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# Reconstruction of Glacier States from Geo-Referenced, Historical Postcards



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# Preface

The exciting thing about the present Master thesis is that it combines the fields of Cartography, Photogrammetry and Glaciology. Every field itself is very interesting, but their combination makes them even more valuable. For me, this thesis was a chance to widen my knowledge, combined with a deeper knowledge in each of the three fields. Furthermore, the fact that it was not sure in the beginning, what the exact content of this thesis will be and, if the the analysis will work, motivated me even more.

I would like to thank Samuel Wiesmann and Lorenzo Oleggini, who offered me the opportunity for this topic. Additionally, I would also like to thank them for their great support during this thesis. Their competent inputs in conceptual work, or in the interpretation of the results and in the corrections of my report were very useful.

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# Abstract

This Master thesis deals with the reconstruction of former glacier states of the Rhone glacier. The glacier states are reconstructed by digitizing the glacier tongues from historical images. Since the camera parameters of these images are unknown, the image georeferencing is done first. Camera parameters include the geographical (position and rotation) and optical (image center, focal length) parameters of a camera. The image georeferencing is achieved by estimating the camera parameters based on the monoplotted principle.

To verify the quality of the digitized states, the quality of the georeferencing using the WSL Monoplotted Tool is evaluated as a first step. Influences on the georeferencing quality, like the use of different digital elevation models (DEMs), are examined.

The georeferencing of single, terrestrial images could be realized in the expected accuracy range of one to five meters in a 2D world space. These results are useful in regard to the application field of glaciology. The quality of the georeferencing is though dependent on the image resolution, the incident angle of the camera light beam with the topography, the accuracy of the DEM and the resolution of the orthophoto.

The reconstructed glacier tongues are then visualized in a printed map and a web map application in order to illustrate the glacier tongue retreat of the Rhone glacier.

The present thesis succeeded in georeferencing single, terrestrial images with unknown camera parameters using the WSL Monoplotted Tool. This is advantageous for the application field of Glaciology in order to illustrate glacier retreats. Additionally, this method can be used for other application fields, where single pictures are available.

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# 1. Introduction

## 1.1. Preface

The present Master thesis is tangent to research fields of photogrammetry (e.g. georeferencing on the basis of the monoplotted principle), glaciology (e.g. glacier tongue retreat) and cartography. This thesis deals with the possibility to reconstruct glacier tongue states by means of georeferencing historical, terrestrial images, mainly postcards. historical images or postcards are mostly single images with unknown camera parameters. So, the camera position, the viewing angle and the camera itself (image center, focal length,...) are not known. This lack of camera parameters complicates the georeferencing of these images. But, the use of these images is highly advantageous for the reconstruction of glacier tongue states. This is because these images are, available a lot earlier than accurate topographic maps and, on the other hand, they are available in a higher density than existing surveying data.

## 1.2. Motivation

To use historical images for the reconstruction of glacier tongue states, the problem of georeferencing single, terrestrial images with unknown camera parameters, has to be solved.

As a further point, not much software exists for that purpose. For several years, there has been a few softwares for georeferencing single images (Chapter 2.5.1). Unfortunately, they are very subject-specific and only available for specialists [8].

For this purpose, the group of researchers for “Insubiric ecosystems” at the “Swiss Federal Institute for Forest, Snow and Landscape Research (WSL)” in Bellinzona has developed a software (“WSL Monoplotted Tool”, chapter 2.5.1, which enables the georeferencing of single, terrestrial images. This is currently still a prototype, which is based on the monoplotted principle (chapter 2.4.2).

The possibilities of “WSL Monoplotted Tool” for the reconstruction of glacier tongue states, will be evaluated in this Master thesis. Other application fields are mentioned in Chapter 2.2.

## 1.3. Objectives of this Thesis

The overall goal of this thesis is the reconstruction and visualization of former glacier tongue states of the Rhone glacier. This is done on the basis of historical, terrestrial images. The resulted glacier tongue states will be visualized on the one hand in a printed map and on the other hand in an interactive web map application.

Furthermore, a relative and absolute accuracy estimation of the method of georeferencing single, historical, terrestrial images, will be done. The absolute accuracy will be estimated

by comparing the resulted glacier tongues to reference data, such as topographic maps or already existing glacier tongue states. The relative accuracy has the goal to evaluate the influence of the used data (especially the digital elevation model) to the accuracy of the resulting camera calibration and feature extraction, such as glacier tongue states.

Besides, a rough analysis of the glacier tongue retreat will be done. This enables the adding of a short description of the glacier retreat to the maps.

## 1.4. Description of the Content

The present Master thesis is structured in six Chapters, besides the introduction.

In Chapter 2, the concept of the applied methodology as well as the software WSL Mono-plotting Tool, which is used in this research, are described. Chapter 3 gives an overview of the available datasets. The used datasets and their selection are thereby described more specifically. Chapter 4 describes the main evaluation process with the absolute and relative accuracy analysis and the reconstruction of the glacier tongue states. With Chapter 5, a new part begins with the description of the design of the printed map and the programming of the interactive web map application. Chapter 6 describes the results and interprets their characteristics. Conclusions are drawn in Chapter 7 and a short outlook is presented.



## 2. Description of the Applied Methodology

### 2.1. Initial Situation

Glacier retreat is a topic with a lot of public interest. Many reports on this topic are written, e.g. the glacier tongue break-off at the Bernese “Giessen glacier” in October 2011 [2] or the glacier tongue retreat in Patagonia, in December 2011 [3]. The regression of glacier tongues is easily observable for researchers, as well as for hikers who can remember former years. Today, exact quantitative statements can be done using data of different surveying techniques. As an example, this data could be satellite and aerial images, as well as data from terrestrial surveying methods. In addition, it is possible to digitize former glacier states from the height lines of former pixel maps (chapter 2.5.1). However, this data was not always available or not in a desired accuracy or temporal density (update-rate). For example, the earliest pixel maps at a scale of 1:25'000 exist since 1952 and have been updated every six years since then. In contrast, terrestrial pictures, such as historical postcards, are available since the 19th century. Depending on the field of interest, these pictures are available annually. This data can thus be helpful for the reconstruction of former glacier states. Reconstructed, former glacier states can be advantageous for many research fields, which are connected with the glacier retreat or the other way around (e.g. sea level rise, climate change, increase of CO<sub>2</sub>-emission).

For the reconstruction of former glacier states, historical glacier images need to be found and geo-referenced. Thereby, the problem of georeferencing single, terrestrial images with unknown camera parameters, has to be solved.

The georeferencing can be done using the software WSL Monoplotting Tool (chapter 2.5.1). This allows the digitizing and further processing of elements out of geo-referenced postcards (that have to be examined). For example, the states of glacier tongues on historical postcards in a GIS or the reconstruction of forest boundary and stage age.

### 2.2. Related Works

The present Master thesis is related to the fields of Photogrammetry, Cartography and Glaciology. The methodology of reconstructing former glacier states is based on monophotogrammetric principles, e.g. monoplotting (chapter 2.4.2). The results though can have a benefit for glaciologist's.

Glaciologist's have a lot of possibilities to derive information about glacier dynamics (retreat of glacier tongue, surface movements and velocities, volume changes) from existing surveying data. This includes satellite and aerial images and surveying data (e.g. Lidar, SAR), as well as terrestrial surveying data, e.g. velocity measurements on the glacier surface. Many datasets are however only available since a certain date, which is depending on

the area of interest. For example, the earliest available surveying data of the Rhone Glacier is from the year 1874 and is updated annually. In order to derive information about former glacier states and dynamics, a gap is existent and other methods have to be used. This could be oral traditions, geocigal characteristics (glacier moraine) or historical pictures.

The present thesis evaluates the possibility of the use of historical pictures. This is done in order to close one gap and to derive information about former glacier tongue states.

The use of historical pictures for the present application requires a georeferencing of these images. This process is done in the WSL Monoplotting Tool (chapter 2.5.1) on the basis of the monoplotting principle (chapter 2.4.2). Apparently, it does not exist a lot of software for georeferencing single images on the basis of monoplotting. However, few softwares exist, e.g. OP-XFORM (1995), JUKE method (2001), Georeferencing oblique terrestrial photography (2004), 3D Monoplotter (2004) and DiMoTep (developed at ETH in the year 2005 [1]). Unfortunately they are very subject-specific, not intuitive and only available for specialists [8]. Mostly these are softwares, which are programed at universities for their own usage and have to be addressed over console requests.

The WSL Monoplotting Tool was developed to close this gap in the availability of mono photogrammetry softwares. Former works dealt with the use and testing of this software. The Office for Natural Hazards (Ti) [7] evaluated the reconstruction of natural events, such as floods and avalanches on the basis of the WSL Monoplotting Tool. In addition, a bachelor thesis at the ETH in the year 2009 had the goal to reconstruct forest boundaries and stage ages [12] as well as to analyze the method of georeferencing single, terrestrial images on the basis of the WSL Monoplotting Tool. Many influences on the quality of the geoprocessing could be established in this thesis. This includes the setting of control points, the image quality, the problem of flat angles and so forth. Further influences, like the use of different DEMs as basis data for the georeferencing, will be analyzed in the present Master thesis in Chapter 2.4.2.

## 2.3. Application Fields

Besides the current application field of this thesis, there are many more fields, where single pictures are available. Hence, several fields can benefit from the WSL Monoplotting Tool [7]:

- archeology and history
  - roads and trails
  - channels for water and material transport
- landscape evolution
  - reconstruction of forest boundary and stage age
  - glacier's dynamics
  - land-use changes (i.e. urbanization)
- reconstruction of natural events
  - floods

landslides

avalanches

- monitoring of current processes
  - surface of glacier melt water
  - snow melt
  - wind erosion

## 2.4. Approach and Methodology

### 2.4.1. Approach

To reach the objectives, described in chapter 1.3, the approach in this Master thesis is the following:

1. Providing a data overview and selection of data of interest
2. Georeferencing of single, terrestrial images
3. Accuracy evaluation of the selected data
4. Digitizing of former glacier tongue states, by taking into account the results of the accuracy evaluation
5. Design of the products (printed map and web map application)

The background for this approach is described in chapter 2.4.2.

### 2.4.2. Methodology

#### Georeferencing of Single, Terrestrial Images

To reach the overall goal of reconstructing former glacier states from single, terrestrial and historical images (chapter 1.3), a georeferencing of these images has to be done first. This will be done using the software WSL Monoplotting Tool (chapter 2.5.1) with the required input data for the software (chapter 2.5.2).

In order to enable statements about the quality of the georeferencing process, the resulted accuracies of the georeferencing process are analyzed. The WSL Monoplotting Tool enables the user to check the accuracy values of the georeferencing process on the basis of different accuracy values (chapter 2.5.1).

#### Relative and Absolute Accuracy Evaluation

In addition, an accuracy evaluation of the resulted, digitized and geo-referenced objects (reconstructed glacier states) will be carried out (chapter 1.3). This evaluation is divided into two main parts:

1. Absolute accuracy estimation
2. Relative accuracy estimation

For the absolute accuracy estimation, the resulted digitized glacier tongues will be compared to reference data (chapter 3.2.5). This means, to data which is already known. E.g. known geographic positions of glacier tongue states from topographic maps or terrestrial surveying data. Based on the assumption of a high accuracy of the reference data, the absolute accuracies of the georeferencing process and the further digitizing of objects can be estimated.

A further goal is to estimate the best possible accuracies of the georeferencing process in the WSL Monoplotting Tool. The question thereby is, which combination of datasets (image, DEM, orthophoto/topographic map) will lead to best accuracy. Does the use of congruent data increase the absolute accuracy or does the use of not congruent data decrease the absolute accuracy?

Congruent data means datasets, which are available from the same year and thus represent the same topographic state of the region of interest. For example, an image, a DEM and an orthophoto or topographic map of the year 1874 are congruent. In contrary, an image of 1874 and a DEM and orthophoto of the year 2010 are not congruent. The disadvantage of the not congruent data combination is that these datasets show differences in the pictured or mapped topography. The advantage thereby is that the newer datasets (DEM, orthophoto) have a higher spatial resolution and are more accurate than the older ones (Chapter 3.2, Appendix C-1).

It is assumed that the georeferencing leads to best accuracies by using congruent data. In addition, it is assumed that the best results can be achieved by using the newest data with a high accuracy. This would be for example, the use of an image, a DEM and an orthophoto of the year 2010 (Chapter 3.2).

To evaluate the influence of the use of different data combinations (congruent vs. not congruent data) on the georeferencing quality, a relative accuracy comparison will be done. To evaluate the relative accuracies, the georeferencing process will be carried out on the basis of digital elevation models (DEMs) from different years and different topographic status. The resulted, digitized glacier tongues will later be compared with each other on the basis of random samples. This means that, on one hand,

- the georeferencing of the images is done on the basis of the most accurate DEM. This is assumed to be the newest one of the year 2010 (chapter 3.2.1).

On the other hand,

- the georeferencing of the images is done on the basis of a DEM, which represents the same topographic status as it is represented in the used image. Consequently, the image and the DEM should be available from the same time period (month or approximately year).



### **Digitizing of Former Glacier Tongue States**

The accuracy evaluations (chapter 2.4.2) are done for at least three chosen years in order to have a single control of the results. Further images will be geo-referenced in a second step. This will be done on the basis of the knowledge about the reachable accuracies with the WSL Monoplotting Tool georeferencing process.

### **Requirements on the Data**

The accuracy evaluations (Chapter 2.4.2) require specific data. The data which is needed for the georeferencing in the WSL Monoplotting Tool is described in Chapter 2.5.2. For the evaluation process, more requirements have to be kept. When working with the software WSL Monoplotting Tool, it is important to have an orthophoto or a topographic map of the same time period as the DEM. Corresponding maps and DEMs decrease the error sources and thus increase the reachable accuracy.

For the comparison of the georeferencing based on different DEMs, pictures of the same time period are needed, e.g. the same year as the orthophoto and the DEM.

To analyze the absolute accuracy, the reference data should be as well available from the same time period (approximately year) as the image.

### **Design of the Products**

Two products will be generated in the present Master thesis. A printed map will be drawn and a web map application will be programmed.

The printed map (Chapter 5.2) will be designed in Adobe Illustrator whereas the web map application (Chapter 5.3) will be designed in scalable vector graphics (svg). Thereby, the interaction of the web map application will be realized over javascript functions. For this, the software “Oxygen XML Editor” will be used.

Alternatively, the web map could be integrated in OpenLayers. OpenLayers “makes it easy to put a dynamic map in any web page. It can display map tiles and markers loaded from any source. OpenLayers has been developed to further the use of geographic information of all kinds. OpenLayers is a completely free, Open Source javascript” [5].

The self-programming of the web map application in svg and javascript is chosen, because it enables a huge flexibility in the map design. Thus, the display of the glacier tongue states on historical postcards as well as on geo-referenced maps (orthophoto, topographic maps) can be realized according to the web map concept (Appendix A).

## 2.5. WSL Monoplotting Tool and Monoplotting Principle

### 2.5.1. WSL Monoplotting Tool

The software WSL Monoplotting Tool enables the georeferencing of single, terrestrial images and was developed to close the gap in the availability of mono photogrammetric softwares (Chapter 2.2). The georeferencing process is implemented according to the monoplotting principle, which is described in Chapter 2.4.2.

#### Software Requirements

The software development project is still ongoing and has the following requirements. At first, there has to be the possibility to georeference historical, single, terrestrial images. Furthermore, the use of the software has to be simple and intuitive, and the software should allow a simultaneous and synchronized visualization of the terrestrial image and the corresponding map or orthophoto. In addition, the data should be compatible with common GIS systems like ESRI ArcGIS or Quantum GIS. [8]

At the current status, a semi-automatic camera calibration is implemented in the software. This means that an interaction with the user is required. Furthermore, the interoperability with GIS systems (e.g. ArcGIS, Q-GIS) is ensured through ASCII files. Future developments involve the improvement of the camera calibration process and a robust accuracy estimation. Furthermore, the integration in ArcGIS will get enhanced. [7]

#### Different Coordinate Systems

In the context of the WSL Monoplotting Tool, two different coordinate systems are mentioned:

- image coordinate system (in pixel)
- world coordinate system (in meter)

The image coordinate system has its origin in the top left point of an image. The image dimension is defined in pixel (e.g. 1400 px \* 700 px). Thus, the relative location of an image in the world space (e.g. swiss national grid) is unknown.

The world coordinate system in the context of this thesis is defined as the swiss national coordinate system (swiss grid in LV03 coordinates). Thereby, the origin is located in Bern with the y and x coordinate values of 600'000 m and 200'000 m.

The goal of georeferencing these images is to define a conjunction between the image coordinate system and the world space. This enables to relate the image to the world space and transformations between the two coordinate systems are possible. This relation is done over the use of control points.

Control points are similar points which are set in the pixel image (image point **p**: available in pixel coordinates, Figure 2.2) and in the topographic map or orthophoto (real point **P**: available in world coordinates, Figure 2.2).

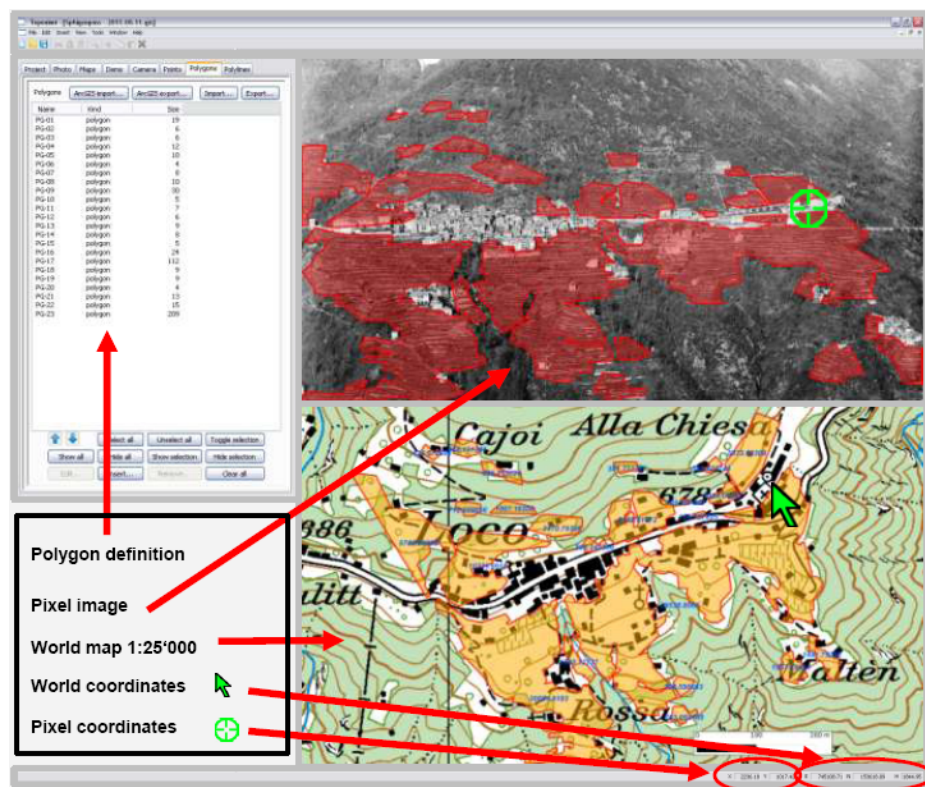


Figure 2.1.: Screenshot of the WSL Monoplotting Tool. On top right lies the terrestrial picture and on bottom right is the orthophoto placed. The data is loaded over the specific tabs on top left. [7]

### Structure of the WSL Monoplotting Tool

The WSL Monoplotting Tool is structured into three main sections (Figure 2.1). First, there is the tab-section where it is possible to import the input data (Chapter 2.4.2) and to define control points, polylines or polygons. The second section represents the pixel image, whereas the topographic map or the orthophoto is displayed in the third section.

After the camera calibration process (Chapter 2.5.1), a correspondence between the pixel image and the topographic map or orthophoto is defined. Thus, image and world coordinates are displayed for all the input data.

### Implemented Camera Calibration

The camera calibration is a process, which determines the geographical ( $O_x$ ,  $O_y$ ,  $O_z$ ,  $R_x$ ,  $R_y$  and  $R_z$ ) and optical ( $C_x$ ,  $C_y$  and  $D$ ) camera parameters. The software enables the determination of the camera parameters after the setting of minimally five control points (Chapter 2.5.1). This means the camera calibration is done on the basis of the defined control points.

