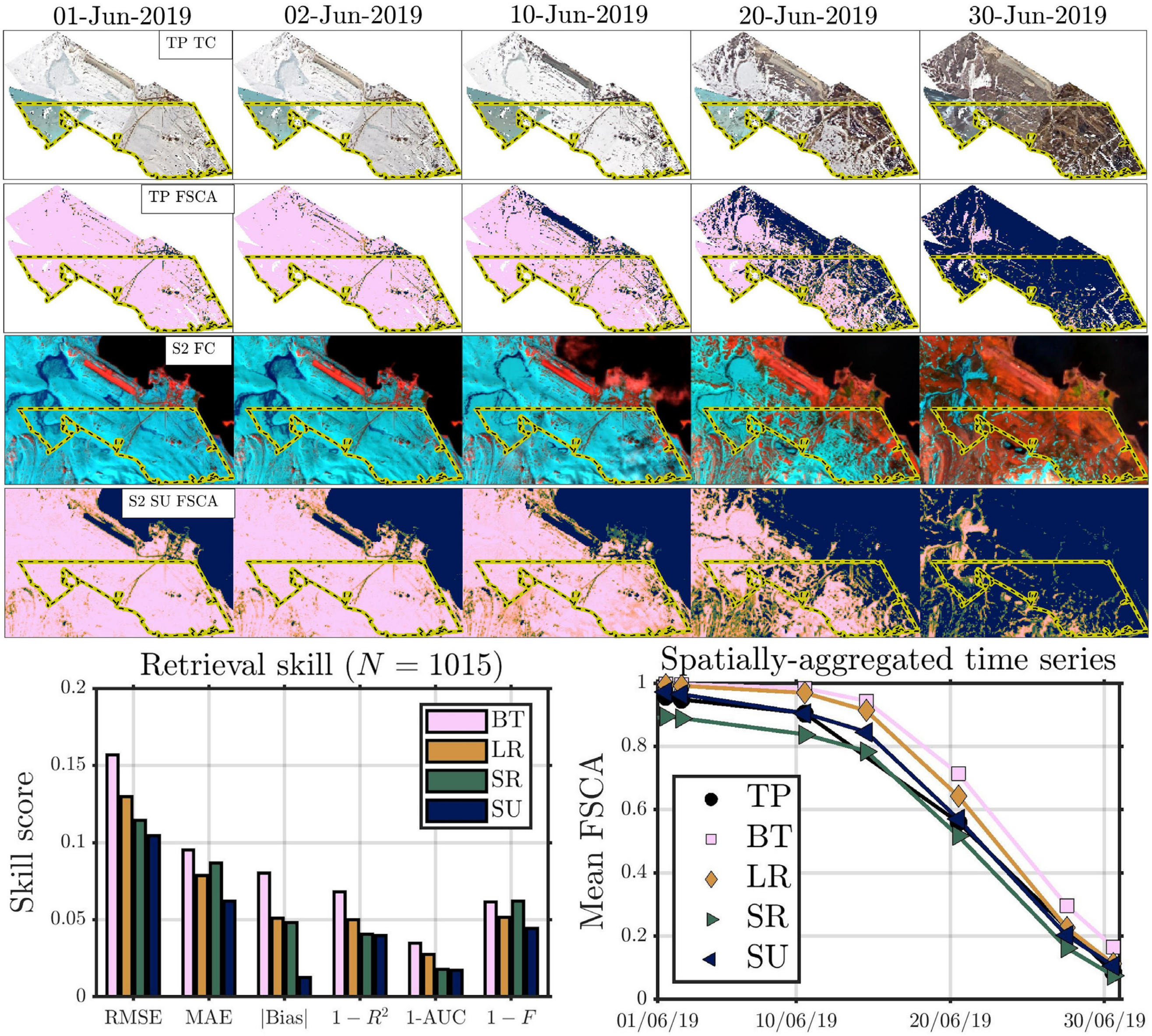

Figure 4: *True colour orthophotos from Zeppelin (first row), Fractional Snow-Covered Area (FSCA) retrievals from these orthophotos (second row), false colour imagery from Sentinel-2 (third row), and FSCA retrieved from this imagery using Spectral Unmixing (fourth row). The yellow polygon is the Area of Interest. The bar chart (bottom left) shows the skill scores of the Sentinel-2 FSCA retrievals using 1015 coincident satellite-camera samples. The time series (bottom right) shows the evolution of the spatial mean FSCA during June 2019 from the retrievals: Terrestrial Photography (TP); Binary Thresholding (BT); Linear Regression (LR); Sigmoid Regression (SR); Spectral Unmixing (SU).*

