



## FINAL REPORT

# Advances in Visual Applications:

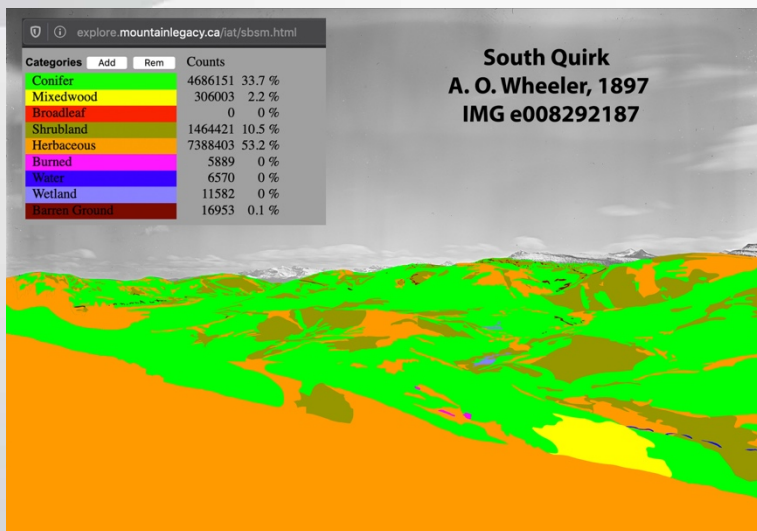
## *Visualizing & Quantifying Landscape Change in SW Alberta Using Mountain Legacy Project Photography*



Final Report  
fRI Research Landscapes in Motion,  
part of Healthy Landscapes Program

June 1, 2020

Eric Higgs, Mary Sanseverino, Mike Whitney, and Julie Fortin  
University of Victoria, School of Environmental Studies



**fRI** Research  
Informing Land & Resource Management



## ABOUT THE AUTHORS

The Mountain Legacy Project, which anchors the Visual Applications Team, explores all that changes in Canada's mountain landscapes. Working with the world's largest collection of systematic historical mountain photographs, MLP researchers follow the footsteps of historic surveyors to retake the original images. MLP scholars engage university researchers, managers, and practitioners in understanding the how and why ecosystems, landscapes, and human communities change over time. Based in the School of Environmental Studies at the University of Victoria, MLP's work since 1998 involves repeat photography, archival research, image interpretation and analysis, software development, and making these images widely available.

Learn more at [mountainlegacy.ca](http://mountainlegacy.ca)

Or, examine the historic and repeat images in their geographic context using MLP's Explorer website:

[explore.mountainlegacy.ca](http://explore.mountainlegacy.ca)

Prepared by

Eric Higgs, Professor, UVic School of Environmental Studies. Principal Investigator, Mountain Legacy Project.

Mary Sanseverino, Teaching Professor Emerita, UVic Department of Computer Science.

Research Associate, Mountain Legacy Project. *Communicating author:* [msanseve@uvic.ca](mailto:msanseve@uvic.ca)

Michael Whitney, PhD Research Associate, Mountain Legacy Project.

Julie Fortin, MSc Research Associate, Mountain Legacy Project.

## DISCLAIMER

Any opinions expressed in this report are those of the authors, and do not necessarily reflect those of the organizations for which they work, or FRI Research.

June 1, 2020



## OUR PARTNERS





## ACKNOWLEDGEMENTS

We would like to thank the Forest Resources Improvement Association of Alberta for funding. MLP also gratefully acknowledges our research partners and collaborators at Library and Archives Canada / Bibliothèque et Archives Canada LAC/BAC. Their sustained care and curation of Canada's heritage as well as their commitment to sharing it with researchers enables us to carry the Mountain Legacy Project forward.

We also acknowledge with gratitude and humility the outstanding efforts of MLP field crews past and present. Without their enthusiasm, passion, care, and dedication none of this work would be possible.

## INDIGENOUS PEOPLES ACKNOWLEDGEMENTS

**MOUNTAINS** make up one quarter of the Canadian land mass. They have been home to a vibrant diversity of Indigenous Peoples for thousands of years. We wish to recognize the traditional, and in some cases unceded, territories of First Nations, Métis, and Inuit upon which we carry out our repeat photography fieldwork. In an era where efforts at meaningful reconciliation with Indigenous peoples are being made, it is important to the Mountain Legacy Project that we wholeheartedly acknowledge the peoples whose land we move through, making our work possible and meaningful. Currently, our fieldwork stretches over Alberta, British Columbia, the Yukon and the Northwest Territories on Treaty 6, 7, 8 and 11 lands, including much unceded territory where treaties were not signed.



## REPORT SUMMARY

This report surveys the research participation, challenges, accomplishments, and contributions the Visual Applications Team made to the overall Landscapes in Motion (LiM) project. Based at the University of Victoria's School of Environmental Studies, scientists from the Mountain Legacy Project (MLP) formed the Visual Applications Team. With expertise in repeat photography, analysis of historic and modern images, and access to an extensive collection of historic imagery – 1888 to the 1950s – MLP was an excellent fit with the LiM study area. The LiM project provided both resources and collaboration that helped MLP researchers develop an end-to-end process for visualizing, classifying, and quantifying landscape change as seen in images from the study area. This is a signal accomplishment: the development of new software unlocks the potential of a large collection of oblique (ground level) photographs. One of MLP's key goals as part of the LiM project was to generate georeferenced viewsheds of land cover classes identified in the historic images. Through development of MLP's Image Analysis Toolkit (IAT) this goal was realized. This report details the development behind three key IAT processes that made this possible: The Alignment Process, the Virtual Photograph Process, and the Viewshed Creation Process. Examples from the LiM study area in the SW Canadian Rocky Mountains are featured throughout.