The iterative camera calibration process estimates the following parameters (Figure B.1):

- $O_x, O_y, O_z$ : Camera position in world coordinates [m]
- $R_x, R_y, R_z$ : Rotation parameters in world coordinates [°]
- $C_x, C_y$ : Image center in pixel coordinates [px]
- $D$ : Focal length in world coordinates [mm]

The image center is defined on the basis of the image size, whereas the focal length will be estimated by means of control points. The camera gets calibrated by firstly defining an initial value for the camera position in the orthophoto. Based on the intersection of the initial camera position and the measured image point  $\mathbf{p}$ , the light ray  $\mathbf{r}'$  is defined (Figure 2.2). Further, the intersection of the light ray  $\mathbf{r}'$  and the digital elevation model calculates the real point  $\mathbf{P}'$ . Whereas, the intersection of the light ray  $\mathbf{r}$  and the plane  $\Pi'$  calculates the real point  $\mathbf{P}_{\Pi'}$ . Thereby, the plane  $\Pi$  goes through the real point  $\mathbf{P}$  and is perpendicular to the light ray  $\mathbf{r}$ .

In addition, the light ray  $\mathbf{r}$  is defined based on the intersection of the measured real Point  $\mathbf{P}$  and the initial value of the camera position. The intersection of the light ray  $\mathbf{r}$  and the image plane  $\Pi$  calculates the image point  $\mathbf{p}'$ . This procedure is iteratively calculated for every single control point.

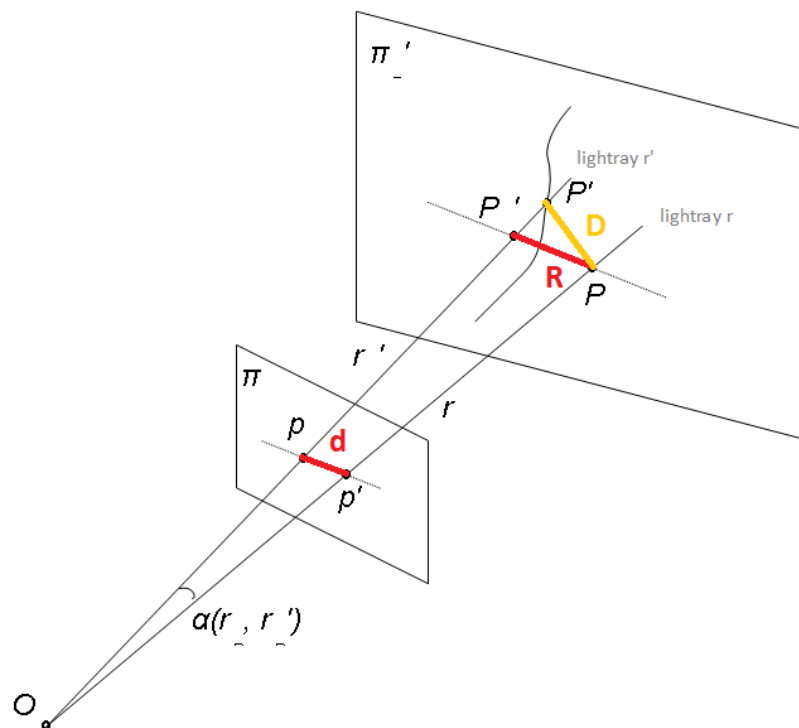


Figure 2.2.: Camera calibration principle [7].

### Camera Calibration Quality

Error	Unit	Index	Description
Pixel	px	$d$	Distance from $\mathbf{p}$ to $\mathbf{p}'$
Angle	$^\circ$	$\alpha(\mathbf{rp}, \mathbf{rp}')$	Angle between $\mathbf{rp}$ and $\mathbf{rp}'$
Radius	m	$\mathbf{R}$	Distance from $\mathbf{P}$ to $\mathbf{P}\Pi'$
3D-space	m	$\mathbf{D}$	Distance from $\mathbf{P}$ to $\mathbf{P}'$
2D-space	m	$\mathbf{D2d}$	Projection to a horizontal plane of $\mathbf{D}$

Table 2.1.: Camera calibration errors which indicate the accuracy of the camera calibration [7]

Based on a perfect camera calibration, the points  $\mathbf{p}$  and  $\mathbf{p}'$  as well as the points  $\mathbf{P}$  and  $\mathbf{P}'$  should be exactly the same. This means, the blue and red circles should lie exactly on top of each other (Figure 2.3). Thereby, the distances  $d$  and  $\mathbf{D}$  as well as the angle  $\alpha(\mathbf{r}, \mathbf{r}')$  should be zero. However, there are several influences which disable this perfect situation (see Chapter 2.5.2).

Therefore, the software allows the user to check the camera calibration quality after the first approximate camera calibration. The values in Table 2.1 give an indication on the estimated accuracy. Thereby, the errors  $\mathbf{D}$  and  $\mathbf{D2d}$  are dependent on the used digital elevation model. In contrast, the errors in the definition of the light rays as well as in the point  $\mathbf{p}'$  estimation are only depending on the implemented software algorithm.

The camera calibration is done iteratively until the errors in pixel, angle and radius get minimal. These error values are shown once in the WSL Monoplotting Tool for every control point. In addition, these error values are shown as a mean value of the errors of all control points (Figure B.1, in Appendix B).

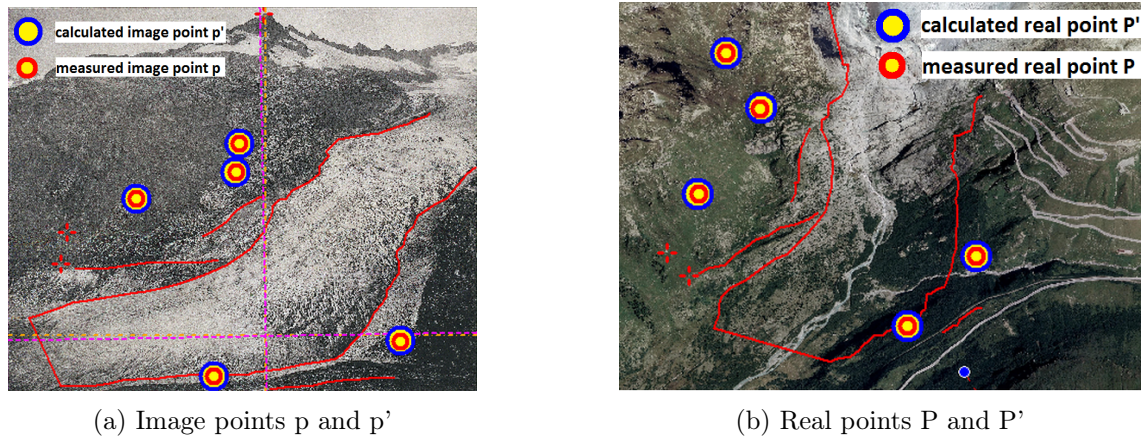


Figure 2.3.: Congruence of the measured and calculated image and real points in the WSL Monoplotting Tool, based on the camera calibration.

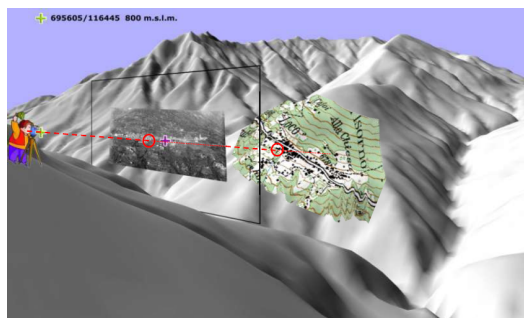
### 2.5.2. Monoplotting Principle

The georeferencing of single images is based on the principle of monoplotting. Thereto, the following data is needed:

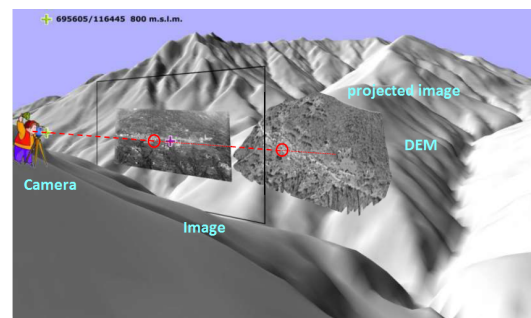
- image (image coordinates)
- orthophoto or topographic map (world coordinates)
- digital elevation model DEM (world coordinates)
- control points (known image and world coordinates)
- camera parameters

In the case of the usage of single, historical, and terrestrial images, the used camera is mostly unknown. This means that the geographical and optical camera parameters are not known (Chapter 2.5.1). Geographical parameters include the position and rotation of the camera, whereas the image center and the focal length are defined as optical parameters. To enable the georeferencing of these images, the camera parameters have to be estimated with an iterative camera calibration process which is based on the monoplotting principle.

Though, the “camera and the image have to be placed in the world space, so that a ray from the camera through a point on the image will intersect the DEM at the corresponding real point[7]” (Figure 2.4). These corresponding points are called control points and have to be known in the image and world space. On the basis of these known control points, light rays through each control point pair can be defined. The camera position is then determined as the intersection of the different light rays. Based on an initial camera position, the rotation of the camera and its focal length can be estimated as a further step (Chapter 2.5.1).



(a) Conjunction between the camera, image and the topographic map (overlayed on the DEM)



(b) Based on the georeferencing, the image could be projected on the DEM

Figure 2.4.: Monoplotting principle. This shows the conjunction of the camera, the image and the world space (topographic map and the DEM). [7]

Once the camera is calibrated, world coordinates are assigned to every pixel in the image. This is based on the intersection of the light rays (between camera position and the object in world space) with the image plane. Furthermore, image coordinates are assigned to every

pixel of the orthophoto or topographic map, based on the same principle. As a result, a conjunction between the image and the orthophoto exists, as well as between the image and world coordinates.

### **Influences on the Monoplotting Quality**

The georeferencing (monoplotting) quality is thus highly dependent on the accuracy of the defined control points. On the one side, it is important to define many control points which additionally are well distributed over the whole image. On the other side, the accurate definition of these control points is dependent on the following factors:

- resolution of the image
- accuracy of the topographic map or orthophoto
- accuracy of the digital elevation model
- topographic congruence of the digital elevation model with the orthophoto or topographic map

To increase the quality of the georeferencing, these influences should be minimized. Therefore, the following requirements should be kept:

- well defined and accurate control points which are stable over a long term period and, which are detectable in old images as well as in new orthophotos,
- a good distribution of the control points over the whole image, as well as around the region of interest (e.g. glacier tongue),
- accurate DEM with no or small distortions (especially in steep areas),
- and a high resolution of the image and the orthophoto.

In addition, the georeferencing quality of the is dependent on the angle of incidence of the camera light ray with the DEM (Figure 2.5). With a decreasing angle, increases the distance error in the object space, based on the setting of the control points.

Furthermore, an other error influences the quality of the georeferencing. This error is caused by so called “hidden areas”. This means that the target pixels in the image are hidden behind an other object, e.g. the camera light ray is interrupted by rocks. Therefore, the corresponding world coordinate is wrong. This is, because the world coordinate for the hidden object is calculated based on the intersection with the interrupted DEM point, instead of the point which lies behind this object. In order to avoid this problem, the WSL Monoplotting Tool has implemented a function, which enables the user to identify the real intersection of the light beam with the DEM.



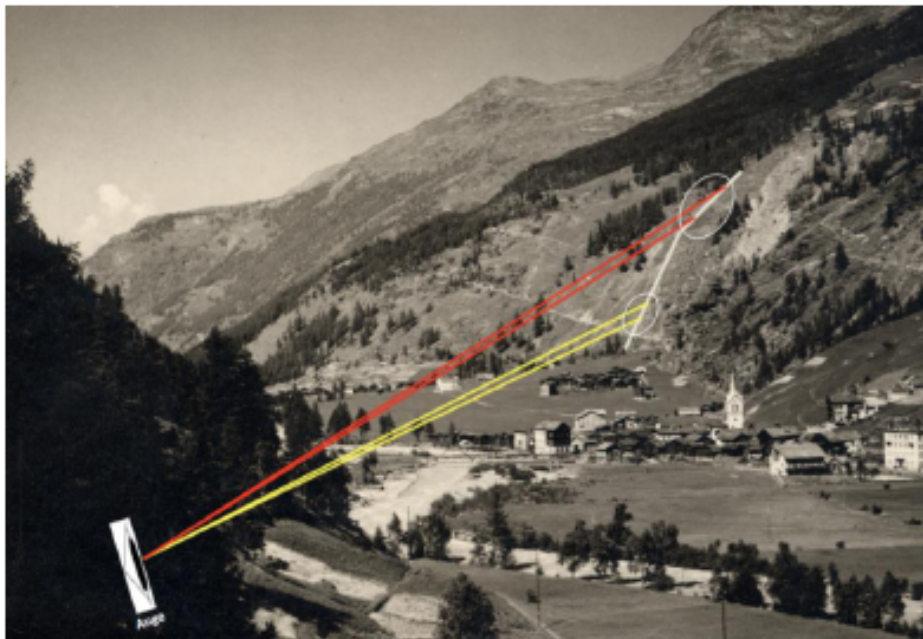


Figure 2.5.: Illustration of the flat angles difficulty. A decreasing angle, increases the error at the setting of control points [12].

## 3. Description of the Available Datasets

### 3.1. Study Area

To evaluate the characteristics of the applied method, the Rhone glacier was chosen as study area.

The Rhone glacier is located in the upper part of the Swiss canton of Valais and belongs to the Bernese Alps (Figure 3.1). In the summer, the glacier is accessible over the Furka Pass. The highest point of the glacier is the Dammastock at 3630 meters above sea level. The glacier tongue reaches down to almost 2200 meters above sea level (year 2012), near to the famous hotel “Belvedere” on the Furka Pass. The Rhone glacier extends to approximately 9 km in length and 3.5 km in width (year 2012) , whereas the valley is oriented as NNE and SSW and surrounded by many summits (e.g. “Galenstock, Dammastock, Tieralplistock, Gärstenhörner”). The topography of the valley is simple, because it is just one lateral valley with limited dimensions. From a hydrographic point of view, the Rhone glacier is the source of the Rhone river which flows in the Mediterranean sea in France.



Figure 3.1.: Overview and location of the Rhone glacier. Swiss topographic map 1:50'000 (1999), source ETH Zurich.

The Rhone glacier is chosen as a study area for this research, because there is a considerable amount of data available. A lot of pictures or postcards can be found for the Rhone glacier because it is easily reached by car and well accessible by public transport. In addition, it is a famous touristic spot.

Furthermore, there are elevation models from different years of the glacier region available and there is a high temporal availability of known positions of the glacier tongue (mostly every year since 1874). This data can be used for comparison reasons to evaluate the absolute accuracy of the estimated results (chapter 4 on page 25).

## 3.2. Description of Available Datasets

The data which is available for this research will be described in the following sub-sections. These datasets have differences in their accuracy, in their spatial and temporal resolution, their availability, and their sources. Adequate data will be selected out of the available datasets.

### 3.2.1. Digital Elevation Models

Digital Elevation Models (DEMs) of the Rhone glacier region are available for the years 2000, 1991, 1980, 1959, 1929, and 1847. These datasets are provided by the “Versuchsanstalt für Wasserbau und Glaziologie” (VAW ETH, Andreas Bauder) and the “WSL Birmensdorf” (Christian Ginzler) for the years 2009 and 2010. In addition, the “DHM25” (DEM with a cell size of 25 meters) is an available product from swisstopo. These DEMs are calculated from different data sources. The DHM25 as well as the DEMs from the years 1874 and 1929 are digitized out of the height lines of the corresponding topographic maps (Appendix C-1). The DEMs from the years 1959 to 2000 are calculated on the basis of corresponding photogrammetric orthophotos. The DEMs of the years 2009 and 2010 are calculated based on an autocorrelation from the corresponding swisstopo image flight ADS40/80 pictures (Appendix C-1). Additionally, a swisstopo image flight was done in October 2001, but the DEM 2011 is not yet calculated from these pictures.

Due to these different data sources, the DEMs have differences in their accuracy, and in their spatial and temporal resolution. The accuracy ranges from approximately 60 cm (2009, 2010) to some meters (1874, 1929, DHM25), whereas the resolution differs from 1 meter (2009, 2010) to 25 meters (1874, 1929, DHM25). Appendix C-1 provides an overview of these different DEMs, their characteristics and their sources.

### Selection of DEMs of Interest

On the basis of the characteristics of the different DEMs, the DHM25 and the DEM of the year 2010 are used for the evaluation process. Table 3.1 shows the specifications of the DHM25 and the DEM 2010. However, it is necessary to pay attention when working with the DHM25, since the exact year of updates or of the state of the glacier tongue and its surface is not known.

The DEM 2010 is selected instead of the DEM 2009, because the DEM 2009 shows distortions in steep areas, although the resolution is the same as for the DEM 2010. Furthermore,

Specifications	DHM25	DEM 2010
Data source	Topographic map, 1:25'000	Autocorrelation of aerial images (ADS40/80)
Height Accuracy	3 to 8 m	0.60 m
Resolution	25 m	1 m
Year	1990 to 1995	2010

Table 3.1.: Specifications of the DHM25 and DEM 2010 of the Rhone glacier region

the DEM 2009 possesses error pixels in regions, where the autocorrelation did not work well, e.g. in glacier surface regions with snow and without many other structures or in steep areas (Appendix D-1). The regions, where the autocorrelation did not work well, could have been filled with data from other DEMs or interpolated from the surrounding areas.

The DEM 1874 or 1929 should have been used for the evaluation process to analyze whether it is more important to have a DEM with a high resolution or a DEM, which is calculated the same year as the used terrestrial picture. Unfortunately, these two DEMs could not be used, because they are clipped and only made for the glacier surface itself, out of topographic maps. This means that they do not cover the glacier surroundings. These surrounding regions however are important to set the control points for the georeferencing. Because the control points should be set on stable grounds (Chapter 2.5.2), they are set on the glacier surrounding rocks, stones or infrastructures. These surroundings (instead of the glacier surface) should thus correspond to the topography of the terrestrial picture.

The knowledge about the small coverage of the DEMs 1874 and 1929 came recently after the finishing of the conceptual work. Therefore, this circumstance leads to a break in the planned approach and changes the methodology at this point. To fill this lack of information, the later comparison with the use of different DEMs will be done with the DHM25.

The reason for this is, that the DHM25 is calculated in years which are closer to the old images (so this represents more the topographic state of former years) and the resolution is approximately the same as in the DEMs of the years 1874 and 1929. Furthermore, it can be assumed that the differences in the topography of the glacier surroundings are within the accuracy of the DHM25. This assumption should be verified, which could be done based on a comparison of the height lines of the corresponding topographic maps. This procedure indicates height changes of the topography between these map years. Though, the suggested verification is not done during this thesis.

### 3.2.2. Orthophoto

There are three types of orthophotos available, which cover the Rhone glacier region. These are the Landsat mosaic, Spot mosaic and the SWISSIMAGE 50. They are recorded from different satellites with varying resolutions. Table 3.2 and Appendix C give an overview on the specifications of the orthophotos.

The Landsat and Spot mosaics are mosaics of digital satellite images of Switzerland. They are assembled from several individual images taken from the American satellite Landsat 5

and the French satellite Spot. “Due to uniform scale and balanced colors the mosaic appears to be one single image.” [9]

In contrast, the “SWISSIMAGE 50 is a composition of digital color aerial photographs over Switzerland” [6]. Since 2005 the pictures are captured with the Leica ADS40 digital camera which allows a high resolution and a digital production chain [6]. Although, the image flight of the year 2010 was realized, the images are currently just partially processed. Therefore, the raw images have to be used in this thesis. These raw images are available from the “WSL Birmensdorf” (Christian Ginzler) as a “CIR” and a “HDR” image. A CIR image defines a colored infrared image, whereas a high dynamic range image is called HDR image.

Specifications	Swissimage 50	Landsat mosaic	Spot mosaic
Data source	Digital aerial images (Leica ADS40)	Satellite Landsat 5 (USA), 20 images	Satellite Spot (F), 50 images
Accuracy	3 to 5 m	unknown	unknown
Spatial Resolution	0.5 m	25 m	5 m
Year	2009, 2010 (CIR,NIR)	1990	2005

Table 3.2.: Specifications of different orthophotos of the Rhone glacier region

### Selection of Orthophotos of Interest

It is important to have orthophotos with a high resolution in order to recognize accurate control points. Therefore the CIR and HDR images of the swissimage 50 flight in the year 2010 are chosen. Even though, it does not exist a true color image, a lot of information is still observable. The images from the year 2010 are chosen instead of the SWISSIMAGE 50 of the year 2009, because the orthophoto of 2009 shows considerable distortions in steep areas, which would affect the results. These distortions are caused by the errors in the DEM 2009 (Chapter 3.2.1, Appendix D-1), which is used for the orthophoto generation.

Generally, the orthophoto is chosen as the reference world map instead of a topographic map, because it is easier to identify control points and structures and additionally, it is more familiar for the human eye. Furthermore, it might be more accurate, because it is not generalized compared to a topographic map. A topographic map is only chosen when an orthophoto is not existing (e.g. before the first image flights in the 1930s).