available. We estimated FSCA at 10 m resolution from the Sentinel-2 imagery using: (i) binary thresholding (BT) on the NDSI as used in the old LIS approach (Gascoin et al. 2019) and in several studies in Svalbard (Vickers et al. 2021); (ii) linear regression (LR) on the NDSI originally proposed for MODIS; (iii) sigmoid regression (SR) now used in LIS (Gascoin et al. 2020), and (iv) spectral unmixing (SU; Aalstad et al. 2020). To target scales that are relevant for most snow modelling in the validation, we aggregated the retrievals from 10 to 100 m resolution.

Based on this validation exercise (see Figure 4) we found that the SR-based retrieval approach used in the new LIS algorithm performed very well, outperforming both LR and BT for most of the skill scores considered (see Aalstad et al. 2020 for definitions). It was only outperformed by SU, which is considerably more computationally intensive and requires knowledge of local non-snow end-members (i.e., land cover). Through further tuning of SR, we were able to match the performance of SU, showing that this is a promising and computationally feasible approach for Svalbard-wide FSCA mapping with higher resolution optical satellites such as Sentinel-2 or Landsat. Our preliminary validation could be extended to other sites, sensors, and emerging algorithms such as generalised approaches to SU.

3. Unanswered questions

This terrestrial photography survey in the Svalbard archipelago is a key action for the identification of relevant data sources for different disciplines. The optimisation of active and future observing systems will be designed considering the PASSES legacy where different setups were included ranging from heterogeneous camera devices (different sensor resolutions, fore optics, sensor types), to installation features (site elevation, perspective coverage, acquisition seasoning), image data processing (ortho-rectification and classification), and uncertainty quantification. There is a need for a shared strategy for the different components of these data processing chains, and the final solution will be a compromise between maintenance issues, logistic requirements, resource allocation and data/privacy constraints. This update also highlighted the need for integrating terrestrial photography as a cal/val tool for satellite remote sensing, which is arguably the application of terrestrial photography with the largest potential scientific impact.

4. Recommendations for the future

Several problems and knowledge gaps hinder the full use of the opportunities presented by terrestrial photography. To enhance its usefulness for snow cover and related topics, we propose the following actions that can be taken by the SIOS community to support research in this field:

1. Promote actions and projects that use time-lapse cameras, especially in the more remote areas of Svalbard. Cameras that cover the field of view of higher-elevation terrain should be particularly welcomed.
2. Stimulate the creation of a Svalbard camera system network. There is a need to create a common and easy-to-apply algorithm for processing large quantities of images from different devices for snow cover applications.
3. Promote the integration between terrestrial photography and satellite remote sensing since this approach is a promising strategy for extending in situ observations to improve regional monitoring.

4. Stimulate the use of time-lapse cameras by different disciplines where high time-resolved information can be retrieved for different purposes (glaciology, hydrology, plant and animal ecology, coastal processes, sea ice tracking, satellite cal/val).

5. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Time-lapse cameras in Svalbard ver 2	Camera locations and ancillary information	2000-2021	Svalbard archipelago	http://iadc.cnr.it/cnr/metadata_view.php?id=113	CNR
FSCA at Ny-Ålesund	FSCA	2020	Bayelva	http://iadc.cnr.it/cnr/metadata_view.php?id=128	CNR
Satellite NDSI at Ny-Ålesund	NDSI	2014-2020	Bayelva	http://iadc.cnr.it/cnr/metadata_view.php?id=129	CNR + UiO
Satellite NDSI at Hornsund	NDSI	2014-2020	Fuglebekken	http://iadc.cnr.it/cnr/metadata_view.php?id=130	CNR + UiO

6. Acknowledgements

This work was supported by the Research Council of Norway, project number 291644, Svalbard Integrated Arctic Earth Observing System – Knowledge Centre, operational phase. This activity was supported by the Italian Arctic Station at the Amundsen-Nobile Climate Change Tower and by the Italian Arctic Data Center.

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