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# 1. INTRODUCTION

## 1.1 BACKGROUND

The forests of southwestern Alberta are valued in many ways. They are the headwaters of our rivers; providing opportunities for recreation; diverse habitats for wildlife and fish; and jobs in forestry, ranching, tourism and oil and gas. Like all forest types in Canada, these forests are “disturbance dependent”. They constantly change as natural disturbances such as fire and insect outbreaks reshape the landscape, resulting in a shifting pattern of old and younger forests, habitat types, nutrient availability, and even water flow and sedimentation. In Alberta, our approach to caring for our forests is to learn from these natural patterns and to try to maintain them with the idea that the forest ecosystem will continue to provide the range of services and habitats we value. To do so, we need to understand not only how, where, when, and in what form disturbances occur (i.e. a “disturbance regime”), but how disturbances influence other landscape values over time and space.

Applying this concept to southwestern Alberta has proven to be a challenge for several reasons. First, we are discovering that the pattern of fires is more complex in this area than we previously assumed. Rather than seeing only intense forest fires that kill all the trees, which are then replaced by a completely new, young forest, it appears that lower intensity fires also occur that kill only a portion of the trees. Therefore, rather than having even-aged forests covering the landscape, historic landscapes may have had a mixture of even and multi-aged stands resulting from a “mixed severity fire regime” (MSRF). A second challenge is that many human disturbance activities in our forests are very different from natural disturbances. For example long linear features like trails and roads through the forests are not seen in the patterns created by fires and insects. These human disturbances can create unforeseen, and often negative impacts on forest ecosystems, including altering predator-prey interactions, and increasing sedimentation in streams and rivers. Both challenges have potential implications for forest managers who are trying to be informed by natural patterns in how they can better manage the forests.

Towards addressing this knowledge gap, a larger project proposal for Alberta Innovates called “*Science-based management tools to support Ecosystem-Based Management of forests in Southwestern Alberta*” was developed and approved in 2016 that included four elements with four goals:

- 1) Provide the details of what the historic fire regime in southwestern Alberta was through dendrochronological field sampling, lab processing, cross-dating, and spatial analyses.
- 2) Understand better what the historic landscape condition was, and how they have changed over the last century through the use of historical oblique aerial photos, and
- 3) Create computer models that will integrate knowledge gained from the first two elements to simulate these patterns over time and space.
- 4) Understand the differences between the sedimentation caused by both natural and human caused disturbances.





This report describes the findings and outcomes from the second element from above on oblique photography analyses.

## 1.2 LANDSCAPES IN MOTION

The intimate and logical relationship between the first three of these elements from the original SW Alberta AI proposal quickly teamed up under the lead of Dr. Anderson to enable a) greater integration, communications, and efficiencies, and b) apply for additional funding (as per the AI proposal). This team became known as ***Landscapes in Motion***, or LIM.

The subsequent funding application to the Forest Resource Improvement Association of Alberta (FRIAA) not only allowed for the completion of the original objectives from the Alberta Innovates proposal, but expanded on it. The following is a list from the FRIAA proposal. Items 1-4 were the promised deliverables to Alberta Innovates (conditional on finding supporting funding). Items 5-7 (in italics) were the additional items as part of the FRIAA proposal.

- 1) Develop and refine two interrelated analytic tools for assessing vegetation pattern changes in historical and repeat oblique photographs. The first tool extends from an adaptation of a mono-plotting tool that transforms digital oblique images to an overhead projection suitable for spatial analysis. The second tool uses web-based visualization tools to segment, classify and calculate statistical changes in images over time.
- 2) Develop a first approximation landscape-scale ‘model’ of mixed-severity fire regime dynamics in southwestern Alberta using available related studies, knowledge of mixed-severity fire regimes in related ecosystems, and knowledge gained from objective #1.
- 3) Document the patterns of historical fire severity (including the incidence of partial severity burning), frequency, and size in the SW Alberta foothills.
- 4) Develop a first approximation of a fire spread module capable of dealing with partial mortality.
- 5) *Evaluate the external drivers (i.e. topography, climate) and key self-regulating fire feedbacks (fire severity-frequency interactions) of the historical fire regimes in the SW Alberta foothills.*
- 6) *Integrate the new knowledge from objectives #1, #2, #3, and #5, and the new module from #4, into an existing modular spatial simulation modelling framework called SpaDES. Included in this objective will be the calibration of all modules, and other fire regime parameters (as available) to the SW Alberta study area.*
- 7) *Share the process of the exploration of historical landscape dynamics and model development with stakeholders and the public via a dedicated outreach program.*

This report describes the findings and outcomes from the original first Alberta Innovates LIM element on computer modelling, in support of item #1 above.

## 1.3 STUDY AREA

The study area for the larger SW Rockies project covers about 950,000 ha bordered by the US border to the south, Bow Valley to the north, the treeline to the west, and a mix of parkland and fescue to the east. It is a long, narrow zone in which elevation, physiography, soils, and climate change over very short distances from east to west. It includes parts of the Montane (55%) and Subalpine (45%) natural subregions. The climate ranges from mild summers



and warm winters at lower elevations to cool wet summers and long cold winters at higher elevations, and conditions can change dramatically over very short distances in response to topography. Tree species range from Douglas fir, aspen, lodgepole pine and white spruce to englemann spruce and subalpine fir at higher elevations to the west. Soils are similarly variable, from chernozems to the east to luvisols and brunisols to the west.