#### 3.2.3. Topographic Maps

The first topographic map in Switzerland was the Dufour map, which was produced in the period between 1844 and 1864. The scale of this greyscale map is 1:100'000 and the accuracy is not known, but surely not very high. E.g. Dufour “unterlässt überhaupt jegliche Angabe von Genauigkeitsgrenzen...Wegen der Verschiedenheit der Genauigkeit der einzelnen kantonalen und regionalen Triangulationen,..., scheint dies Dufour nicht ratsam zu sein [9].”

In 1870, the Dufour map was replaced by the Siegfried map, which has a scale of 1:50'000 [4]. Since 1938 (scale 1:50'000) and 1952 (scale 1:25'000), the swisstopo product “Swiss National Maps (Landeskarte der Schweiz)” are existing and represented by a homogeneous appearance since the first maps.

Swiss National Maps of the study area (Rhône glacier) are available since 1948 (scale 1:50'000) and 1965 (scale 1:25'000) [4]. This region is shown on the map sheets 1230 (Guttannen) and 1231 (Urseren) (Figure E.1, Appendix E-1). The update-period is every six years, but it is important to be aware of the state of the updates. First of all, the date of publishing is not the same as the date of the updates. Furthermore, not the whole content of the map is updated (even though it should be, corresponding to the data specifications). Mainly, the surroundings of the glacier were changed, the glacier tongue or the glacier height lines have not changed at all from one published map to the next one. It has to be kept in mind, that the glacier states of a certain pixel map could be determined several years before and is thus not up-to-date.

For the glacier itself, some maps at the scale of 1:5'000 were generated out of terrestrial surveying techniques. The topographic map of 1874 is based on “measuring table” surveying technique with an approximate accuracy of 1.5 m. A few years later, some errors were found and the surveying results of 1874 were recalculated and redrawn in the year 1883. This increased the accuracy to approximately 5 cm [10]. Later, the maps were derived from stereo photogrammetric measurements. Information about updates and available years of topographic maps of the Rhône glacier region is shown in Table 3.3 and attached in the Appendix E.

Map sheet nr.	1230	1231	255
Map sheet	Guttannen	Urseren	Sustenpass
Scale	1:25'000	1:25'000	1:50'000
Published	2009	2009	2009
	2002	2002	2003
	1995/93	1995/93	1996/93
	1988/86	1988/86	1989/86
	1980	1980	1982/80
	1977	1975	1976
	1973	1965	1969
			1965
			1960
			1948

Table 3.3.: Composition of available topographic maps of the Rhône glacier region

### Selection of topographic maps of interest

The maps of the years 1929, 1874 are selected, because topographic maps are needed from the same time period as the DEMs (Chapter 2.4.2 and 3.2.1). Furthermore, no orthophotos are available for this time period (Chapter 3.2.2).

The map content of 1929 was not published until the years 1946/47. The surveying was done indeed in the year 1929, but because of the world war 2, this map was first published after the war. This map is scanned, geo-referenced and thus digitally available in the scale of 1:50'000.

The map of 1874 is available as a printed map, but has to be digitized and geo-referenced first. As an advantage the map does already have a coordinate grid which is similar to the current coordinate grid in Switzerland (CH 1903). As a disadvantage the units of this coordinate grid are different. The map still has civil coordinates with their origin in Bern and therefore positive and negative values are allowed. The current Swiss coordinate system (CH1903) is based on the military coordinate system which has its origin in France and therefore allows only positive values in Switzerland. Because the raster is identic, there are just two translations needed:

$$Y(\text{military}, CH1903) = Y(\text{civil}) + 600'000 \text{ m}$$

$$X(\text{military}, CH1903) = X(\text{civil}) + 200'000 \text{ m}$$

The georeferencing is done with the georeferencing toolbar in ArcMap by the use of eleven control points which lie at the intersections of the coordinate grid lines.

According to the lack of the DEM 1874 and the DEM 1929 (Chapter 3.2.1, Selection of DEMs of Interest), these topographic maps are not necessary anymore for the evaluation process. However, they will be used for the web map application due to visualize former topographic states.

#### 3.2.4. Terrestrial Pictures

The most important data for the applied method, are terrestrial pictures of the Rhone glacier region. These pictures have to achieve the following requirements (according to the planned methodology, Chapter 2.4.2):

- high spatial resolution and contrast
- suitable to set at minimum 5 control points; surroundings of the glacier have to be visible to allow to find some stable points for setting the control points
- their capture angle has to be nearly orthogonal to the scene
- the whole area of interest, should be seen
- same season of capture, to make a comparison between the years easier
- the date of capture (year) has to be known



Pictures of the Rhone glacier region can be found at different data sources:

- picture archive of the ETH
- electronic picture archive of the ETH
- picture archive of the “Versuchsanstalt für Wasserbau und Glaziologie” (VAW, Andreas Bauder) at the ETH
- swisstopo archive in Bern
- Internet

In the picture archive of the ETH, all pictures of the Rhone glacier region are digitized and available at the electronic picture archive. In this electronic archive there are more than 900 pictures available. Therefore they have to be sorted by the mentioned criteria. Table 3.4 illustrates the images which are available and useful for the purpose of georeferencing.

On the Internet a lot of data is available. The problem with data on Internet is, that for the most pictures, the capture year is not known. Furthermore, it is important to pay attention to copyrights.

### **Selection of terrestrial pictures of interest**

For comparison reasons, the pictures of the years 1874, 1929, and 2009 are chosen, because they were captured the year for which a DEM is available (Chapter 3.2.1). To estimate the positions of the glacier tongue every 20 years, more pictures are chosen according to the mentioned criteria. The chosen pictures are captured in the years 1849, 1874, 1885, 1889, 1898 (2), 1919, 1929, 1930 (2), 1940, 1875, 1951, and 1956. This should allow a posterior comparison with pictures of the same year, but which are captured from different viewing angles.

### **3.2.5. Reference Data**

For further processing steps, it is important to have reference data of the study area to compare with (for example, already existing glacier tongue states). Data of various positions of the glacier tongue for several years are collected at the “VAW” (Andreas Bauder) at ETH Zurich. This data is extracted from stereo photogrammetric image processing and is available digitally and more or less annually. The earliest state of the Rhone glacier tongue is available from the year 1874, but the data from 1874 until 1923 is not available digitally and has a local coordinate system.

The accuracy comparison will be done for the years 1874, 1929 and 2009, based on the selected DEMs, orthophotos or topographic map and the pictures (Chapters 3.2.1, 3.2.2 and 3.2.4). Therefore, the reference data is chosen for the same years. The reference tongue of the year 1874 is digitized in ArcMap directly from the topographic map of the year 1874. Thus, this glacier tongue state is geo-referenced.

Data sources			Data sources		
Year	ETH (e-pics)	VAW ETH	Year	ETH (e-pics)	VAW ETH
2011		1	1960		1
2010		1	1958		1
2009		1	1956	1	
2008		1	1951	1	
2007		1	1950	1	
2005		1	1947	1	
2004		1	1946	1	
2001		1	1941		1
2000		1	1940	1	
1995		1	1938		1
1993		1	1934	1	
1990		1	1931	1	
1989		1	1930	4	
1987		1	1929	1	
1986		2	1928	1	
1984		1	1927	1	
1983		1	1925	1	
1981		1	1921	3	
1979		1	1919	1	
1976		1	1908	1	
1975		1	1905	1	
1974		1	1903	1	
1973		1	1901	1	
1971		1	1900	1	
1970		1	1898	1	
1968		1	1896	1	
1967	1		1895	1	
1966		1	1892	1	
1965		1	1889	1	
1964		1	1885	1	
1963		1	1875	1	
1962		1	1874	1	
1961		1	1849	1	

Table 3.4.: Available years and sources of suitable pictures of the Rhone glacier region

### 3.3. Overview of the Selected Data

For the evaluation on the basis of the WSL Monoplotting Tool, the following data are chosen. These datasets are chosen with regard to the requirements, which are described in Chapter 2.4.2 and 2.5.2.

Year	DEM	Orthophoto	Topographic Map	Picture
2010	DEM 2010	CIR and HDR Images 2010	-	2009
1929	DEM 1929 or DHM25	-	Swiss Topographic Map 1968	1929
1874	DEM 1874 or DHM25	-	glacier map 1874	1874

Table 3.5.: Overview over the selected datasets for the evaluation process. There are only three years existing, from 1874 until 2011, where an image, a DEM and a map is available for the same year. Accordingly, the data of the years 1874, 1929 and 2009 are chosen.

All the data, which is used in this research is available on the enclosed DVD (Appendix K).

Copyright and source of the geodata, used in the present Master thesis: Reproduced with permission of swisstopo (JA100120). Federal Office of Topography swisstopo (Art. 30 GeoIV): 5704 000 000

## 4. Accuracy Analysis of the Georeferencing, Based on the WSL Monoplotting Tool

As a first step, it is important to estimate how accurate the georeferencing on the basis of the WSL Monoplotting Tool can be. This can be used later (Chapter 4.2) in order to assess correctly the results of the georeferencing of the images. Furthermore, it is useful for the choice of the right underlying data (e.g. DEM) to achieve the most accurate and realistic results in the georeferencing process.

### 4.1. Absolute Accuracy Estimation of Digital Elevation Models

To estimate the accuracy of the georeferencing on the basis of the WSL Monoplotting Tool (Chapter 4.2), it is required to know the accuracies of the used data. Therefore, it is also important to know, which data comes from which data source and how they are influenced by different factors during the data processing step. Relations between different data sources are shown in Appendix C-1. For example, orthophotos are calculated based on Digital Elevation Models. Thereby, the original image is straightened on the basis of the Digital Elevation Model. Due to their origin, the orthophotos are influenced by the accuracies of the DEM and the original image resolution. Therefore, it is necessary to estimate the accuracies of the DEMs, which are used in this research.

Mostly, the accuracies of the DEMs are given from the data owner. However, this declaration is often generalized over a huge region (e.g. for the Alps) and needs to be specified with other methods. When the accuracy is not known, the accuracies of the DEMs used in this research (DEM 2010 and DHM25) will be estimated manually. The estimation is only done for the height component and should only give a rough knowledge about the accuracy in the dimension of decimeters.

This estimation is done in the software ESRI ArcMap 10.0. Based on known three dimensional coordinates of 19 Ground Control Points (GPS coordinates from a ETH field campaign in 2005 [11], Appendix F-1), the height component of these GCPs can be measured in ArcMap based on the known X and Y coordinate. Afterwards, the differences in the height component of the measured height (in ArcMap) and the known height (GCP) can be calculated as well as its statistics. In this approach, it is assumed that the X and Y coordinates are stable. However, it would be more accurate, to estimate the height component based on a visual GCP measurement in the orthophoto. This is not possible, because the GCPs are not visible in the available orthophotos, although they have a high resolution.

Statistics	DEM 2010 [m]	DHM25 [m]
Mean	-0.81	-4.80
1 Sigma	1.07	6.02
Maximum (at Point no.)	-4.61 (1030)	-19.66 (1030)
Range	6.1	21.40

Table 4.1.: Accuracy values of the height component of the DEM 2010 and DHM25, calculated based on 19 GCP coordinates of the Rhone glacier (Appendix F-1)

The overall results are shown in Table 4.1. It can be seen, that the DEM 2010 has a standard deviation of 1 m and is six-times more accurate than the DEM 25, which has a standard deviation of 6 m. There are, as well, some outliers detectable.

To allow conclusions about the spatial characteristics of the DEM, e.g. like in which regions the DEM is more or less accurate, the GCPs are subdivided in different regions. This allows to recognize differences in the accuracies within one DEM. The results are shown in Table 4.2 and illustrated in Figure 4.1. Results of the DEM 25 are shown in appendix G.

Regions	1	2	3	4	5	6
Mean DEM 25 [m]	-3.19	-3.20	-2.58	-4.66	-8.90	-6.20
Mean DEM 2010 [m]	-0.13	-0.83	-0.41	-0.59	-2.26	-0.58
1 Sigma DEM 25 [m]	6.73	2.15		4.02	7.72	6.57
1 Sigma DEM 2010 [m]	0.90	0.20		0.31	1.67	0.37

Table 4.2.: Accuracy values of the height component of the DEM 2010 and DHM25, split in 6 regions. This enables the observer to make conclusion about the regional characteristics of the DEM.

In Figure 4.1 and Table 4.2, it can be seen that the differences in the standard deviations between the regions are not very high. The range is about 1.5 m for the DEM 2010 and 5.6 m for the DHM25. It is interesting that differences in accuracies within the regions occur from the DHM25 to the DEM 2009. For example, region 7 is compared to the other regions more accurate in the DEM 2010 than in the DHM25. This region has a high slope value and thus the accuracy of the DEM is strongly dependent to the resolution. In both DEMs region 2 is the most accurate and region 6 is the least accurate region. Region 6 is the least accurate region, because of the outlier control point (1030). Furthermore, it can be noted, that the regions 5 and 2 are almost similar. This makes sense, because they represent almost the same conditions (e.g. slope).

Generally, one has to keep in mind that there are not many GCPs available within certain regions. Therefore, the results are not controlled and the conclusion is generalized for the extent of a region (e.g. region 7 which contains the area of the glacier tongue).

### Photogrammetric Passpoints of the Rhoneglacier tongue

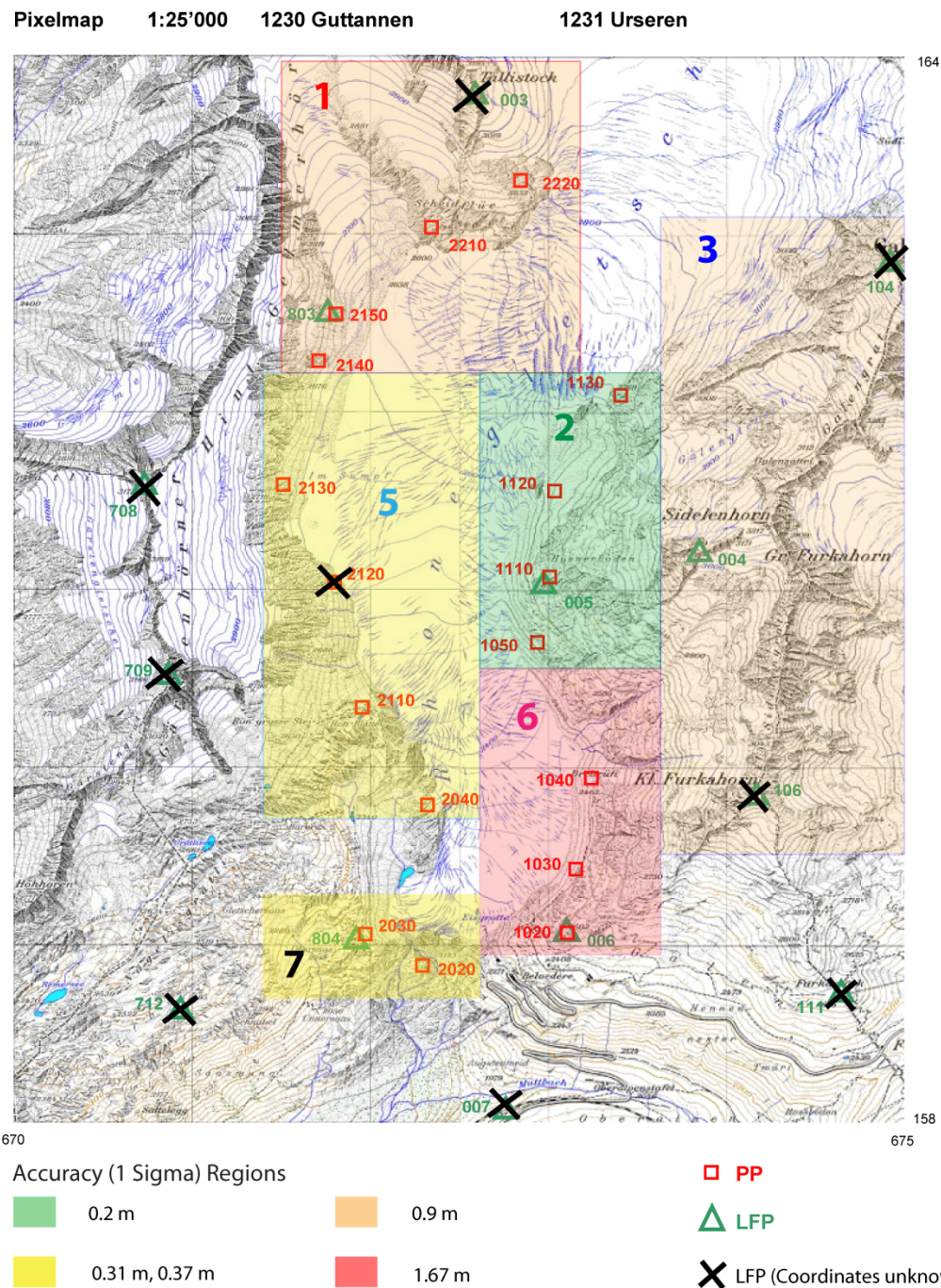


Figure 4.1.: Pixelmap 1:25'000 shows the DEM 2010, which is split in regions of similar accuracy values of the height component. This enables the observer to make conclusion about the regional characteristics of the DEM.

## 4.2. Relative and Absolute Accuracy Estimation of Reconstructed Glacier Tongues

The goal of the relative accuracy estimation is to evaluate which data matters most for achieving the most accurate results (Chapter 2.4.2). Depending on the acquisition year of the DEM and its accuracy, the results concerning the accuracy of the georeferencing can vary. Thus, the accuracy of the reconstructed glacier tongues can vary significantly. Therefore, it has to be established whether the use of the DEM of the same year as the terrestrial image or the use of the most accurate DEM leads to the best absolute accuracy (Chapter 2.4.2). The DEM with the highest resolution and highest accuracy is the current DEM 2010 with an standard deviation of 1 m (Chapter 4.1).

This accuracy evaluation is done for the years 1874 and 1929. The DEM, which represents the closest topography state to the terrestrial images of 1874 and 1929, is the DHM25 (Chapter 3.2.1, page 17).

Table 4.3 shows, which data is used for the relative accuracy evaluation. This approach is chosen, because of the data availability (Chapter 3.3).

Year	DEM	Orthophoto	Picture
2009	DEM 2010	Images 2010 (CIR,HDR)	2009
1929	DEM 2010	Images 2010 (CIR,HDR)	1929
	DHM25	Images 2010 (CIR,HDR)	1929
1874	DEM 2010	Images 2010 (CIR,HDR)	1874
	DHM25	Images 2010 (CIR,HDR)	1874

Table 4.3.: Approach of the relative accuracy estimation, based on the data availability (Chapter 3.3). This shows the data combinations, which will be used in this approach.

Besides the relative accuracy estimation, the absolute accuracy is also estimated (Chapter 2.4.2). Its goal is to evaluate the possibility of achieving accurate absolute results with the georeferencing process based on the WSL Monoplotting Tool. Thus, a comparison of the reconstructed glacier tongues with already known positions of glacier tongues (reference data, Chapter 3.2.5) will be done for the years 1874, 1929 and 2009.

#### 4.2.1. Accuracy Evaluation of the Reconstructed Glacier Tongue in 2009

##### Relative Accuracy Estimation - Comparison Between the Use of Different DEMs as Basis Datasets

The evaluation for the year 2009 is made for reference reasons to evaluate how accurate the results can be with the use of the newest data. Because it is made with the newest data (DEM 2009 and orthophoto 2009), it can be assumed that the data has a high accuracy and therefore should give highly accurate results. In addition, the data are congruent, so the used DEM, orthophoto and terrestrial image are available for the same time period. This means that the topography is almost the same and thus the influence on the accuracy is minimized.

Because the DEM 2009 has some distortions, a rough comparison between the results of the DEM 2009 with the DEM 2010, which looks more stable and accurate, is made. For the year 2009, no difference could be seen due to the used DEM (Figure 4.2, the two lines “Tongue\_2009\_DOM2009” and “Tongue\_2009\_DOM2010” are exactly overlapping). This is because the glacier tongue is located in a low slope region where the DEM 2009 shows as well good results. But it can be assumed, that the use of the DEM 2010 gives better results for steep areas than the use of the DEM 2009. Therefore, the evaluation will be done with the use of the DEM 2010 to be consistent over the whole evaluation process. Accordingly, the temporal resolution between the terrestrial image (2009), the DEM (2010) and the orthophoto (2010) is worse than with the use of a DEM and an orthophoto of the year 2010. However, there is still a high congruence of the data and thus the results should be representable.

##### Absolute Accuracy Estimation - Comparison with Known Glacier Tongue Positions

Table 4.4 and Figure 4.2 show the absolute accuracy evaluation of the year 2009. In the Figure 4.2, the dark green line shows the reference data. The light green line indicates the digitized glacier tongue based on the DEM 2010, whereas the olive green line illustrates the digitized glacier tongue based on the DHM 2009. There is no difference between the light green and the olive green line.