## 1.4 INDIGENOUS PEOPLES

The Landscapes in Motion study area is strongly associated with the traditional territory of the *Piikáni* Nation (Reeves and Peacock 2001, McMillan and Yellowhorn 2004) and is encompassed by *Kitaowahsinnoon*, the broader territory of the Blackfoot Confederacy (Blackfoot Confederacy 2020). As well, the traditional territory of the *K'tunaxa* Nation, who live west of the Rocky Mountains, overlapped the southern Alberta Foothills where they travelled annually to hunt (Brink 1986, Reeves and Peacock 1995, 2001, McMillan and Yellowhorn 2004, *?aq'am* 2020).

Since time immemorial, the southern Alberta Foothills have been home to the *Piikáni* (Peigan), *Iyarhe Nakoda* (Stoney Nakoda), and *Tsuut'ina* (Sarcee) Nations, as well as the *Siksika* (Blackfoot) and *Kainai* (Blood) Nations who live on the Great Plains to the east (McMillan and Yellowhorn 2004). Today, the *Siksika*, *Kainai* and *Piikáni* (*Apatohsippiikani* in Alberta and *Amsskaapiikani* in Montana) are collectively known as *Siksikaitstapi* or the Blackfoot Confederacy (Yellowhorn and Plain Eagle undated, McMillan and Yellowhorn 2004, Oetelaar and Oetelaar 2006).

The member Nations of the Blackfoot Confederacy travelled seasonally within their territories to hunt game and collect plants, moving onto the grasslands in summer and returning to the valleys of the foothills during winter (Reeves and Peacock 2001, McMillan and Yellowhorn 2004, Oetelaar and Oetelaar 2006). The foothills environments also provided year-round habitat for bison (*iini*), a coveted resource that provided food, clothing, shelter, and was the foundation of many cultural and spiritual customs (Yellowhorn and Plain Eagle undated, McMillan and Yellowhorn 2004). A rich archaeological record within our study area (Brink 1986, Reeves and Peacock 1995, 2001, Hannis 2012, Zedeño et al 2014), including important sites such as Heads-Smashed-In Buffalo Jump (Reeves 1978, Brink 2008) and Napi's Playground (Yanicki 2014), attest to the enduring and intimate use of this landscape by the *Siksikaitstapi* and other First Nations.

The name "Blackfoot" comes from a legend of walking across burned prairie (McMillan and Yellowhorn 2004). Oral histories and physical evidence indicate controlled burning was practiced to cultivate plants for harvesting and maintain productive meadows for bison and horses, especially near seasonal encampments and bison jumps (McMillan and Yellowhorn 2004, Brink 2008, Oetelaar and Oetelaar 2008, Zedeño et al. 2014, Roos et al. 2018). As well, burning the perimeter of camps, especially near tree groves near springs and river crossings along travel corridors, reduced surface fuels and the chance of crown fire ignited by uncontrolled grassfires (Oetelaar and Oetelaar 2008). Journal entries by Peter Fidler of the Hudson Bay Company, who lived with the *Piikáni* in 1792-3, documented these practices (Fidler 1991). He recorded numerous controlled burns over large areas in the grasslands along the Foothills between November and March and noted they were ignited by people (Fidler 1991), rather than lightning (Oetelaar and Oetelaar 2008). Although Fidler did not report burning in mountain valleys, others have attributed the establishment and persistence of grasslands in river valleys of the Foothills, including the Old Man River, to Indigenous fire management (Pickard 1981; Stockdale et al. 2019).



The arrival of Europeans disrupted the Blackfoot way of life, with direct and indirect impacts on cultural fire practices (Stockdale et al. 2019). Epidemics of smallpox and other diseases were introduced by Europeans in 1730s, 1830s and 1860s (Reeves and Peacock 1995, 2001, McMillan and Yellowhorn 2004, Hannis 2012). The rapid destruction of bison herds to near-extinction during the 1860-80s undermined the lifeblood of the Blackfoot traditional land and cultural practices (McMillan and Yellowhorn 2004, Brink 2008, Oetelaar and Oetelaar 2006). In 1877, the Blackfoot Treaty (Treaty #7) was signed by the five Indigenous Nations of southern Alberta, yielding 129,500 square kilometers of land in return for reserves, the promise of livestock, farming implements and other considerations (Government of Canada 2009). Ultimately, the Treaties and Indian Act largely removed the Blackfoot from their traditional territories and cultural practices by confining people to reserves where farming and ranching were controlled by federal Indian Agents and by requiring children to attend residential schools (McMillan and Yellowhorn 2004, Appendix 1 in Yanicki 2014). Nevertheless, many Blackfoot traditions remain strong and Elders hold knowledge of their traditions associated with the land, plants, and animals (Reeves and Peacock 1995, McMillan and Yellowhorn 2004), which is critical for understanding, managing and restoring the Foothills landscape (Oetelaar and Oetelaar 2006, 2008).

## 1.5 PARTNERS

The Southern Rockies project began as an Alberta Innovates project on behalf of the Government of Alberta. The delivery of the four project elements was the responsibility of fRI Research, who managed that administration and budget. The fRI Programs involved includes the Healthy Landscapes Programs (elements 1-3, or LIM) and the Water Program (element 4). The LIM component was further supported by a FRIAA application, as well as two successful Mitacs Accelerates, and two more Mitacs Elevates.