In average, the digitized glacier tongue has an accuracy of about 6 meters (Table 4.4). According to the accuracy of the DEM 2010 (ca. 0.6 m) and the camera calibration (5.4 m), this is a satisfactory result. However, there are some regions (A and B in Figure 4.2) with a worse congruence and an accuracy of about 34 m. The reason is that these regions are hidden behind some barriers (Chapter 2.5.2, “hidden areas”). At region A, the lightbeam is interrupted by stones and, therefore, the ice border is not visible from this viewing angle. This causes a displacement of the digitized glacier tongue. At region B, the border of the ice is hidden behind the horizon of the glacier. This is caused by the low viewing angle. Nevertheless, there are some regions with an absolute accuracy of 10 m (region C etc.) and some with an accuracy of about 1 m (region D etc.).



Camera Calibration Errors		Absolute Accuracy of Tongue Positions [m]			
2D RMSE [m]	Pixel RMS [px]	Mean	Maximum	Minimum	Range
5.4	6	6	34	1	33

Table 4.4.: Results of the camera calibration and results of the absolute accuracy estimation of 15 samples. The absolute accuracies are measured differences in the glacier tongue positions of the digitized glacier tongue of the year 2009 (geo-referenced by using the DEM 2010) and the reference glacier tongue of the year 2009.

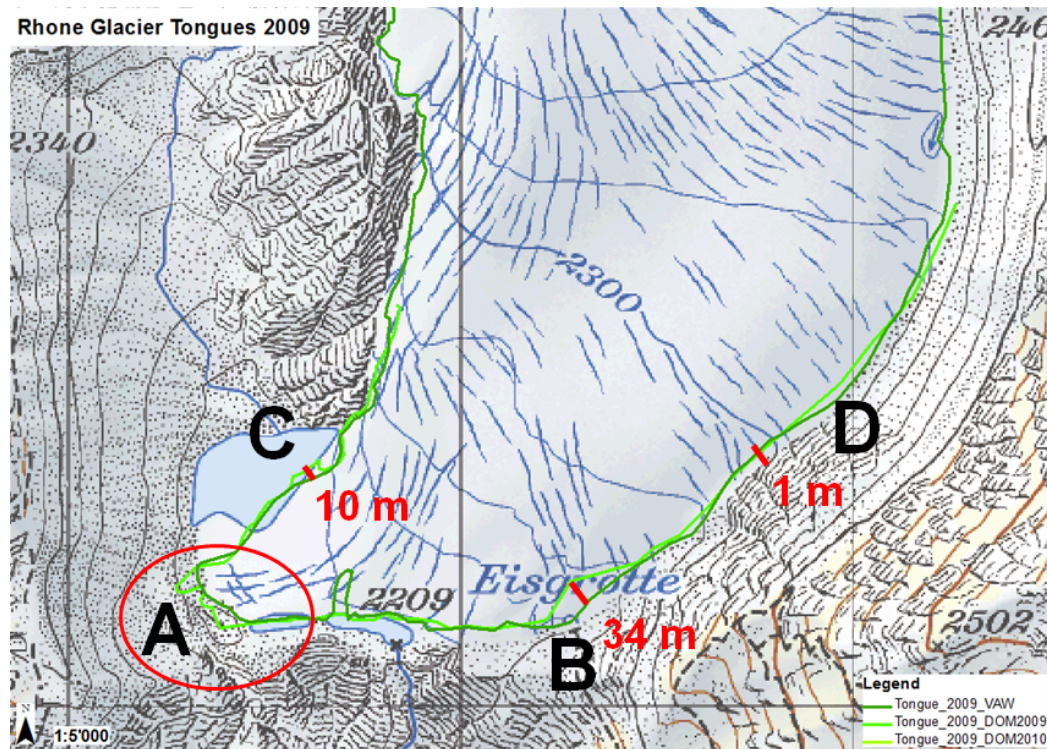


Figure 4.2.: Congruence of the resulted, digitized glacier tongues of the year 2009 (light green and olive green line) with the reference data (dark green line). This is illustrated on top of the Swiss National Map of 2007.

#### 4.2.2. Accuracy Evaluation of the Reconstructed Glacier Tongue in 1874

##### Relative Accuracy Estimation - Comparison Between the Use of Different DEMs as Basis Datasets

The accuracy evaluation of the reconstructed glacier tongue in the year 1874 is done based on the georeferencing of the terrestrial image of 1874 (Figure H.1, Appendix H-1). First, the georeferencing is done due to the use of the DEM 2010 and the orthophoto 2010. Second, the georeferencing is done using the DHM25. Therefore, the image of 1874 is geo-referenced in two different ways. Thus every pixel of the image gets two different world coordinates once the georeferencing is finished. This affects the world coordinates of the digitized glacier

tongue. Therefore, the digitized glacier tongue based on the DEM 2010 and the one based on the DHM25, are different.

Figure 4.3 illustrates the differences in the results. The dark blue line shows the reference data (glacier tongue state of the topographic map of 1874). The light blue line indicates the resulting, digitized glacier tongue of the year 1874 based on the georeferencing from the DHM25. The green line indicates the same glacier tongue, but based on the georeferencing from the DEM 2010. It can be seen that the lines are mostly identical with a 2 meters range. Differences occur in regions with a high slope value, e.g. region C and D in Figure 4.3. These differences are about 8 meters. Significant differences are recognizable in region B. They are about 100 meters and might be caused by the exposure angle of the light beam. The exposure angle is very flat for region B (flat angle problem, Figure 2.5). On the other hand, the slope value in this region is high, which can cause some inaccuracies in the DHM25, due to the fact that certain regions are hidden behind the DEM ("hidden areas", Chapter 2.5.2).

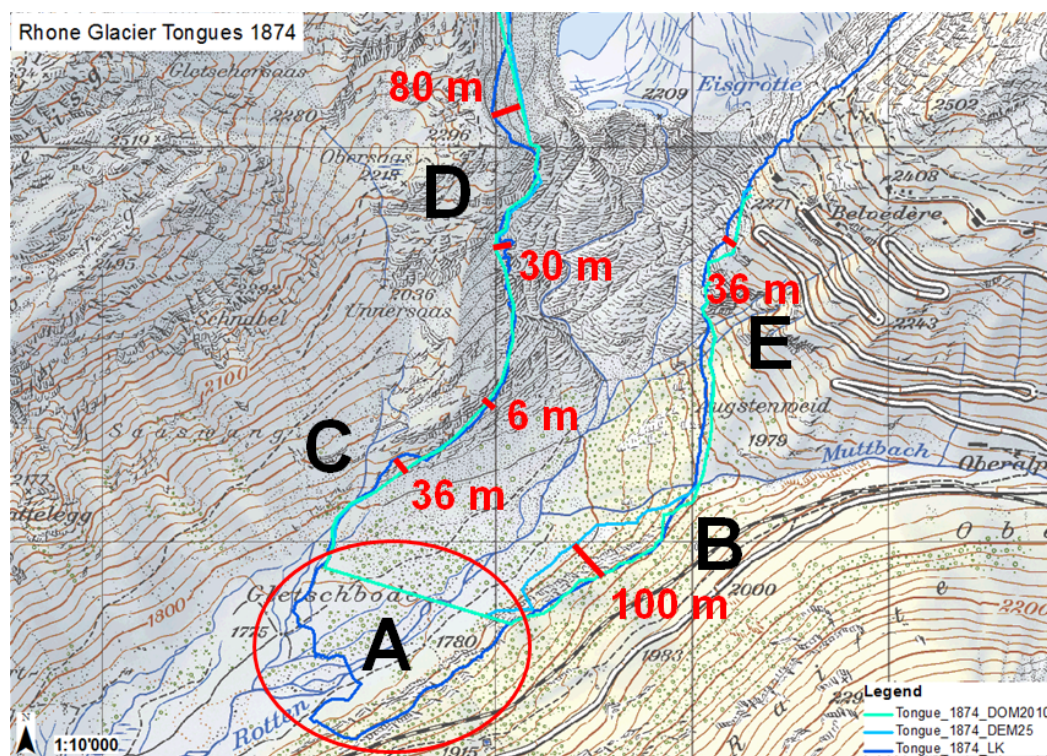


Figure 4.3.: Congruence of the resulted, digitized glacier tongues of the year 1874 (light blue and green line) with the reference data (dark blue line). This is illustrated on top of the Swiss National Map of 2007.

### Absolute Accuracy Estimation - Comparison with Known Glacier Tongue Positions

A visual comparison between the absolute glacier tongue positions and the known tongue positions (reference data, Chapter 3.2.5) is made. It shows that the georeferencing using the DEM 2010 fits better to the reference data. It also has the most accurate results, which leads to think that it is important to use a DEM with a high resolution and accuracy. The following exact numerical comparison will be done with the glacier tongue polyline, which is generated by the use of the DEM 2010. Differences between the reference glacier tongue and the digitized glacier tongue using the DEM 2010 are measured in ESRI ArcMap. This is done on the basis of 15 samples.

Unfortunately the picture does not cover region A in Figure 4.3 and thus there is a lack of information for this region.

The results of the estimation of the camera calibration are illustrated in Table 4.5. The measured differences of the samples are varying within a range of 30 meters and a camera calibration with an accuracy of nearly one pixel and one meter was achieved. These problems occur mostly in regions which are not nearby a control point or which have high slope values. This provides distortions in the georeferencing of the images in those regions. Figure 4.3 shows a difference in region C. This difference is about 35 meters and could be caused by the angle of view of the picture. The border of the glacier is hidden behind the horizon of the glacier ice, because of the viewing angle and the viewpoint, from where the image was taken. As a further point of uncertainty, the date of the picture capturing is not known very well, so that there could be some weeks or months in between the capture of the picture and the measurement of the reference data (Chapter 3.2.5). Because the glacier is highly dynamic, this time interval between the compared data (glacier tongue position from the image and from the reference data) can cause small differences (meters) as well.

It exists also a difference of about 80 meters in region D. This might be caused by the uncertainty of identifying the glacier tongue in a region of existing debris. Thus, the glacier state of 1874, digitized from the topographic map of 1874 can have inaccuracies.

Camera Calibration Errors		Absolute Accuracy of Tongue Positions [m]			
2D RMSE [m]	Pixel RMS [px]	Mean	Maximum	Minimum	Range
1.2	1.2	10	36	3	33

Table 4.5.: Results of the camera calibration and results of the absolute accuracy estimation of 15 samples. The absolute accuracies are measured differences in the glacier tongue positions of the digitized glacier tongue of the year 1874 (geo-referenced by using the DEM 2010) and the reference glacier tongue of the year 1874.

As a conclusion, the results are about 12 meters accurate, which is a satisfactory result. Especially, when one considers that the control points had to be set using the image of the year 1874 and the orthophoto of the year 2010. There was a huge difference in time, which caused changes in the vegetation. This fact made it difficult to find reference points in the corresponding images.

### 4.2.3. Accuracy Evaluation of the Reconstructed Glacier Tongue in 1929

#### Relative Accuracy Estimation - Comparison Between the Use of Different DEMs as Basis Datasets

The accuracy evaluation of the reconstructed glacier tongue in the year 1929 is done based on the georeferencing of the terrestrial image of 1929 (Figure H.4, Appendix H-1). First, the georeferencing is done due to the use of the DEM 2010 and the orthophoto 2010. Second, the georeferencing is done using the DHM25. Therefore, the image of 1929 is geo-referenced in two different ways. Thus every pixel of the image gets two different world coordinates once the georeferencing is finished. This affects the world coordinates of the digitized glacier tongue. Therefore, the digitized glacier tongue based on the DEM 2010 and the one based on the DHM25, are different (analog to Chapter 4.2.2). In order to control the results of the accuracy evaluation of the year 1874 independently, the evaluation of the image of 1929 is done additionally. This serves as a single control of the results.

Figure 4.4 shows the differences in the results. The red line shows the reference data (glacier tongue state of the terrestrial surveying campaign in the year 1929, data source “VAW ETHZ”). The yellow line indicates the digitized glacier tongue based on the DEM 2010, whereas the orange line illustrates the digitized glacier tongue based on the DHM25. The differences between the glacier tongues are located in region A and B (Figure 4.4), as well as in region C and D, but especially in region A. They vary from 2 to 35 meters. Problems occur in same regions as for the year 1874 and might be caused by the same factors as mentioned in Chapter 4.2.2. For example, because of a high slope value or the setting of control points which are too far away from the glacier tongue.

#### Absolute Accuracy Estimation - Comparison with Known Glacier Tongue Positions

All in all, the differences are not significant and it is difficult to estimate, which DEM gives better absolute results. Due to a visual comparison, the use of the DEM 2010 (yellow line) seems to reach more accurate results, corresponding to the reference tongue position (red line, reference data 3.2.5, data source “VAW ETHZ”). Therefore, the following exact numerical comparison will be done with the glacier tongue polyline, generated using the DEM 2010.

The results of the absolute accuracy of the digitized glacier tongue and the camera calibration of the year 1929 are illustrated in Table 4.6 and Figure 4.4. There exist some differences of the digitized glacier tongue according to the reference data, especially in region A (Figure 4.4). These differences vary from 15 to 40 meters. Due to a visual comparison between the reference data and the data of the Swiss National Map of the year 1968 (Figure 4.4), differences are showed as well. Regional distinctions can be caused by different dates of the data sources, although they are collected in the same year. This is due to the high dynamics of glaciers. Compared to the data of the Swiss National Map, the left part of the glacier tongue (region A, C, and D) has a 4 meter accuracy, on average. The right part of the glacier tongue (region B and E) seems to be less accurate, about 12 m in average with some outliers. This might be caused by less control points near the glacier tongue in region E, or some barriers (e.g. rocks, glacier ice). Barriers make it difficult to see the border line of the glacier tongue, what means that they are hidden behind the ice horizon (Chapter 2.5.2, “hidden areas”).



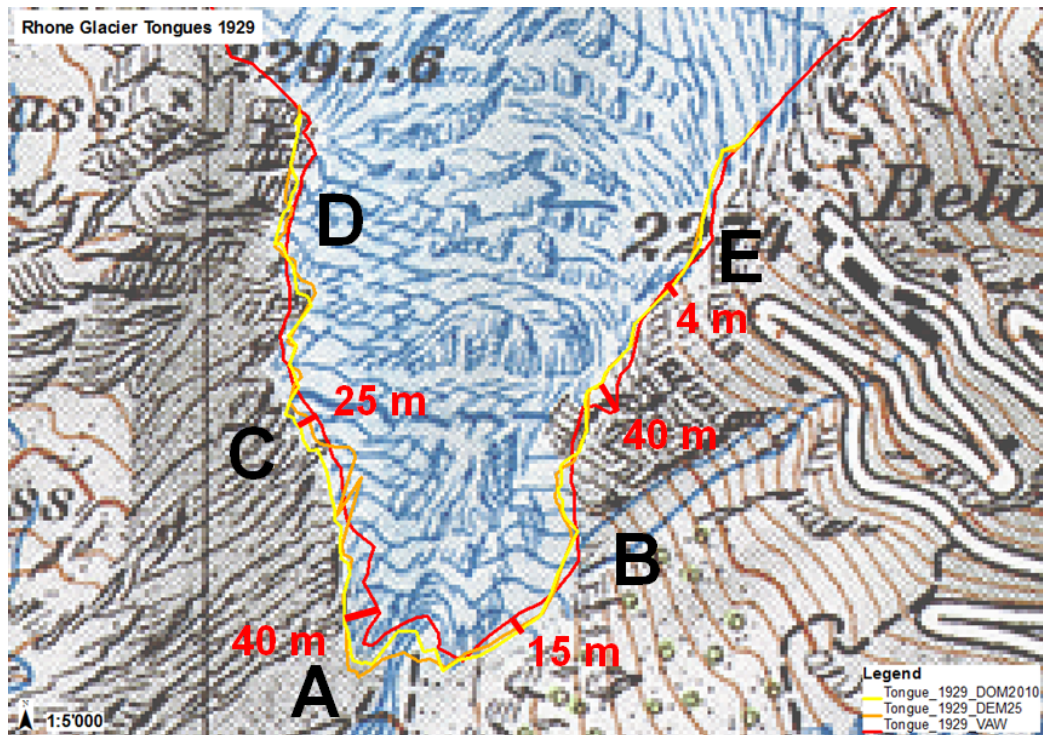


Figure 4.4.: Congruence of the resulted, digitized glacier tongues of the year 1929 (yellow and orange line) with the reference data (red line). This is illustrated on top of the Swiss National Map of 1986 (map content of the year 1929, Chapter 3.2.3, Selection of topographic maps).

Compared to	Camera Calibration Errors		Absolute Accuracy of Tongue Positions [m]			
	2D RMSE [m]	Pixel RMSE [px]	Mean	Maximum	Minimum	Range
VAW data	2	4	18	40	4	36
National Map	2	4	8	40	4	36

Table 4.6.: Results of the camera calibration and results of the absolute accuracy estimation of 15 samples. The absolute accuracies are measured differences in the glacier tongue positions of the digitized glacier tongue of the year 1929 (geo-referenced by using the DEM 2010) and the reference glacier tongues of the year 1929 (once from “VAW” and once from the topographic map).

### 4.3. Selection of the Best Method

The best method could not be evaluated as planned, because the data was missing, such as the DEMs from the years 1874 and 1929 (Chapter 3.2.1). Because of the distortions in the DEM 2009, this DEM was not selected either (Chapter 3.2.1). Therefore, only the DEM 2010 as well as the DHM25 could be used. The DHM25 shows less accurate results, especially in steep areas, than the newer DEM 2010. A rough analysis with the use of the DEM 2009 instead the DEM 2010 was done as well. The results get more accurate with the use of the DEM 2010 than the DEM 2009, even though it is not from the same year as the image (e.g. image 2009). This means that the overall accuracy of the DEM and its distortions affect the accuracy of the further camera calibration significantly. This is the reason why the DEM 2010 and the orthophoto of 2010 are used for further processing steps. Furthermore, it is more important to have a good distribution of the control points around the glacier tongue than to have the perfect camera calibration (Table 6.1). It can be that the overall camera calibration result is very accurate, but there are distortions near the glacier tongue, which are caused by a bad distribution of control points. In addition, it is very important, to have images, where the light beam of the camera has a good angle to the image, e.g. not too flat (Figure 2.5).

### 4.4. Georeferencing and Digitizing the Positions of the Glacier Tongues, Based on the Accuracy Analysis

The geo-referencing of the postcards and the following digitization is done in the software WSL Monoplotting Tool (Chapter 2.5.1, on page 10), on the basis of minimal five control points. This procedure is done for the years 1874, 1898, 1919, 1929, 1951 and 2009. The evaluation of the year 2009 will be described as an evaluation example in the following section. The other images are evaluated the same way and are not described in this report.

#### 4.4.1. Georeferencing of the Terrestrial Image of 2009

To obtain a good camera calibration, it is important to set control points which are well scattered around the image (Chapter 2.5.2, page 14). Especially around the features which need to be digitized afterwards. Therefore, the control points are set around the glacier tongue on stable features like rocks, buildings, or streets. Figure 4.5 shows that it is not easy to set control points in an adequate distribution around the image and especially around the glacier tongue. There are many regions which are not stable, e.g. boulder areas, ice or vegetation areas. In these regions, control points cannot be set. Therefore it is important to find rocks in surrounding areas, which are well recognizable in both images, the postcard and the orthophoto. This is mostly the hardest issue to deal with. This is for example, because there exist well recognizable rocks in the postcard, but it is very difficult to identify the same rocks in the corresponding orthophoto. This can be, because the area has changed in the time between the capture of the postcard and the orthophoto image flight. Or, the reason is that there is not a lot of the surroundings shown in the picture. Therefore, it is difficult to recognize the same surroundings of the rocks in the orthophoto.

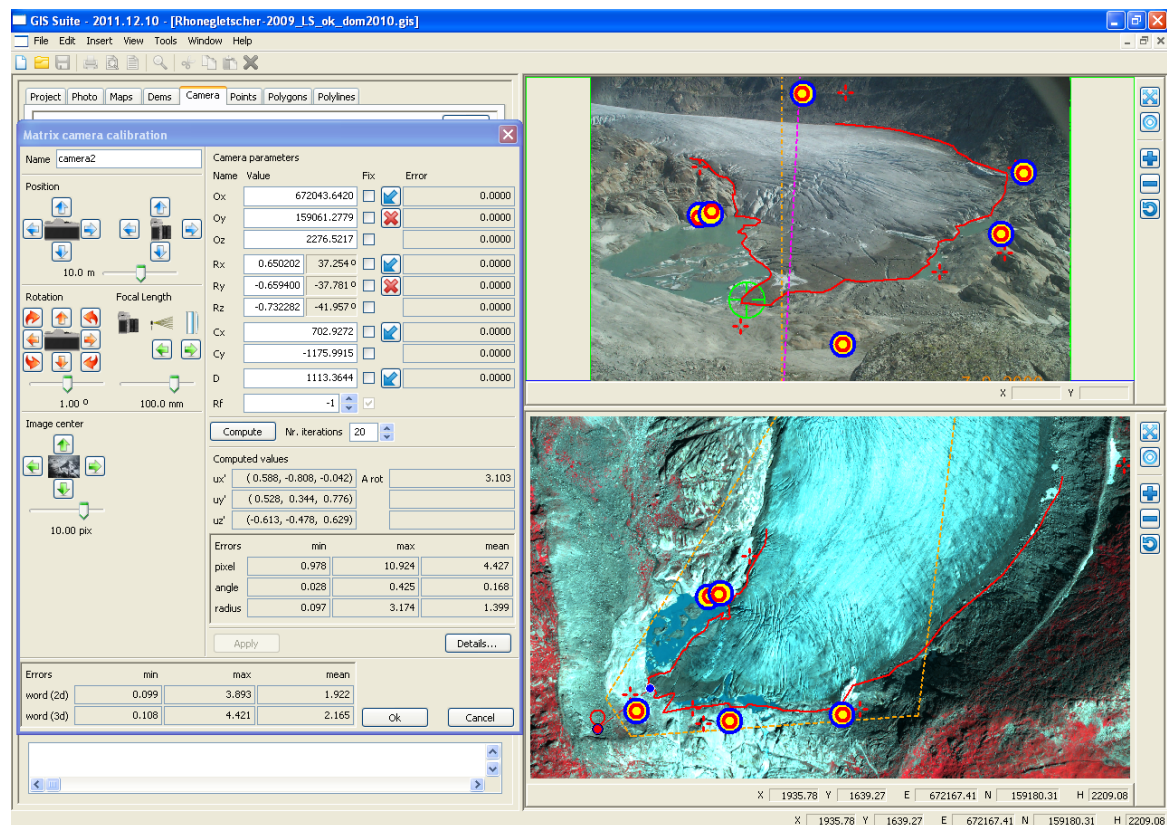


Figure 4.5.: This screenshot of the WSL Monoplotting Tool shows the accurate results of the camera calibration while georeferencing the image of the year 2009.

After the setting of minimally five control points, the camera is calibrated iteratively and the image is geo-referenced (Chapter 2.5.1, page 10). As a result of the camera calibration, the root mean square error is shown in the software WSL Monoplotting Tool for the image and the world coordinates (Chapter 2.5.1, page 12). Visually, this error is shown in the corresponding postcard and the orthophoto. There, the control points, which are set manually are shown as red circles. The computed, corresponding control points are drawn in blue circles (Chapter 2.5.1). The difference between them reflects the error of the camera calibration in image and world coordinates. Mostly, the regions around the control points are well geo-referenced and the accuracy of the georeferencing minimizes with an increasing distance to the control points.

After the camera calibration, every pixel gets a corresponding world coordinate (Chapter 2.5.1, page 10). Therefore, it is possible to digitize the features of interest in the postcard. The feature of interest in the present Master thesis, is the glacier tongue.

Afterwards, this feature is exported as a textfile in image and world coordinates. Therefore, the glacier tongue can be used for further processing steps, for instance in a GIS (e.g. ArcMap) or visualization software (e.g. Adobe Illustrator).



#### 4.4.2. Georeferencing of the Terrestrial Image of 1898

Problems occurred in images which are not adequate for geo-referencing, e.g. the image of the year 1898 (Figure 4.6).

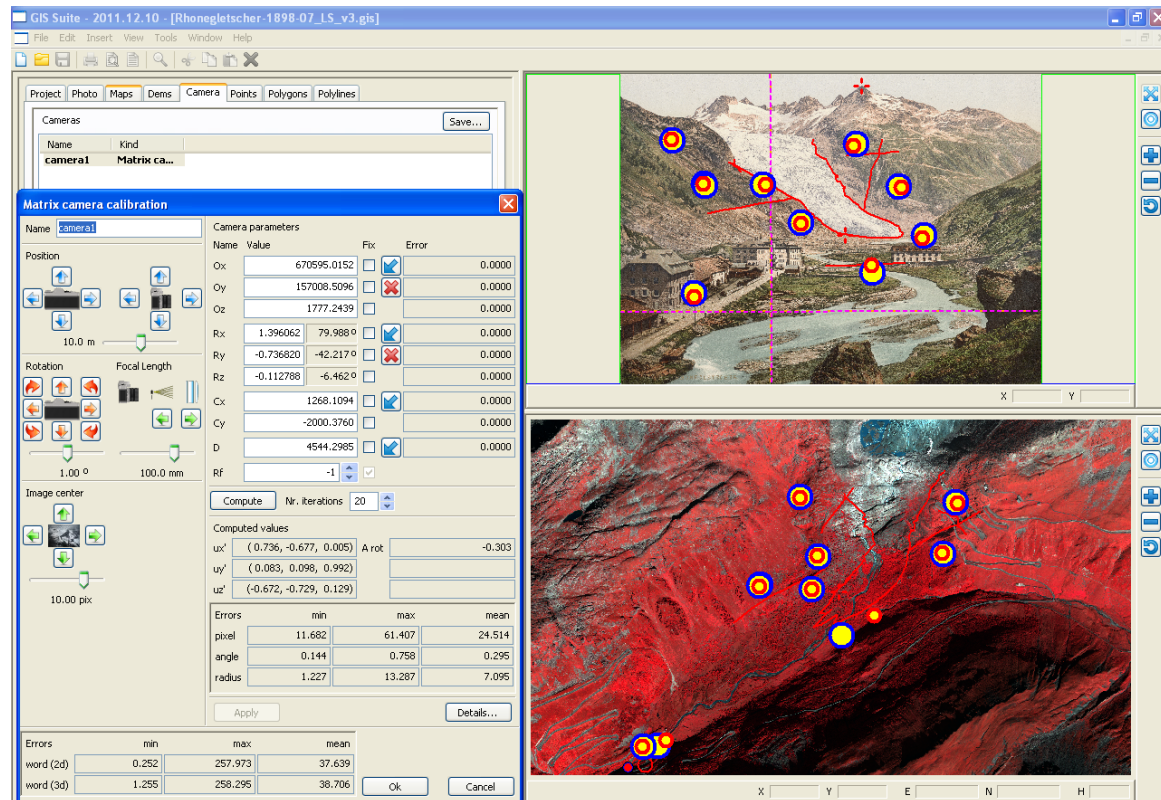


Figure 4.6.: This screenshot of the WSL Monoplotting Tool shows the inaccurate results of the camera calibration while georeferencing the image of the year 1898.

There are many possibilities to set control points in the image of the year 1898 (Figure 4.6) in a good distribution around the image. The problem is, that it is very difficult to set control points in the low area of the glacier tongue. The capture angle arrives very flat to this area and therefore, a few pixel error can cause significant errors in world coordinates (Figure 2.5, page 15). As a further point, it is difficult to find control points in this area which were stable between the capture of the image (year 1898) and the orthophoto image flight (year 2010). In addition, the resolution of the region, which surrounds the glacier tongue, is not very high and thus, it is difficult to set control points as well. Finally, this picture is not used in this Master thesis, because it was not possible to georeference this image.



#### 4.4.3. Conclusions Concerning the Handling of the WSL Monoplotting Tool

This section only documents conclusions concerning the software WSL Monoplotting Tool, because this was the main software used for the evaluation process. Furthermore, the softwares Adobe Illustrator and Photoshop, and ESRI ArcGIS are already well known.

WSL Monoplotting Tool is a user friendly software, which allows the user to handle easy an evaluation process. In addition, the software allows to import and export a lot of different format types (.map, .png, .tif,...). Unfortunately, it is not possible to export digitized features directly as shapefiles or .svg files. Therefore, it is needed to transform the exported textfiles to a shapefile. In this thesis, this step was done with a python script, written by Samuel Wiesmann.

The software shows all important informations concerning the setting of control points, and it is possible to change or unset certain control points. In addition, it is very useful that the camera calibration is mainly computed automatically, and that it is possible to change all the camera parameters as well manually.

Problems occurred with a long loading time of the DEMs and Maps in WSL Monoplotting Tool, however this was mainly reasoned by a low capacity of the used computer.

## 5. Visualization of the Reconstructed Glacier Tongues

The reconstructed glacier tongues will be visualized as polylines in a printed map and in a web map application. Thereto, the data needs to be prepared firstly in order to get web compatible. Thus, this chapter describes the data preparation and the further design of the two products as well as the programming of the web map application.

### 5.1. Data Preparation of the Glacier Tongue Layer

The feature glacier tongues are exported as textfiles from the software WSL Monoplotting Tool and has to be converted to shapefiles in order to visualize them in the software ArcMap. This conversion is done with the help of a python script which is written by Samuel Wiesmann, ETH Zurich. The layers with the glacier tongues can later be exported as Adobe Illustrator layers (.ai) for the designing of the printed map and as svg-layers (.svg) for the implementation in the web map application. A disadvantage of this export procedure is, that the georeferencing gets lost.

This can be a problem for the web map application, if it should be geo-referenced. However, in the case of this Master thesis, the web map application will work with pixel coordinates and therefore, it does not need to be geo-referenced. Alternatively, the shapefiles could be converted to svg-layers with the tool “ogis2svg”. This tool is programed at the institute of cartography and geoinformation and is able to keep the georeferencing.

### 5.2. Design of the Printed Map

The language of the printed map is German and the map theme is “Rhonegletscher; Rückgang der Gletscherzunge seit dem Jahr 1874 bis zum Jahre 2009”.

The map is structured in a title section, a postcard image with different, overlaying states of glacier tongues, a map legend and a short description of the glacier tongue retreat. The map is designed in the format DIN A3, which allows to hang it up at the glacier site and to communicate the states of the glacier retreat to tourists. To emphasis, the glacier retreat, small pictures of the years 1919, 1929, 1951 and 2009 are shown as well. This helps the observer to imagine the glacier tongue retreat in its full dimensions (Figure 6.2, Chapter 6.2).

The printed map is drawn in the software “Adobe Illustrator CS3” and the states of the glacier tongues are taken out of the geo-referenced postcards in WSL Monoplotting Tool.

While designing the map, care was taken to structure the map in different map sections. These sections are visually placed in groups, which are arranged on hidden guide lines. In

addition, the offset on top of the map is smaller than the one at the bottom of the map. This is to set the map center to the optical center.

### 5.3. Design and Implementation of the Web Map Application

As a further product, an interactive web map application presents the data. The language of the web map is as well as the printed map German. The map theme is the same as in the printed map: “Rhongletscher - Rückzug der Gletscherzunge seit dem Jahre 1874”. In contrary to the printed map, the target group should be the general public. Therefore, the map will be put online. With the creation of this map, cartographic principles will be applied with respect to the user-friendliness [13].

A main part of the web map application, will be its interactivity. The interactivity allows the user to discover a lot of information without the disadvantage of an overloaded map content. Thereto, the following functions will be applied:

- on- and off-switches for layers
- display of information on a mouseover event
- highlighting of the glacier tongues and related legend on a mouseover event
- display of pictures on a mouseclick
- animation of the glacier tongue retreat
- navigation (zoom and pan)

The map is designed after the specifications, described in the map concept (Appendix A-1). The basis layers consist of a postcard of the year 1874, an orthophoto of the year 2007 and a selection of topographic maps (years 1874, 1929 and 2007). The thematic layer displays the glacier tongues as polylines of the years 1874, 1919, 1929, 1951 and 2009. According to cartographic rules, the thematic layers are displayed on top. The application is based on a svg-document, whereas the interactive functions are implemented in javascript (chapter 2.4.2).

#### 5.3.1. SVG Web Mapping

In a first step, the design of the whole map is created in Adobe Illustrator and exported as an svg-document. With the export, all layers from Illustrator are kept in groups in the svg-document. Therefore, the svg-document is well structured. This procedure has the advantage that it is easier and faster to draw a map in Adobe Illustrator instead of creating every single objects in svg. For the web display of pictures, their resolution is minimized and all pictures are embedded as web-compatible png-files.

Furthermore, the document is structured in an attribute definition section, a javascript section and in the main svg-document.

In the attribute definition section, self-chosen attributes are defined for different svg-objects (e.g. groups, circles, rectangles,...). These attributes can be addressed over their

namespace-url. Self-chosen attributes are for example, attributes, which describe the status of an object (e.g. attribute “zustand”). These attributes can thus be changed over javascript-functions.

In the javascript section, predefined javascript functions are embedded. These functions are written by the institute of cartography and geoinformation and allow the creation of predefined windows, selection lists and checkboxes and refer to other predefined javascript-files.

The svg-document is structured in three main sections. In the first section, all symbols and styles are defined. The second section holds the thematic layers (glacier tongues) in image and world coordinates (main map frame). Finally, the third section holds all layers for the GUI (reference map, legend information, title, and map source and imprint). The display of the elements follows the painters model.

The main map frame holds the map content, e.g. the postcard image and the overlaying glacier tongues. Two viewboxes are defined for the main map frame. This is caused by the use of different coordinate systems (chapter 2.5.1). First, for the case with the image coordinates of the postcard and the corresponding glacier tongues (layer “Tongues\_Pix”). Second, for the case with world coordinates of the orthophoto and the topographic maps and their corresponding glacier tongues (layer “Tongues\_World”). The use of different viewboxes allows the display of both coordinate systems in the same map frame.

### 5.3.2. Implementation of an Interactive Information Display

→ *Function* : *showInfo(evt), showDescription(evt)* at Tools.js-section “Mouseevents on Glacier Tongues”.

For the web map application, the interactive functions will be programmed with javascript. Therefore, attributes like “onmouseover” and “onmouseout” can be assigned to svg-elements or svg-groups. These attributes will be allocated to the glacier tongue groups “Tongues\_World” and “Tongues\_Pix”. The function “showInfo” with its event-variable (e.g. type “mouseover”) will be declared as an attribute value:

$$onmouseover = "showInfo(evt)"$$

This function is loaded over the script-element

$$< script\!link : href = "tools.js" type = "text/ecmascript" / >$$

in the beginning of the svg-document.

In the javascript function, the information text of the corresponding glacier tongue is stored in the variable “rueckgang” with the method “getAttributeNS”. In the next step follow different treatments depending on the event-type (mouseover or mouseout). Then, the variable rueckgang is written in a text-element (in the svg-document), if the event-type is a mouseover:

$$document.getElementById("infotext_beschreibung0").firstChild.nodeValue = rueckgang;$$

In case of a mouseout event, the text will be set to an empty string and the stroke-opacity of the corresponding group will be set to the initial situation. With a new mouseover, the element contents will be overwritten.

### 5.3.3. Implementation of Highlighting while Mouseover

→ *Function* : *showInfo(evt)*, at Tools.js-section “Mouseevents on Glacier Tongues”.

Further, highlighting of the glacier tongues is realized as an advancement of the function *showInfo(evt)*. The crossed glacier tongue change its transparency with the following method:

```
evt.target.setAttribute(“stroke – opacity”, “1”);
```

As soon as the cursor abandons the glacier tongue, the transparency is set back to its original value. The link to the transparency change of the corresponding legend-stroke is realized over a constraint concerning its color value.

Therefore, the legend-elements are evaluated in a for-constraint. The stroke color of each legend-element is compared to the stroke color of the target glacier tongue. If these colors are the same, then the stroke opacity gets increased for the present legend stroke. An opposite function changes the transparency back during a mouseout-event.

### 5.3.4. Implementation of Layer Controls

→ *Functions* : *showTongues(evt)*, *showPostkarte(evt)*, *showOrtho(evt)*, *showLK(evt)* at Tools.js-section “Mouseclick events: Checkboxes, Radiobuttons”.

To enable layers to be switched on or off by the user, checkboxes and radiobuttons are programmed. These buttons permit to show the content of a layer or to hide it. Accordingly, the visibility of the corresponding layers is set to “visible” or to “hidden”:

```
document.getElementById(“image”).setAttribute(“visibility”, “visible”);
```

Since this method is dependent on other checkboxes/layers, the checkbox first has to check which other checkbox is checked. This is done over the attribute “zustand” of all layers.

```
varzustand_check = evt.target.getAttributeNS(url, “zustand”);
```

```
if(zustand_check == “unchecked”)
```

Then, all the orders can be runned and the corresponding layers are set to visible and the other layers are set to hidden.

The layer control function *showTongues(evt)*, is the function which sets the visibility of the glacier tongues to visible, so that they are shown in the map application. This event is dependent on the basis layer. If the layer “postcard” is checked, the glacier tongues should be shown in image coordinates (svg-group *Tongues\_Pix* are visible). In contrary, if the layers “orthophoto” or “landeskarte” are checked, the glacier tongues should be shown in world coordinates (svg-group *Tongues\_World* are visible).

These functions are called by an onclick mouseevent on the checkbox or radiobutton rectangle or circle in the svg-document.

### 5.3.5. Implementation of a Selection List

→ *Function* : *showLKyear* at Tools.js-section “Mouseclick events: Checkboxes, Radiobuttons”.

In case of the topographic maps, the possibility of choosing a map year with a selection list is applied. This selection list is created in the javascript section of the svg-document:

```
varmySelectionList = newselectionList(“yearsSelectionList”, ..., showLKyear);
```

The last attribute “showLKyear” describes the function which is called by the use of the selection list. There, the corresponding layer will be set to visible, if the selection list is clicked. The corresponding layer is chosen over the string-attribute “year” of the selection list. Alternatively, the request could be realized over the list-attribute “selNr”, which defines the position of the element in the selection list. Thus, it would be independent of the use of a string and is more flexible.

### 5.3.6. Implementation of a Picture Display on Mouseclick

→ *Function* : *showPhoto(evt)* in the javascript section of the Webkarte.svg document.

The function *showPhoto(evt)* is called with an onclick event on the layer “Glacier Tongues”. The pictures of the corresponding years will be showed in a window, which is able to be moved, minimized, maximized or closed.

Thus, a window for each picture and year has to be created within the function:

```
myMapApp.windows[“photoWindow1”] = newWindow(“photoWindow1”, ...);
```

Further, the picture which should be shown within the window is appended to the window:

```
myMapApp.windows[“photoWindow1”].appendContent(“photo1”, true);
```

This function is defined in the javascript section of the svg-document, because it references itself to other javascript-files.

### 5.3.7. Implementation of an Animation

→ *Function* : *animation(evt)* at Tools.js-section “Animation”.

The aim of the animation is to show the different glacier tongue states one after each other by means of visualizing the glacier tongue retreat.

On one hand, animations can be realized in the svg-document over an animate-statement. On the other hand, animations can be performed using a timer function in javascript. The second method is chosen, because it is easier to implement. The timer function can be implemented in javascript by different orders:

```
document.getElementById(“tongue_0_pix”).setAttribute(“visibility”, “visible”);
```

These orders are part of a subfunction (e.g. `befehl2`) of the animation function. These subfunctions are executed after a predefined time period after an onclick event on the start-svg-button:

*`window.setTimeout(befehl2, 1200)`*

Thereby, the time period is defined in milliseconds (e.g. 1200 ms).

## 6. Results

The results of this Master thesis are at one side, the evaluation of the accuracy analysis. On the other side, a printed map and a web map application are designed with the common goal to visually illustrate the retreat of the Rhone glacier tongue. These results are described and interpreted in the following sections.

### 6.1. Accuracies of the Geo-Referenced, Digitized Glacier Tongues of the Years 1874, 1929 and 2009

Years	Camera Calibration Errors		Absolute Accuracy of Tongue Positions [m]			
	2D RMSE [m]	Pixel RMSE [px]	Mean	Maximum	Minimum	Range
1874	1.2	1.2	10	36	3	33
1929	2	4	8	40	4	36
2009	5.4	6	6	34	1	33

Table 6.1.: Absolute accuracy estimation results of the digitized glacier tongues of the years 1874, 1929 and 2009. The digitizing is based on the georeferencing of terrestrial images using the DEM 2010

Figure 6.1 shows an overview of the digitized glacier tongues of the years 1874, 1929 and 2009. Table 6.1 illustrates the overview of the camera calibration and absolute accuracy results of the years 1874 (Chapter 4.2.2), 1929 (Chapter 4.2.3) and 2009 (Chapter 4.2.1). It can be seen that the absolute accuracy gets better from the year 1874 to the year 2009. This seems to be independent of the accuracy of the achieved camera calibration results. More emphasis comes with the temporal difference between the used orthophoto or DEM and the image. The results show, the higher this temporal difference is, the worse the absolute accuracy of the digitized glacier tongue is. This can be caused by the difficulty to set the control points. The problem is that the image is captured about 150 years before the used orthophoto. During that, many regions changed and some others were overgrown. This makes it difficult to find places which were stable over the years and which are still detectable in the orthophoto. Therefore, control points are mostly set further away from the glacier tongue, which then causes inaccuracies in the digitalization. Another reason could be the inaccuracies in the DEM 2010 in steep areas (Chapter 4.1). This affects only the georeferencing of the images of 1874 and 1929, where the glacier tongue is still located in the steep areas. In contrary, the glacier tongue of the year 2009 is located in a region with a small slope value and thus the DEM is very accurate in this region (Chapter 4.1). This affects the georeferencing of the image of 2009 positively.