## 2. THE MOUNTAIN LEGACY PROJECT

In 2016 [Mountain Legacy Project](#) (MLP) scientists joined [Landscapes in Motion](#) as the Visual Applications team. As described above, we feel that combined the teams go beyond what any could accomplish separately. Not only has MLP provided scientists and expertise to the Oblique Photography group, but its extensive collection of historic imagery – 1888 to the 1950s – is an excellent fit with the study area (Figure 1). There are between 400-500 historic survey stations within the study area boundary. Each station has an average of five historic images and, in the majority of cases, their repeats. In total approximately 2000 – 2500 images cover the area.

For some years the Mountain Legacy Project has offered a geographically ordered view into the landscapes of change in the Canadian mountain west through the web-based [Mountain Legacy Explorer](#). At present the site hosts approximately 16,000 historic images of mountain landscapes and just below 9,000 modern repeats.

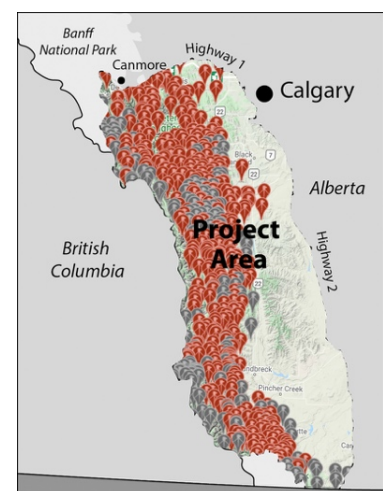
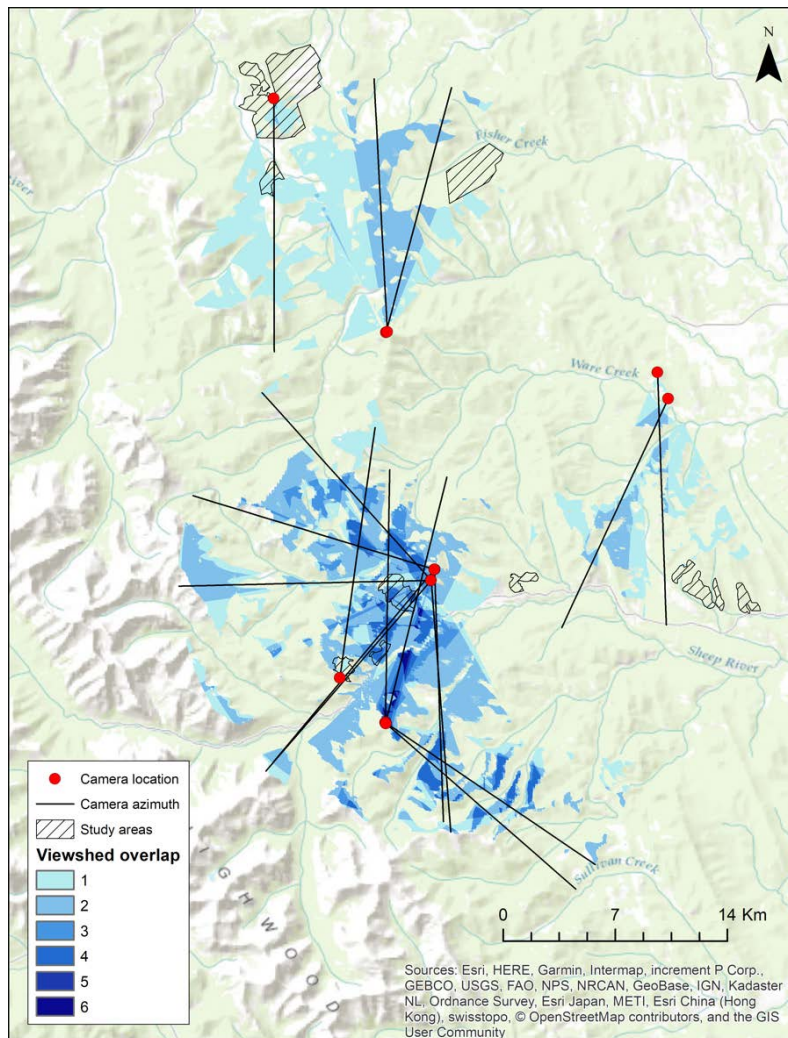


FIGURE 1: THE STUDY AREA WITH MLP IMAGE COVERAGE. VISIT [EXPLORE.MOUNTAINLEGACY.CA](https://explore.mountainlegacy.ca) FOR IMAGE DETAIL.



The LiM project provided both resources and collaboration that helped MLP researchers further develop the Image Analysis Toolkit (IAT), an end-to-end process for visualizing, classifying, and quantifying landscape change as seen in the images. Although difficult to select from within the thousands of images in the MLP collection, close collaboration, especially with the Fire Regime Team, brought MLP focus onto both a region within the overall study area and a specific set of matching images.

The region in focus encompasses the upper Elbow and Sheep River watersheds. As a trial of the newly developed image analysis processes, 17 historic images from eight common station locations in this area were selected for in-depth analysis. In all, these images, taken in 1895, 1897, 1916, and 1940, look out over approximately 350 square kilometres of land. Figure 2 gives an overview of the Stations, images, and Field of View (FoV) each covers. The *Study Areas* denoted on the Figure 2 map show part of the Fire Regime Team’s research locations.



**FIGURE 2: SELECTED MLP STATIONS AND IMAGES WITH APPROXIMATE IMAGE FOV.**

**MAP DESIGNED AND CREATED BY JAMES TRICKER, PHD CANDIDATE,  
UVIC SCHOOL OF ENVIRONMENTAL STUDIES, AND MLP RESEARCH ASSOCIATE.**



This report details the processes encompassed by the Image Analysis Toolkit and presents a full example of end-to-end image visualization and land cover quantification from one of the images: Arthur Oliver Wheeler's 1897 South Quirk Station, IMG W97-14-7 (Library and Archives Canada ecopy # e0082922187).

A website featuring all 17 of the images and allowing for downloads of all digital assets associated with each can be found at [mountainlegacy.ca/project/iattool](http://mountainlegacy.ca/project/iattool).

While there is still development needed on a number of fronts, we are confident in characterizing IAT as a modular, flexible, and comprehensive means for analysing oblique photographs. As demonstrated here IAT can be used as an effective end-to-end application for handling a variety of tasks critical to interpreting and analysing oblique photographs: aligning, virtualizing, classifying, and rectifying. Continuing to improve IAT, especially through collaborations like LiM, not only puts the vast oblique image collections of the Mountain Legacy Project within the grasp of more researchers, but helps to open them to more and deeper analysis.

The LiM project has assisted us in embracing the challenge of applying computer image processing and visualization techniques to the collection of images that make up the Mountain Legacy Project. The work is difficult, but the rewards of being able to push our look at landscape change back to the late 19<sup>th</sup>, early 20<sup>th</sup> century has ramifications for better understanding these environments, especially in an ever-warming world.

## 3. METHODOLOGY

Since its inception in 1998, the Mountain Legacy Project has used historic images and matching modern repeat photos to examine landscape level change in the Canadian cordillera. Analysis has been both qualitative and quantitative and has played a significant role in a diverse array of research projects and papers. See for example an overview of the resource by Trant et al., [1], use of historic/modern images in estimating landscape composition by Fortin et al., [2]; use of repeat photography in assessing land cover change by Rhemtulla et al., [3].

### 3.1 METHODOLOGY OVERVIEW

In 2015 a group of computer scientists attached to MLP began to look through the diversity of MLP research to see if it was possible to develop a suite of image analysis tools that would help MLP and other research teams better pursue their work. The computer scientists asked the following research question: "What kind of visual applications will help researchers explore, interpret, and discover meaning in the images"? The first step in answering this question was the Image Analysis Toolkit (IAT). Its initial development underpins much of the methodology discussed here. An overview of its features was published by Sanseverino et al. in Mountain Research and Development in 2016 [4]. IAT development context as of 2016 can be seen in Figure 3 below. The area highlighted in light green represents IAT development pre-Landscapes in Motion (LiM).

Resources and collaboration facilitated by LiM afforded MLP the opportunity to work on building out IAT into an end-to-end process that allows the following:



- Align historic and modern images.
- Compare images visually using fades, scaling, sweeps, and windows.
- Apply user-initiated landscape classification categories to the images.
- Generate landscape classification masks from the images.
- Visualize change between classification masks and their associated images.
- Quantify change within classification masks between images.
- Quantify the actual “on-the-ground” extent of each class in a given image (e.g., hectares, square metres).
- Produce a georectified viewshed of the landscape classification mask for a given image.

Other guiding concepts for IAT development encompass the following:

- Support for an end-to-end process for MLP’s unique workflow.
- Be entirely accessible to researchers from all mountain study areas – hence a commitment to web-based development.
- Work with the strengths of MLP’s oblique image collection rather than converting immediately to rectified images.
- Be adapted to the finest resolution MLP’s image collection could provide.

Figure 3 is a process diagram showing how IAT can be used to take an initial historic/modern image pair from segmenting into landscape classification masks through to creating georeferenced viewsheds of those masks. Such viewsheds are suitable for incorporating into a GIS for further spatial analysis.

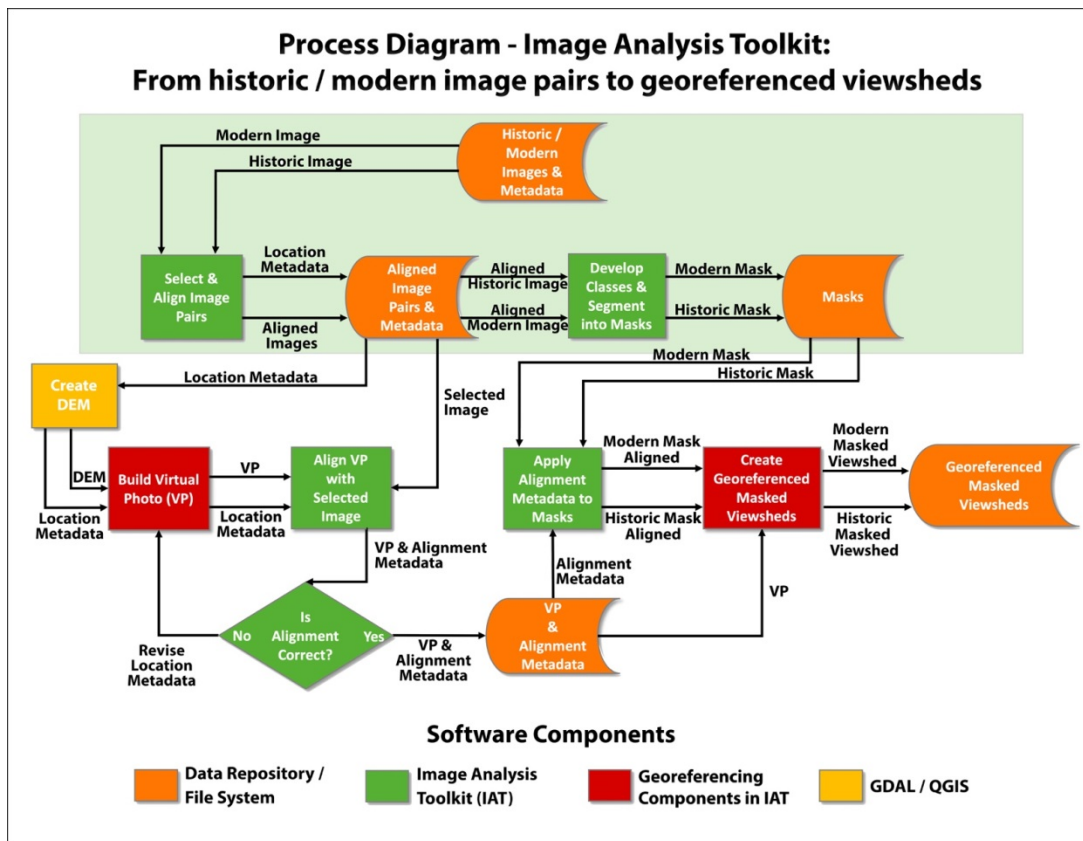
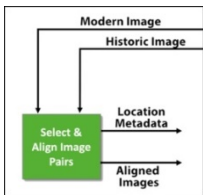