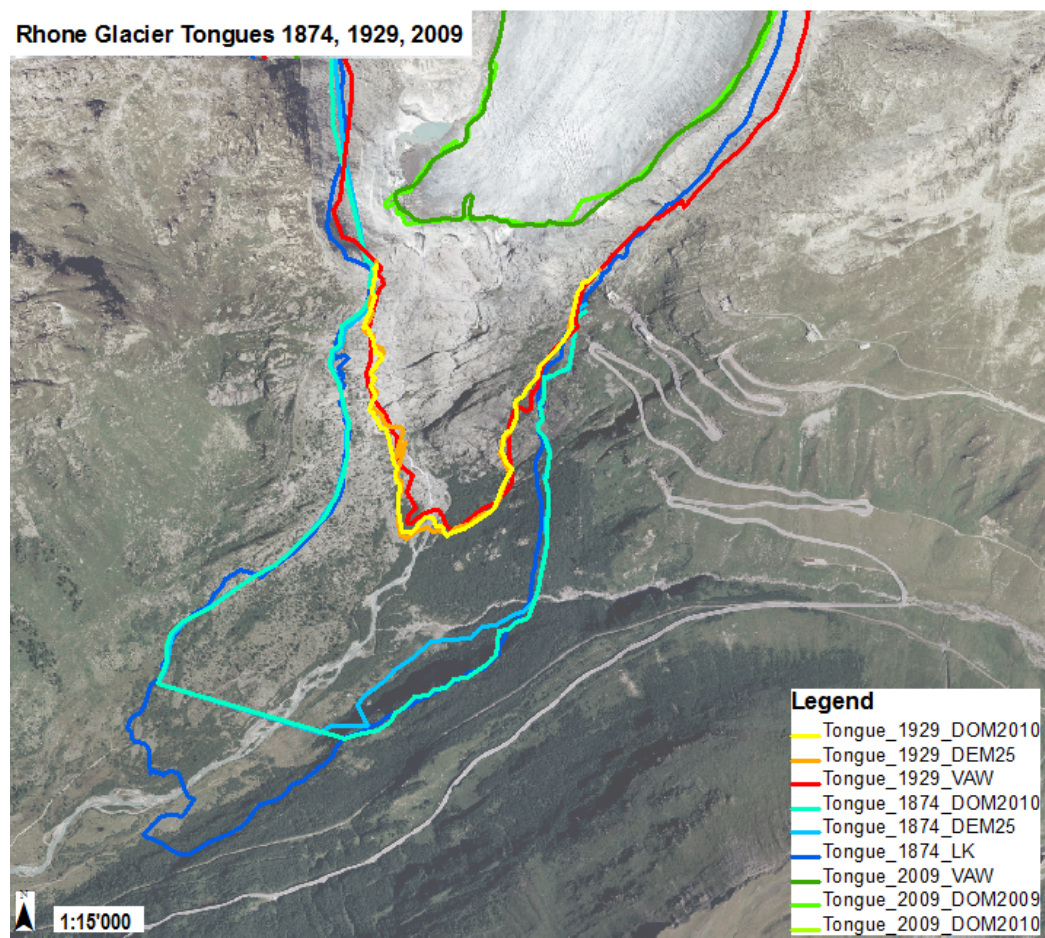


Figure 6.1.: Congruence of the resulted, digitized glacier tongues of the years 1874, 1929 and 2009 compared to reference data (dark green, red and dark blue lines), illustrated on top of the orthophoto of 2007.

Table 6.1 shows another phenomenon, concerning the increasing camera calibration error from the year 1874 to the year 2009. The high georeferencing RMSE values of the image of 2009 might be caused by the problem of a flat angle of incidence of the light beam (Figure 2.5, page 15). Thereby, a small error in the setting of image control points can cause higher errors in the corresponding world space. This affects the georeferencing of the terrestrial image. The angle of incidence is a lot better for the images of 1874 and 1929 and thus the georeferencing could be more accurate. Another reason might be, the inaccuracy of the DEM 2010 in region 6 (Figure 4.1, Chapter 4.1). The outlier point 1030 (4.6 m accurate) could affect the georeferencing of the image 2009. The image 2009 is dependent of this DEM region in contrary to the images of 1929 and 1874, which do not tangent this region.

## 6.2. Printed Map

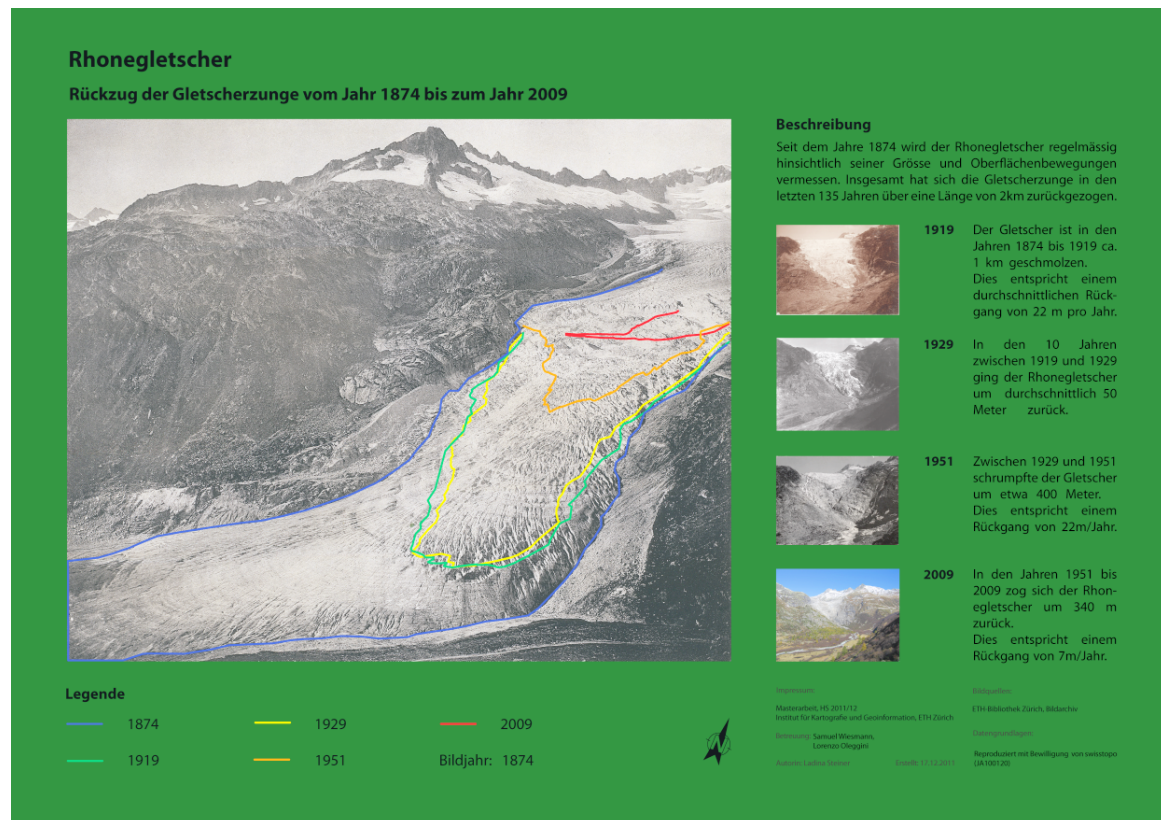


Figure 6.2.: Designed product. Printed map of the format DIN A3, which shows the retreat of the Rhone glacier tongue between the years 1874 and 2009.

### 6.2.1. General Design

Figure 6.2 and Appendix I show the resulted, printed map. Generally, the map background is drawn in green. This suits for natural topics and reminds the observer of the common information boards, e.g. for nature reserves. The font is black in order to achieve a good contrast to the background color.

The map content is structured into different sections, which are visually arranged in groups. These sections involve the title, the main map, the map legend, a short description about the glacier tongue retreat and the map imprint and sources. Thus, the different sections provide a good overview for the observer and the map content is not overloaded.

The map format is designed to hang it up, e.g. at the kiosk at the glacier site. For this reason, it would have been better to use a bigger map format, which experience more attention. In addition, an English map version was created, which is advantageous for touristic observers.

### 6.2.2. Thematic Elements

The five glacier tongue states are displayed as polylines. The color scheme for the glacier tongues is chosen as a green to red color gradient. This should illustrate the negative development of the glacier tongue retreat. The latest glacier state (1874) should be green. In order to achieve a good color transition and contrast with five used glacier states, the color gradient is extended to blue (instead of green). So, it results a blue to red scala.

The descriptions about the glacier tongue retreat are written from a year to year perspective. Small images of the different glacier tongue states complement these descriptions. This helps the observer to visually imagine the glacier tongue retreat. In addition, the map goal of illustrating the Rhone glacier tongue retreat, is clearly evident.

### 6.3. Interactive Web Map Application

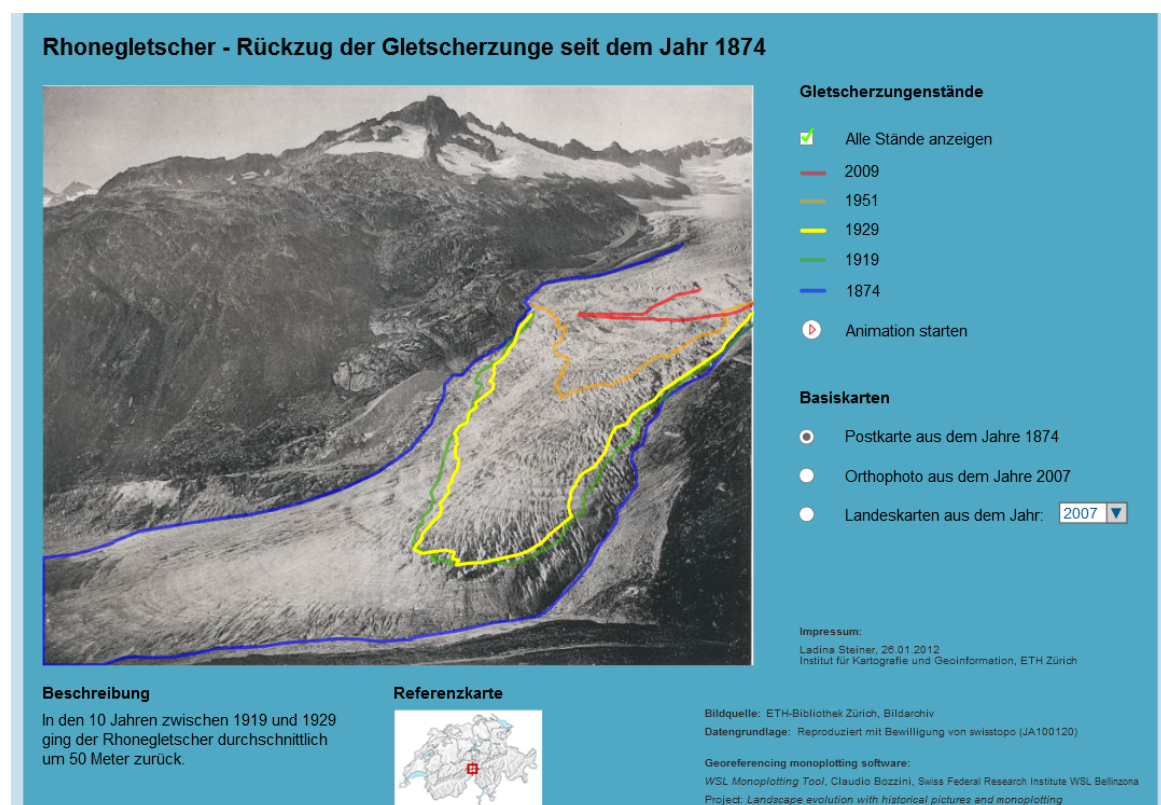


Figure 6.3.: Resulted web map application, which shows the retreat of the Rhone glacier tongue between the years 1874 and 2009. This interactive map is designed for the web use and thus available for the general public.



### 6.3.1. General Design

Generally, the design of the web map is held in blue colors in order to give a neutral and attractive impression (Figure 6.3 and Appendix J). “Arial” (respectively “Helvetica”) is chosen as a rather common font, which is well readable on the screen. The black font color conveys a high contrast and enhances the legibility.

The map is framed by a lot of functional groups, such as the title, the legend, thematic navigation elements, reference map, the map imprint, sources and additional information. The division between the map and the functional groups is realized over the blue background. Functional groups increase the overview without overloading the map content by means of unnecessary frames. Additionally, the map content is restricted to the essentials, which appears over a “thin design”. Furthermore, a small reference map is added in order to offer the user an overview about the Rhone glacier location. This map shows the rough location of the Rhone glacier in Switzerland (Figure 6.3).

The legend and layer control elements are located on the right side of the web map application, because this is more intuitive for the user (Figure 6.3).

### 6.3.2. Graphical User Interface and Interactivity

The map design on the basis of a Graphical User Interface (GUI) allows the user to gain control on the map content in a clearly laid out way. This interaction with the computer is realized over buttons, checkboxes, radiobuttons, dropdown-menus (Figure 6.4a) and appearing windows (Figure 6.4c). These buttons are reduced to the minimum, so that the user is able to recognize them and interpret their meaning. Thus, the design is user-centered and the usability is easy understandable. Therefore, the map is a good product to address the target group, the general public.

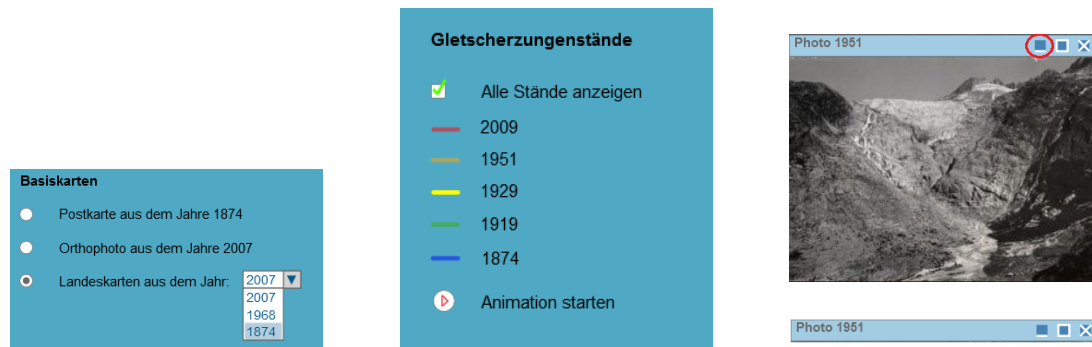
The interactivity is realized in the following elements:

- layer control (Figure 6.4a): it is possible to activate radiobuttons or checkboxes for all layers, in order to display the target layer
- animation (Figure 6.4b): an animation, which displays the glacier tongue retreat, can be started. This shows a time series of the different glacier tongue states

The following interactivity elements are realized by mouseevents either on the glacier tongues or on the glacier tongue legend:

- highlighting (Figure 6.4b): the opacity of the corresponding glacier tongue legend or glacier tongue is increased with a mouse over event
- display of information (Figure 6.4b): a short description about the Rhone glacier retreat is displayed with a mouseover event
- display of pictures (Figure 6.4c): on a mouseclick event, pictures of every showed glacier tongue state are shown in a separate window

The realization of interactivity and smart legends enables the user with a high usability in order to get more information and overview. E.g. at a mouseover event on a certain glacier tongue, the corresponding legend increases its opacity. This allows the user to recognize the chosen glacier tongue. Simultaneously, a description about the last glacier tongue retreat is displayed.



- (a) The GUI is realized by radiobuttons and dropdown-menus, which enable a layer control in order to activate and display the target layer.
- (b) “Smart legend”, the legend polylines are highlighted after a mouseover event on the corresponding glacier tongue. This helps the user to understand the map content and to navigate in terms of the thematic space.
- (c) The GUI is realized over appearing windows. Pictures are displayed in the windows after a mouseclick event on the glacier tongues and their legend. The windows can be minimized, maximized, closed and moved.

Figure 6.4.: Elements of the Graphical User Interface (GUI)

### 6.3.3. Thematic Elements

The five glacier tongue states are showed as polylines. The color scheme for the glacier tongues is chosen as a blue to red color gradient (Chapter 6.2.2). This should illustrate the negative development of the glacier tongue retreat.

### 6.3.4. Browser Compatibility

The present web map application should operate on many popular browsers in order to achieve the target audience. Therefore, the browser compatibility was tested. All interactive functions are working in the most popular browsers Opera Web browser, Mozilla Firefox and Google Chrome. Internet explorer does not support the implemented javascript functions. But this fact is neglected in regard to the decreasing popularity of this browser.

## 6.4. Interpretation of the Results

The obtained accuracy of the georeferencing based on the WSL Monoplotting Tool lies in the expected range of one to five meters in the 2D world space (Chapter 6.1). Thus, these results are useful for applications, which occur within an accuracy range of some meters.

The accuracies of the georeferencing are mostly within the same range, independent of the used DEM. It is however necessary to pay attention by the interpretation of this results. On one hand, the results are only controlled once. On the other hand, the estimated accuracy values are based on 15 samples. Furthermore, the evaluation of the influence of different DEMs on the georeferencing process could not be evaluated as planned (Chapter 3.2.1). This evaluation is based on an assumption according the use of the DHM25 (Chapter 3.2.1).

The printed map (Chapter 6.2) is more or less consistent with the map concept. The map design is clearly laid out, whereas the map content is well legible based on a high contrast. In addition, the map goal is clearly evident. A lot of informations are showed without an overloaded map content. A disadvantage is the format of the map. DIN A3 is a bit to small to hang it up at the glacier site. Furthermore, it is advantageous that the map is designed twice, once in German and once in English. This helps to reach the target group of tourists.

The web map application (Chapter 6.3) is attractively presented and informative, especially caused by the high level of interactivity. The interactive functions are working reliable and enable the observer to discover a lot of information. The target audience is reached well and the map goal is clearly evident, thanks to the thin design of the map. Although, the design seems to be rather unprofessional.

Nevertheless, many extensions or improvements could be made for the web map application. This could be the implementation of spatial navigation elements, e.g. zoom or pan possibilities. This possibility was initially planned in the web map concept, but not realized due to the complex javascript implementation of these functions and the available time limit. Furthermore, the description about the glacier retreat could be more profound. In addition, information could be displayed over a tooltip element.

## 7. Conclusions and Outlook

### 7.1. Conclusions

The main question of this thesis was, if it is possible to reconstruct former glacier tongue states by georeferencing single, historical images (Chapter 1.3). The answer is that it is possible. Based on the use of the WSL Monoplotting Tool, historical images with initially unknown camera parameters can be geo-referenced by estimating the camera calibration parameters (Chapter 2.5.1). This estimation is possible with an accuracy of one to five meters and the WSL Monoplotting Tool is thus a good method for georeferencing single, historical images.

However, an other goal was to estimate the absolute accuracy of the digitized, reconstructed glacier tongue positions (Chapter 1.3). The reconstructed glacier tongue positions are accurate within a five to ten meters range compared to the reference data (Chapter 6.1). Hence, the results meet the accuracy expectations and are useful with regard to the application field.

Nevertheless, it could be seen that some factors influence the accuracy of the georeferencing (Chapter 2.5.2). A very important factor is, the resolution of the image, as well as the incident angle of the camera light beam and the existence of hidden areas. Furthermore, it is important to have a possibility to distribute control points around the image and especially around the feature of interest. These factors should be considered in order to reach most accurate results.

The influence estimation of the use of different DEMs for the georeferencing process, could not be done as planned in the approach (Chapter 2.4.2). The approach changed due to the DEM availability (Chapter 3.2.1). The analysis of the use of different DEMs did not result in significant differences (Chapter 4.3). Therefore, no meaningful conclusions can be drawn for that point. The difference in the use of different DEMs should thus be caught up as a further step.

All in all, the software can have a high potential for the glaciology. Until now, it is only possible to reconstruct historical glacier tongue states from surveying data or existing, historical topographic maps. With the applied methodology, former glacier states can be reconstructed with the help of historical, terrestrial images and an adequate effort. Therefore, more statements on changes in glacier retreats can be made for earlier time periods.

Furthermore, the WSL Monoplotting Tool is a user friendly software, which allows the user to easy handle an evaluation process (Chapter 4.4.3). Very useful is the fact that the camera calibration is mainly computed automatically. Additionally, it is possible to change all the camera parameters as well manually (Chapter 4.4.3).