FIGURE 3: PROCESS DIAGRAM SHOWING THE END-TO-END IMAGE ANALYSIS TOOLKIT (IAT) METHODOLOGY.



Three processes are key to using IAT to generate georeferenced viewsheds from oblique images: 1) Image Alignment, 2) Building Virtual Photos, and 3) Creating Georeferenced Masked Viewsheds.

### 3.2 ALIGN IMAGE PAIRS PROCESS

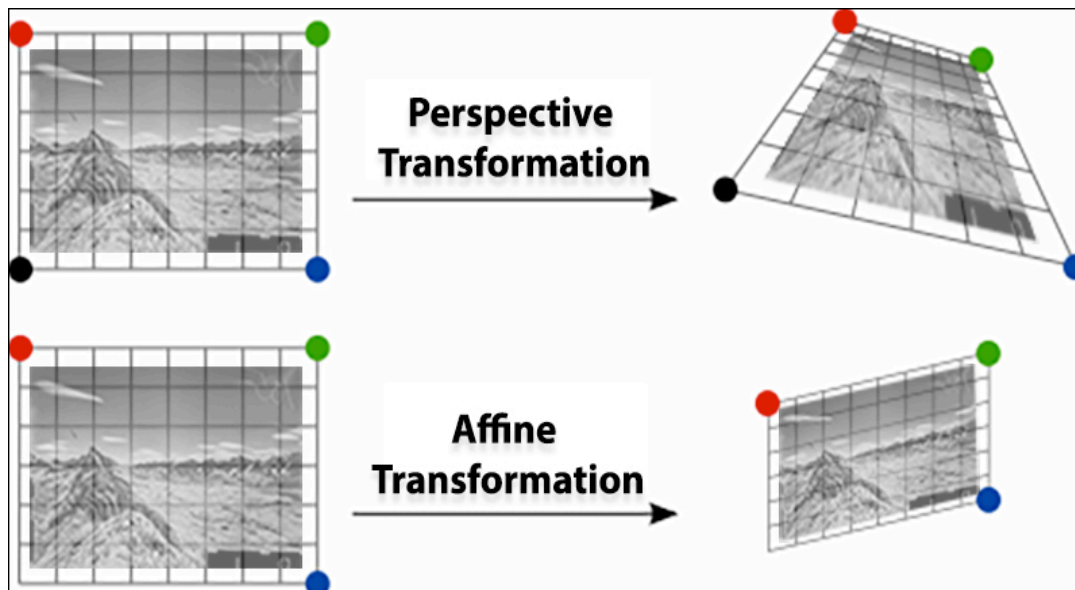


In order to compare an historic photo with its modern repeat the images have to be as accurately aligned as possible. Therefore, the process of image alignment is at the heart of almost all Mountain Legacy analysis. And the key assumption behind any alignment is that matching control points selected in each of the images do indeed accurately describe the same location in the both photos. If this is true, then a mathematical model can be used to transform the images into an aligned pair.

In IAT this foundational process is realized using one of two different models: an affine transformation model or a perspective transformation model.

Both affine and perspective transforms imply that straight lines stay straight, and planes stay planar. In an affine transform parallel lines maintain their parallel nature and length ratio. A perspective transform allows parallel lines to converge. The result of an affine transform on a rectangular image will always be a parallelogram, while a perspective transform yields the more generalized quadrilateral. Figure 4 gives an overview of the difference between the two.

As can be seen in Figure 4, three point pairs are required for an affine transform. In IAT three control point pairs in an historic/modern pair will automatically generate an affine transformation. Four or more control points will result in a perspective transform. An online video illustrates a perspective alignment at work in IAT: [Aligning South Quirk – 1897 and 2014.](#)





If more than four point pairs are defined, IAT minimizes the root-mean-square error (RMSE) among all possible combinations of four pairs. The result is the “best” four pairs. The perspective transformation is performed using these point pairs. For example, if six point pairs are defined, then IAT would choose the best among 15 possible transformations.

The same process and assumptions are used when aligning a selected image to a Virtual Photo (VP) of the same scene. In the first case, use of the alignment tool allows better direct comparison between the historic and modern image pair. In the second case, the alignment tool is used to align a selected image to a Virtual Photo (see section 2.3) of the same scene. In either case, poor alignment can be corrected by selecting control points more carefully. But, in the case of alignment with a Virtual Photograph, it is also possible to adjust the camera location parameters thereby more perfectly aligning VP to the same location as where the actual photo was taken from.