Conclusions concerning the designed printed map and web map application, include that it is advantageous to have two different maps. These maps address different target audiences with the same map content (Chapter 2.4.2, Design of the products). The advantage of the printed map is that it is possible to show it directly at the glacier site, whereas the web map is accessible for everyone over the Internet. The advantage of the web map application is that the observer can discover more informations over interactions by means of a thin map design.

## 7.2. Outlook

The next goal should be to analyze the influence of the use of different DEMs. This is done, to evaluate if the results of the georeferencing are more accurate by the use of the most accurate DEM or the DEM with the same topography as the image (captured in the same time period). Therefore, DEMs of the same years as the used images should be used for the evaluation. Afterwards, these results should be compared with the results, which were generated out of the most accurate DEMs.

Furthermore, the evaluations can be expanded in means of the usage of older data than the available images. For example, this data could be former watercolors or paintings. The problem with this data could be, on the one side the resolution and, on the other side the inaccurate geometry.

The design and programming of the web map can be extended in the future. More scientific information about the glacier retreat can be added. In addition, the map extent and the layers could be extended. This should allow a web map, which covers more glaciers and its retreats and could be used as a information source for the public or scientists. Furthermore, the thematic features could be added as wms-layers. This would allow the storage of the data on a server and a possibility to actualize them continuously.

The georeferencing based on the WSL Monoplotting Tool can be used for other applications. This could be in different fields, where it is necessary to reconstruct former object states with an accuracy in the range of meters. This includes the glaciology, the forestry or generally, if a change in landscape has to be detected. The most important point thereby is the study area. Advantageously, this has to be well accessible and of public interest, so that a lot of images are available.



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## A. Appendix 1: Concept of the Web Map Application

**Ziel**

Erstellen einer thematischen Webkarte zum Rückzug der Gletscherzunge am Rhonegletscher über eine zeitliche Periode vom Jahre 1874 bis zum Jahr 2010.

**Kartenthema**

Rückzug der Gletscherzunge am Rhonegletscher seit dem Jahre 1874.

Thematische Layer:

- Gletscherzungen verschiedener Jahre, dargestellt als Polylinien (ein/ausschaltbar):  
Die Farbe der Polylinien erfolgt in einer Grün-Rot-Farbskala. Dabei wird der älteste Gletscherstand mit grün visualisiert, da damals der Gletscher noch gross war und entsprechend positive Umwelteinwirkungen ausübte. Der kleinste Stand der Gletscherzunge wird mit rot dargestellt, da der Gletscher sich bereits sehr stark zurückgezogen hat, was negativ auffällt.  
Dabei muss darauf geachtet werden, dass je nach Wahl der Basiskarte, die Gletscherzungen in pixel- oder Weltkoordinaten dargestellt werden müssen. Dies sollte automatisch erfolgen.

Datensätze:

<b>Jahr</b>	<b>Gletscherzungen für terrestrische Basiskarte</b> [pixelkoordinaten]	<b>Gletscherzungen für Orthophotos, LK</b> [Weltkoordinaten]	<b>Rückzug zu vorhergehendem Jahr</b> [m]	<b>Höhe tiefster Punkt der Gletscherzunge</b> [M.ü.m.]
1874				
1898				
1919				
1929				
1951				
2009				

**Basiskarte**

Basislayer- Gliederung und ihre Darstellung:

- Postkarte vom Jahr 1874 (ein/ausschaltbar)
- Orthophoto 2007 (ein/ausschaltbar)
- Landeskarten -> Dropdownmenu mit versch. Jahren

Dabei handelt es sich um Rasterdaten, welche ein- oder ausschaltbar sind.

## Interaktive Informationen

Beim Überfahren der Karte mit der Maus erscheinen folgende Informationen:

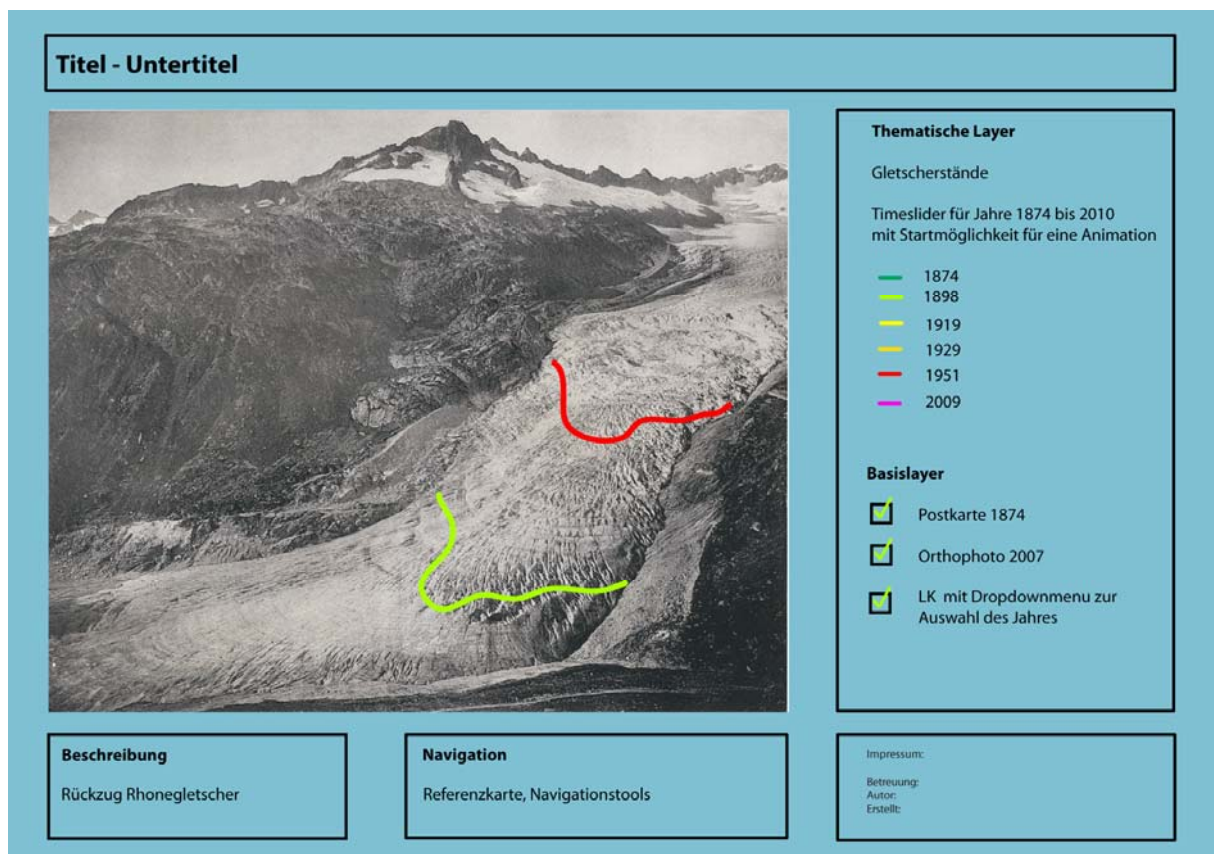
- Layer Gletscherzunge: - Beschreibung über Gletscherrückgang wird angezeigt
- Highlighten der Legende der entsprechenden Gletscherzunge

Beim Klicken der Karte mit der Maus erscheinen folgende Informationen:

- Layer Gletscherzunge: - Erscheinen des Foto der Postkarte aus entsprechenden Jahr
- Highlighten der Legende der entsprechenden Gletscherzunge

Navigation: Referenzkarte der gesamten Schweiz, um Wird übersichtlich gestaltet mit wenigen Navigationsmöglichkeiten, um die Übersicht zu behalten und das Kartenfenster nicht zu überfüllen.

## Kartenskizze



Dabei werden die thematischen Layer als WMS- Layer eingebunden. Dies hat den Vorteil, dass die Karte erweiterbar wird, falls mehrere Gletscherstände in Zukunft digitalisiert werden. Dazu müssen die Gletscherstände in einer Datenbank vorliegen.

Die Basislayer sind in einem SVG-Dokument eingegliedert und daher statisch.

## B. Appendix 2: Camera Calibration Results in the WSL Monoplotting Tool

**Matrix camera calibration**

Name:

**Position**

10.0 m

**Rotation**

1.00 °

**Focal Length**

100.0 mm

**Image center**

10.00 pix

**Camera parameters**

Name	Value	Fix	Error
Ox	672667.0414	<input type="checkbox"/>	0.0000
Oy	157614.1520	<input checked="" type="checkbox"/>	0.0000
Oz	2294.8017	<input type="checkbox"/>	0.0000
Rx	0.910686	<input type="checkbox"/>	0.0000
Ry	0.451958	<input checked="" type="checkbox"/>	0.0000
Rz	0.345274	<input type="checkbox"/>	0.0000
Cx	1876.2642	<input type="checkbox"/>	0.0000
Cy	-2388.6321	<input type="checkbox"/>	0.0000
D	2207.9196	<input type="checkbox"/>	0.0000
Rf	-1	<input checked="" type="checkbox"/>	

Compute    Nr. iterations: 20

**Computed values**

ux' ( 0.847, 0.532, 0.015)    A rot -1.055

uy' (-0.304, 0.460, 0.834)

uz' ( 0.437, -0.711, 0.552)

Errors	min	max	mean
pixel	0.208	2.942	1.241
angle	0.005	0.067	0.028
radius	0.066	1.782	0.756

Apply    Details...

Errors	min	max	mean
word (2d)	0.187	2.395	1.270
word (3d)	0.190	2.403	1.339

Ok    Cancel

Figure B.1.: Camera parameters and errors in camera calibration, shown in the WSL Monoplotting Tool

## C. Appendix 3: Overview of Available Data and their Origins

## Datenüberblick Rhonegletscher

	DHM			
	DHM25	DHM 2009	DHM 1847	DHM 1929
Abgeleitet aus	LK 1:25'000 aus linearen Elementen: vektorierte Höhenkurven und Seebodenkurven vektorierte Seekonturen Hauptbruchkanten im Alpengebiet aus punktförmigen Elementen: digitalisierte Höhenkoten und Seebodenkoten	ADS40/80 Luftbilder aus Autokorrelation d.h teilweise Fehler bei Gebieten mit schlechten Korrelationseigenschaften (Schatten, Eis)	Topografische Gletscherkarte 1:5'000  gescannt: 1-2m Pixelgrösse Digitalisieren (manuell): Subpixel Orientieren: mehrere Pixel (Fehler)	LK 1:50'000 1947/48 Gletscherstand von 1929 <b>ev. aus genauerer Karte</b>
Genauigkeit	3 - 8 Meter (Alpen) 1.5 Meter (Mittelland, Jura) 2 Meter (Voralpen, Tessin)	0.60 Meter (Höhengenaugigkeit)	ca. DHM25 (einige Meter)	ca. DHM25 (einige Meter)
Auflösung	25 Meter	1 Meter		
Jahr	ca. 1990 bis 1995	2009	1847	1929
Datenbesitzer	ETHZ (geovite, swisstopo)	WSL Birmensdorf (swisstopo)	VAW ETHZ	VAW ETHZ
Bezugsrahmen				
Bemerkungen	Jahr des Stand des Gletschers unbekannt (teilweise Nachführung) Datum der jeweiligen Kartenblätter ist der swisstopo bekannt	ca. 15 GCPs bekannt		
Quelle	<a href="http://www.swisstopo.admin.ch/internet/swisstopo/de/home/products/height/dhm25.html">www.swisstopo.admin.ch/ internet/swisstopo/de/home/ products/height/dhm25.html</a>	Samuel Wiesmann	VAW ETHZ	VAW ETHZ

**ORTHOPHOTOS**

<b>LK</b>			<b>LK</b>	
<b>Swissimage50</b>	<b>Landsat</b>	<b>Spot</b>	<b>1874</b>	<b>1948</b>
Flug mit Leica ADS40 (digital) und Leica RE30 (analog)	Satellit Landsat5 (USA) aus 20 Bildern von CH	Spot 5 (FR) aus 50 Bildern von CH	aus Messtischaufnahmen mit: - Messlatte - Distanzmesser (Messband, Basislatten) - Planchette, Bussole - 60 Fixpunkte	Aus Stereophotogrammetrie
3 bis 5 Meter (basierend auf DHM25)			1:5'000	1:50'000
0.5 Meter (je nach Region +2.5m)	25 Meter	5 Meter		
LK Nr. 1230/1231: 2009 (jedoch noch nicht ausgewertet) LK Nr. 1250/1251: 2009	1990 (Wallis)  ETHZ (geovite)	2005 (Kachel Nr. 26 E)  Swisstopo		ETHZ (geovite)
Seit 2008: LV95 (LV03 auch erhältlich)				
Nachführung alle 3 Jahre	gratis bei swisstopo geeignet für Massstab 1:100'000	geeignet für Massstab 1:25'000	Erstvermessung ungenau (ca. 1.5m) 1883 Neuberechnung der alten Messungen von 1874 -> genauer (ca. 5cm)	Stand Rhonegletscherzunge von 1929
<a href="http://www.swisstopo.admin.ch/internet/swisstopo/de/home/products/images/ortho/swissimage_production.html">http://www.swisstopo.admin.ch/internet/swisstopo/de/home/products/images/ortho/swissimage_production.html</a>  PDF: Infos_swissimage50.pdf	<a href="http://www.swisstopo.admin.ch/internet/swisstopo/de/home/products/images/ortho/landsat.html">http://www.swisstopo.admin.ch/internet/swisstopo/de/home/products/images/ortho/landsat.html</a>	<a href="http://www.swisstopo.admin.ch/internet/swisstopo/de/home/products/images/ortho/spot.html">http://www.swisstopo.admin.ch/internet/swisstopo/de/home/products/images/ortho/spot.html</a>	Buch Mercanton, 1916	VAW ETHZ



## D. Appendix 4: Error Pixels in the DEM 2009

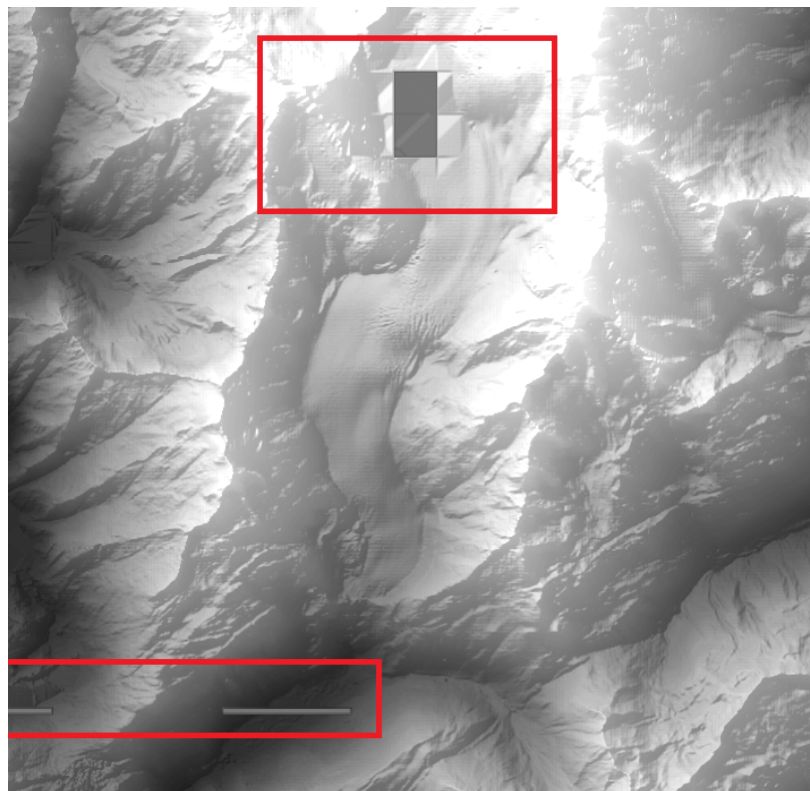


Figure D.1.: Error pixels of the DEM 2009. These errors are caused by the autocorrelation of the image flight ADS40/80 pictures. Thereby, the matching did not work well in regions with nearly no contrast, e.g. glacier surface region with snow and without many other structures in steep areas.

## E. Appendix 5: Overview of Available Swiss National Maps

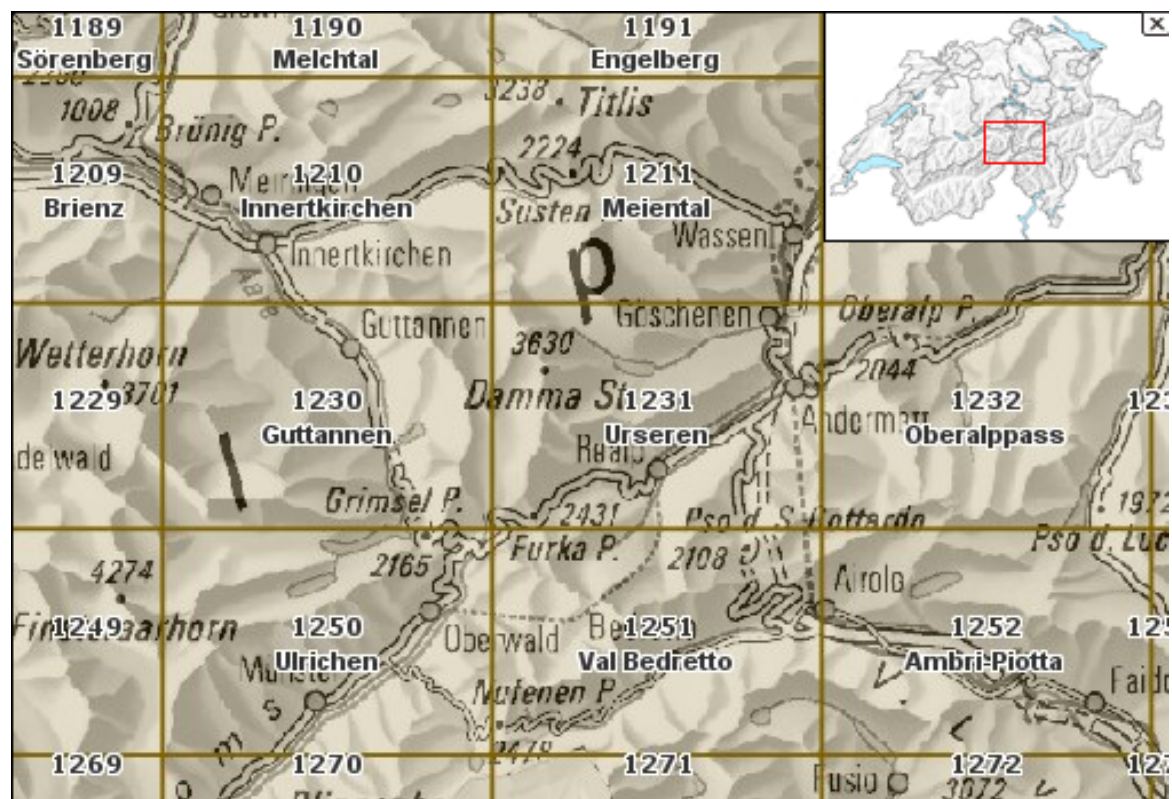


Figure E.1.: Map Sheet Classification of Swiss National Maps, 1:25'000 [6]

**LK Bestand Rhonegletscher 1:25'000**

Blattnr.	1230	1231	
Blatt	Guttannen	Urseren	Bemerkungen
Ausgabe	2009	2009	Gesamtnachführung 2007, Einzelnachträge 2008
	2002	2002	Stand des Karteninhaltes 1999
	1995/93	1995/93	Gesamtnachführung 1993
	1988/86	1988/86	Gesamtnachführung 1986
	1980	1980	Gesamtnachführung 1980
	1977	1975	Gesamtnachführung 1977/1975
	1973	1965	Erste Ausgabe 1973/65

**LK Bestand Rhonegletscher 1:50'000**

Blattnr.	255	
Blatt	Sustenpass	Bemerkungen
Ausgabe	2009	Gesamtnachführung 2007, Einzelnachträge 2008
	2003	Stand des Karteninhaltes 1999
	1996/1993	Gesamtnachführung 1993
	1989/86	Gesamtnachführung 1986
	1982/80	Gesamtnachführung 1980
	1976	Gesamtnachführung 1976
	1969	Gesamtnachführung 1969
	1965	Gesamtnachführung 1960, Einzelnachträge 1965
	1960	Gesamtnachführung 1960
	1948	Erste Ausgabe 1948

Quelle:

<http://www.library.ethz.ch/de/Ressourcen/Geodaten-Karten/Blattnummer-1162-1239-1-25-000#1230>

<http://www.library.ethz.ch/de/Ressourcen/Geodaten-Karten/Blattnummer-1162-1239-1-25-000#1231>

<http://www.library.ethz.ch/de/Ressourcen/Geodaten-Karten/Blattnummer-250-297-1-50-000#255>