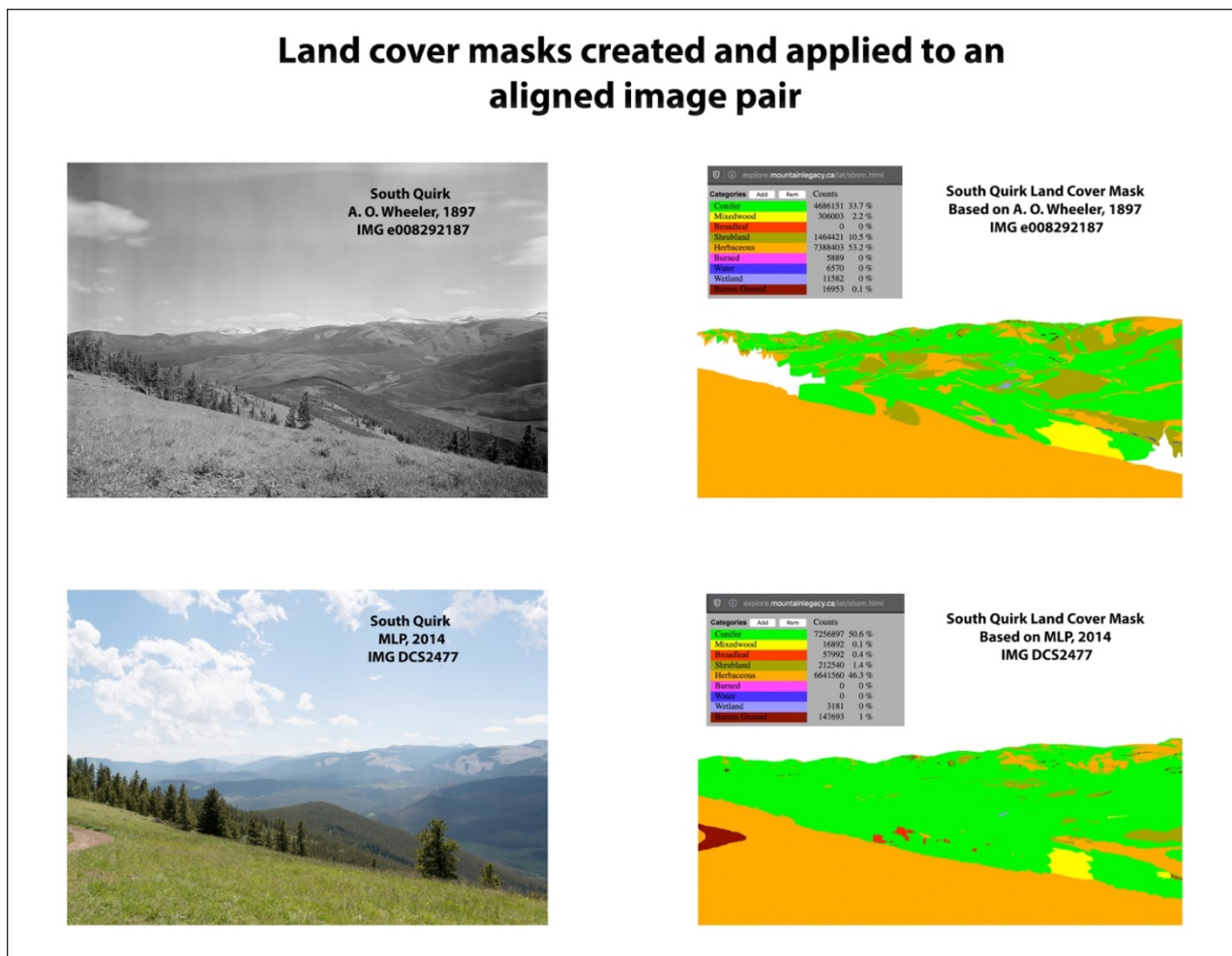


FIGURE 5: WORKING WITH ALIGNED IMAGES ALLOWS LAND COVER CLASSIFICATION MASKS TO BE MORE READILY COMPARED FOR CHANGE.

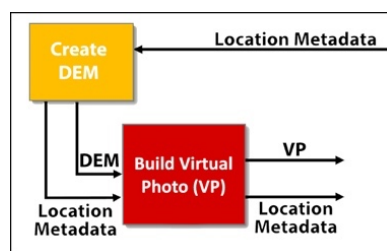




At this point landscape classification and land cover mask creation can take place on two aligned images, which allow land cover masks to be effectively compared and analyzed. Examples of this type of comparison at use can be seen in Fortin et al. [2] and Taggart-Hodge [5]. Figure 5 illustrates the concept with the historic / modern image pair from South Quirk Station – historic photo by Arthur Wheeler, 1897 / modern photo by the Mountain Legacy Project, 2014.

The next step in the process is building a Virtual Photograph (VP) for a selected image. Once a VP is built and correctly aligned with the actual photo, land cover masks from the selected photo can be overlaid on the VP and used to create georeferenced viewsheds.