<https://geodata.ethz.ch>

**Bestand in Geovite**

LK 1:25'000	LK 1:50'000
2007/2006	1947/1948
1999	1960/1961
	1969/1971
	1976/1977
	1980/1981
	1986/1987
	1993
	1999

## F. Appendix 6: Ground Control Points of the Rhone Glacier

<b>Punkt -Nr.</b>	<b>LFP-Punkt</b>	<b>Y- Koordinate</b>	<b>X- Koordinate</b>	<b>Höhe</b>	<b>Lager. pkt.</b>
	1230803	671782.870	162549.790	2700.260	X
	1230804	671963.710	159024.250	2295.580	X
	1231005	672997.720	161068.120	2675.260	X
1020	1231006	673103.490	159075.670	2501.940	X
1030		673156.451	159422.724	2405.660	
1040		673265.293	159916.101	2438.104	
1050		672915.710	160734.990	2518.290	
1110		673002.472	161070.982	2675.806	
1120		673030.178	161527.326	2626.136	
1130		673426.280	162102.585	2768.530	
2020		672256.678	158888.787	2152.431	
2030		671983.137	159049.330	2300.602	
2040		672310.863	159777.835	2337.098	
2110		671960.033	160346.380	2549.493	
2130		671555.197	161549.244	2639.376	
2140		671739.998	162291.230	2666.437	
2150		671805.986	162571.546	2688.615	
2210		672352.362	163028.590	2734.350	
2220		672827.199	163270.243	2862.264	

Figure F.1.: 3D-Coordinates of the 19 ground control points at the Rhone Glacier. These points were measured in the year 2005 during a geodetic project course of the ETH. [11]



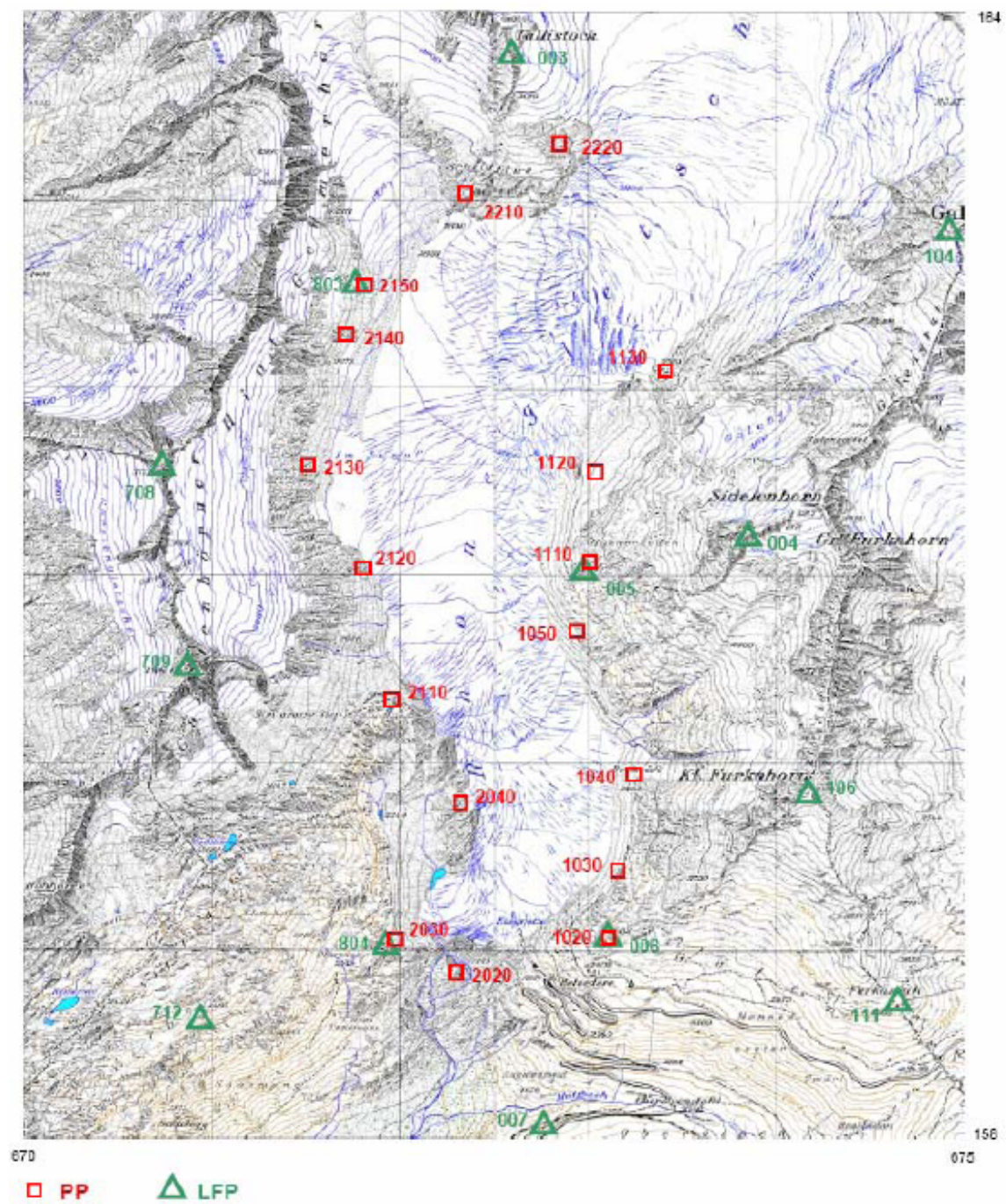


Figure F.2.: Overview of the 19 ground control points at the Rhone Glacier. These points were measured in the year 2005 during a geodetic project course of the ETH. [11]

## G. Appendix 7: Accuracy Values of the DHM25

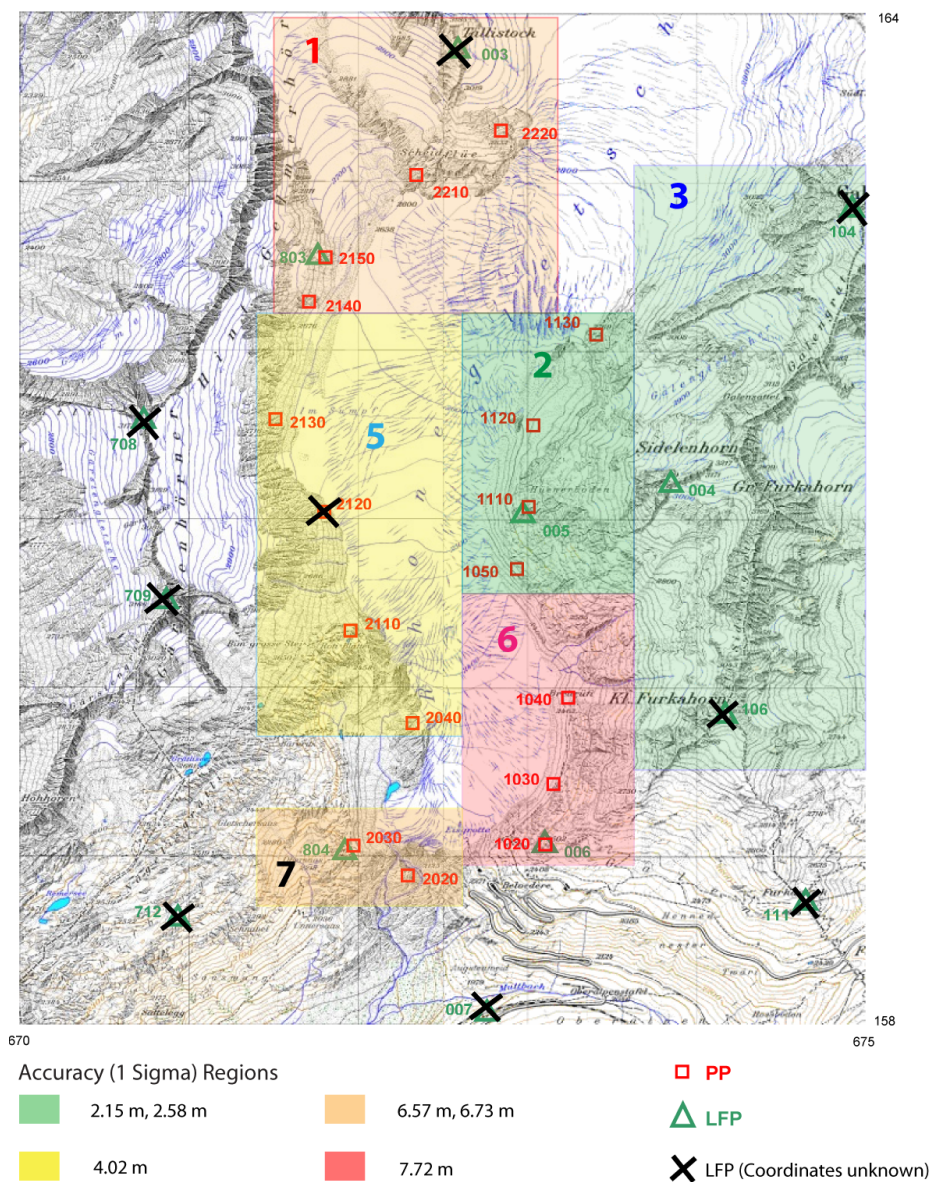


Figure G.1.: Pixelmap 1:25'000 shows the DHM25, split in regions of similar accuracy values



## H. Appendix 8: Pictures, Used in the Present Master Thesis



Figure H.1.: Picture of the year 1874. This picture is used for the accuracy evaluation as well as the visualization in the produced maps. Picture source: “ETH-Bibliothek Zürich, Bildarchiv”



Figure H.2.: Picture of the year 1898. This picture would be used for the visualization in the produced maps. But, it was not used, because it was not possible to georeference this image. Picture source: “ETH-Bibliothek Zürich, Bildarchiv”



Figure H.3.: Picture of the year 1919. This picture is used for the visualization in the produced maps. Picture source: “ETH-Bibliothek Zürich, Bildarchiv”



Figure H.4.: Picture of the year 1929. This picture is used for the accuracy evaluation as well as the visualization in the produced maps. Picture source: “ETH-Bibliothek Zürich, Bildarchiv”





Figure H.5.: Picture of the year 1951. This picture is used for the visualization in the produced maps. Picture source: “ETH-Bibliothek Zürich, Bildarchiv”

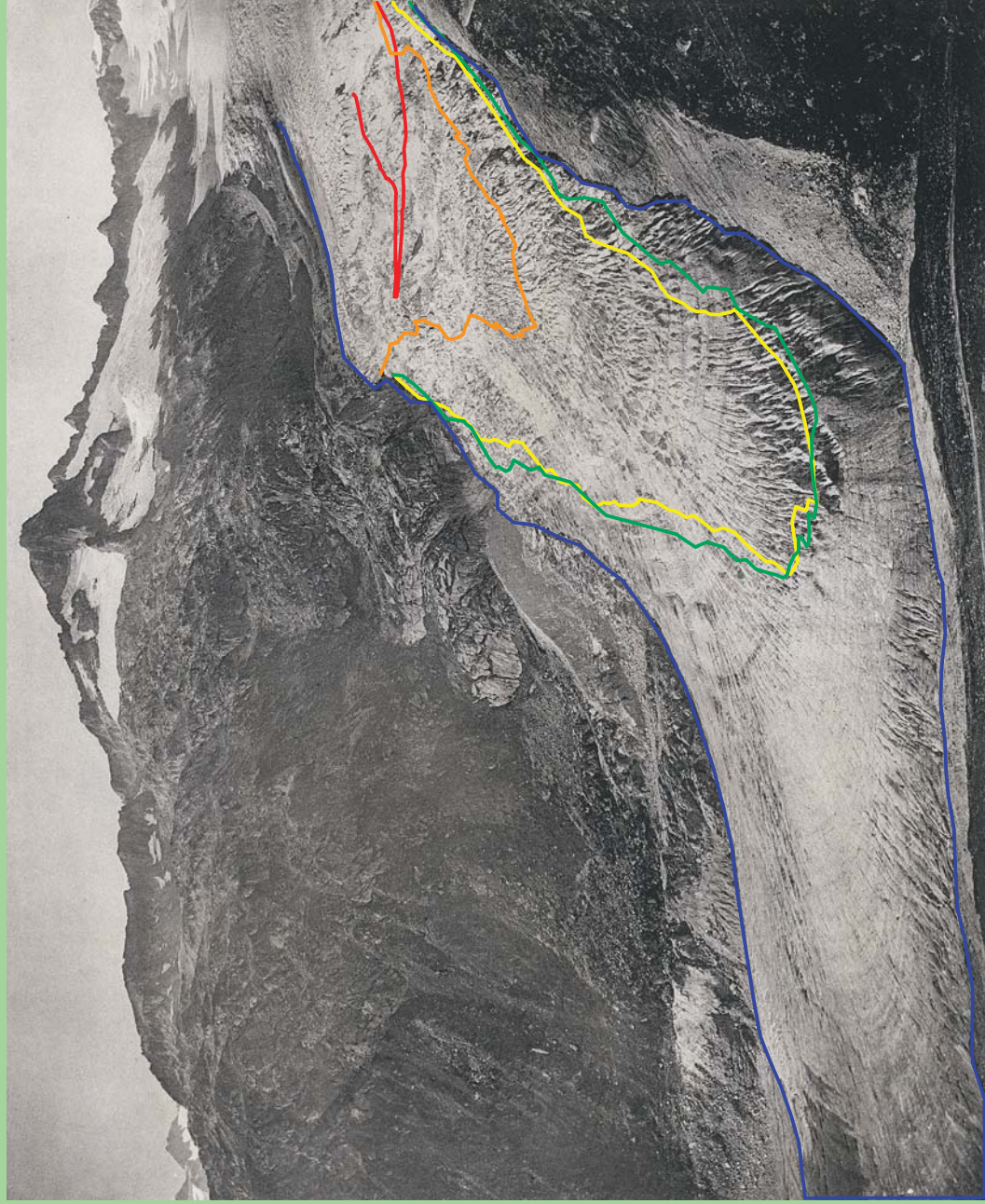


Figure H.6.: Picture of the year 2009. This picture is used for the accuracy evaluation as well as the visualization in the produced maps. Picture source: “VAW ETH Zürich”

## I. Appendix 9: Designed Printed Map

# Rhone Glacier

## Glacier Tongue Retreat between the Years 1874 and 2009



### Legend

- 1874
- 1919

- 1929
- 1951

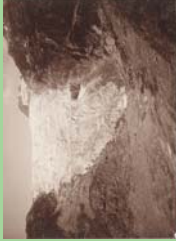
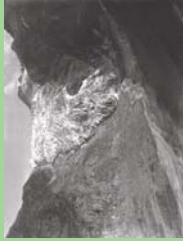
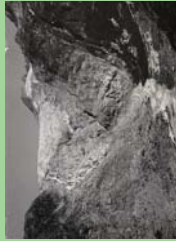

- 2009

Year of the image: 1874



### Description

Since 1874, the Rhone Glacier is regularly surveyed, in terms of its size and its surface movements. Over the last 135 years, the glacier tongue retreated 2 kilometers in its overall length.

	<b>1919</b> Between the years 1874 and 1919, the glacier ice was melted over a length of approximately 1km. This represents a decline of 22 meter per year.
	<b>1929</b> In the 10 years from 1919 to 1929, the Rhone Glacier retreated 50 meters, on average.
	<b>1951</b> Between 1929 and 1951, the glacier shrank circa 400 meters. This represent a decline of 22 meter per year.
	<b>2009</b> From 1951 to 2009, the Rhone Glacier retreated about 340 meters. This represent a decline of 7 meter per year.

### Imprint:

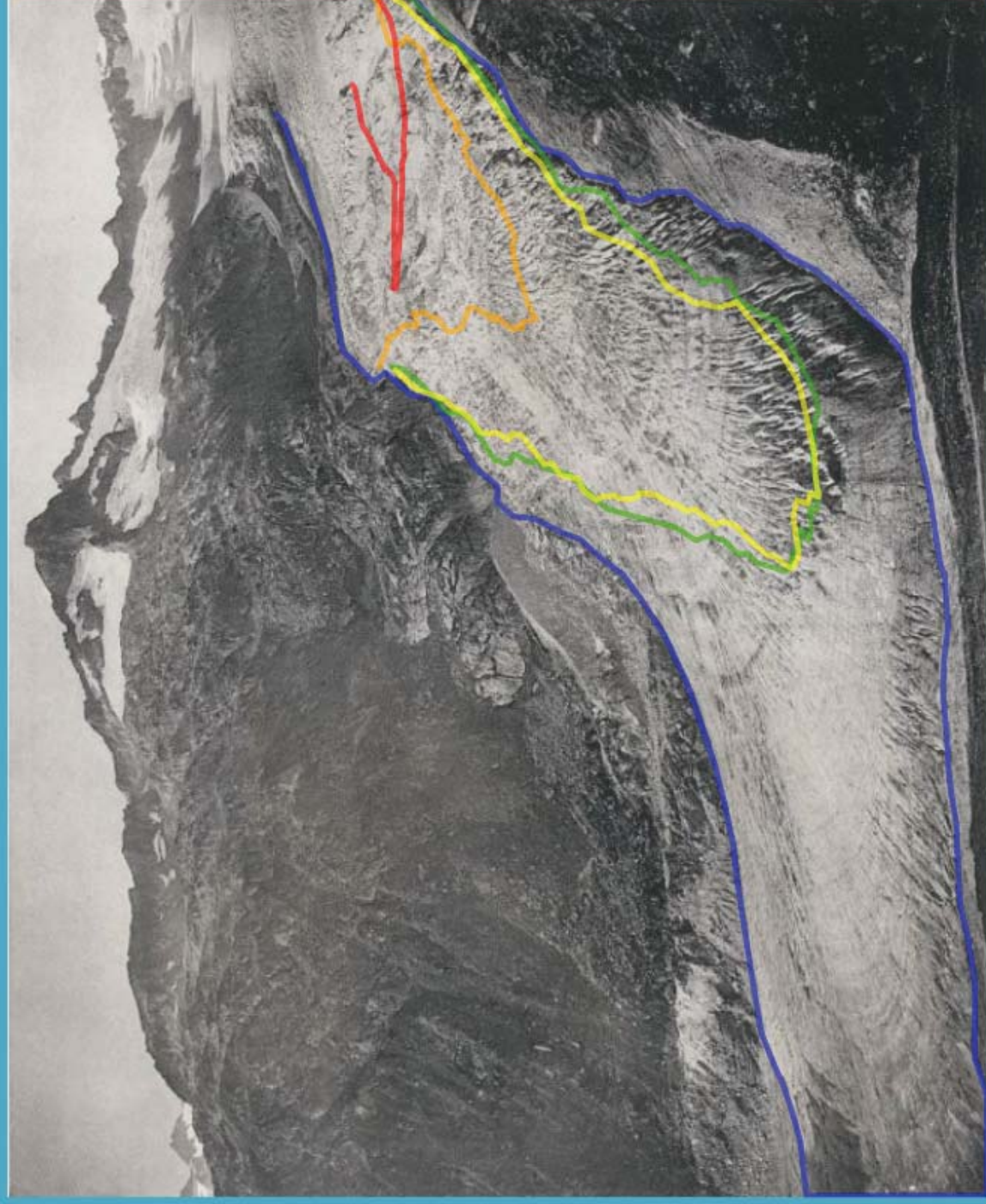
Master thesis, autumn semester 2011/12  
Institute of Cartography and Geoinformation, ETH Zurich  
Supervisor: Samuel Wiesmann, Lorenzo Oleggini  
Author: Ladina Steiner  
Created: 17.12.2011

Image Sources:  
ETH-Bibliothek Zürich, Bildarchiv  
Data Sources:  
Reproduced with permission of swisstopo (JA100120)

## J. Appendix 10: Designed Web Map Application



# Rhonegletscher - Rückzug der Gletscherzunge seit dem Jahr 1874



## Gletscherzungenstände

☒ Alle Stände anzeigen

2009

1951

1929

1919

1874

Animation starten

## Basiskarten

☐ Postkarte aus dem Jahre 1874

☐ Orthophoto aus dem Jahre 2007

☐ Landeskarte aus dem Jahr:

## Impressum:

Ladina Steiner, 26.01.2012

Institut für Kartografie und Geoinformation, ETH Zürich

## Beschreibung

## Referenzkarte



Bildquelle: ETH-Bibliothek Zürich, Bildarchiv

Datengrundlage: Reproduziert mit Bewilligung von swisstopo (JA100120)

Georeferencing monoploting software:

WSL Monoploting Tool, Claudio Bozzini, Swiss Federal Research Institute WSL Bellinzona

Project: Landscape evolution with historical pictures and monoploting

## K. Appendix 11: Structure of the Enclosed DVD

- Bericht
- Grundlagen
  - Auswertungen
  - Daten
  - Literatur
- Karten
  - Gedruckte Karte
  - Web Karte
- Konzept
- Poster
- Praesentation