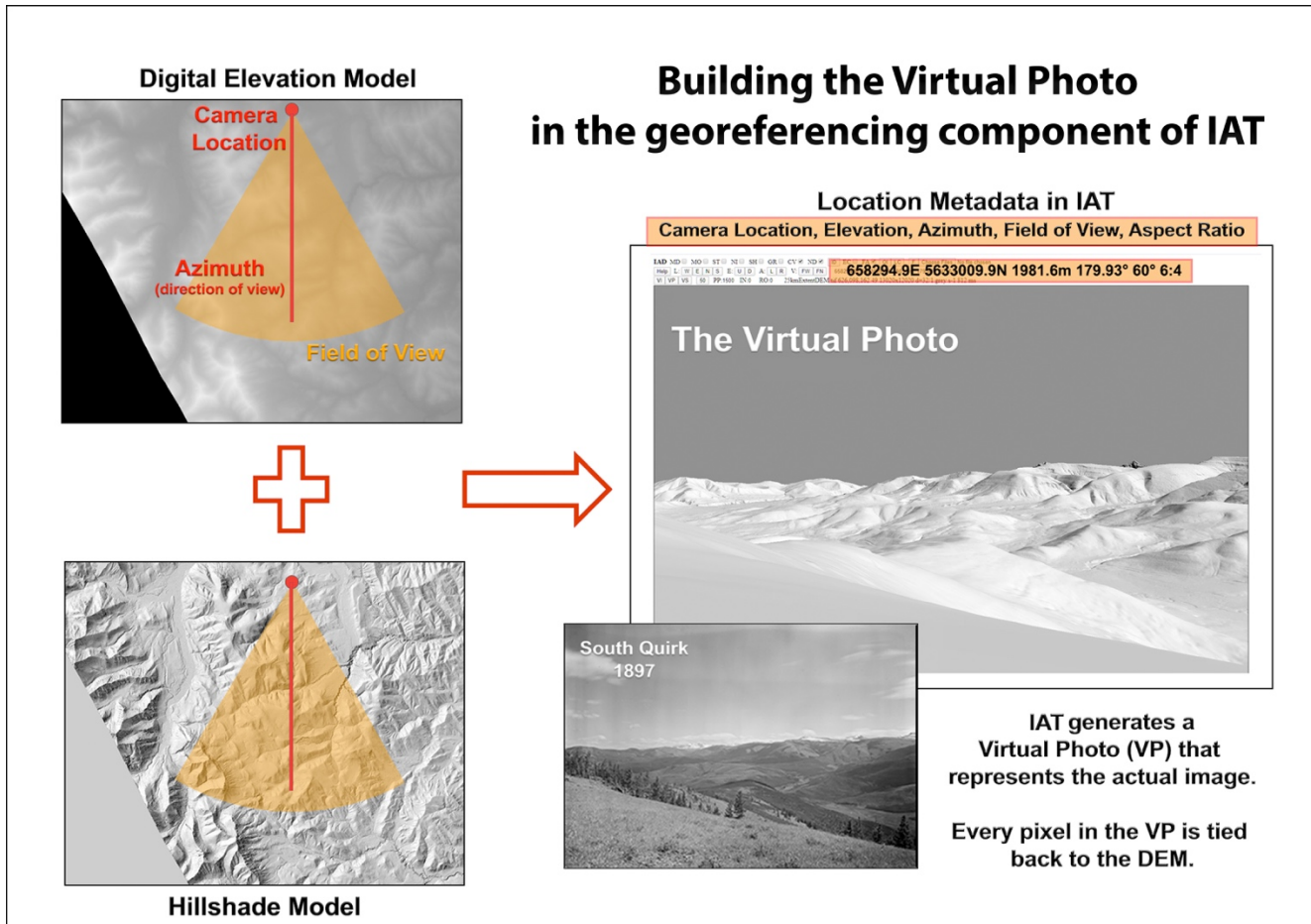
### 3.3 BUILD THE VIRTUAL PHOTO PROCESS



The Virtual Photo is a shaded 3D representation of the terrain in a given photograph – a “virtual” representation of the photograph. The more closely the location metadata agrees with the true camera location, the more accurately the VP represents the actual image. The Build Virtual Photo Process is one of the georeferencing components in IAT. Building a VP depends upon accurate location metadata. This includes the camera location in UTM coordinates, the azimuth

(direction in degrees that the camera is pointed), and the Field of View (FoV) encompassed by the camera. Fine-tuning the VP is often required as standard GPS field units can be out as much as +/- five metres. Such adjustments include moving the camera position, tilting (inclining) the camera up or down, and rotating (rolling) the camera side to side. When a final VP is produced, information about the height and width size (in pixels) and aspect ratio of the actual photo is also required.

Any given Virtual Photo is based upon a Digital Elevation Model (DEM) of the landscape the actual photo looks out into. The DEMs used in the LiM project are created from 2 metre resolution lidar-derived bare earth Digital Terrain Models (DTM), courtesy of Alberta Environment and Parks. The appropriate DTMs are mosaicked into a DEM using a GDAL (Geospatial Data Abstraction Library) component from the Open Source Geospatial Foundation. A hillshade model along with an algorithm designed to look "forward" (the Forward Algorithm - FA) along rays of light emanating from the camera is applied to the DEM. This assists in making a more easily recognizable Virtual Photo of the landscape represented in the actual image. Figure 6 demonstrates the VP Build Process.



**FIGURE 6: THE VP IS A PERSPECTIVE VIEW OF A DIGITAL ELEVATION MODEL WITH HILLSHADING APPLIED VIA THE FORWARD ALGORITHM. THE VIEW DEPENDS ON ACCURATE CAMERA LOCATION METADATA INCLUDING UTM COORDINATES, FOV, AND AZIMUTH. ELEVATION IS ALSO REQUIRED, BUT GIVEN A CAMERA LOCATION IN CONJUNCTION WITH THE DEM, IAT CAN DERIVE ELEVATION.**

### 3.3.1 The Forward Algorithm

The more detailed and realistic the VP, the more accurate its alignment with the actual image. The georeferencing component in IAT implements the Forward Algorithm (FA) to achieve detail that is accurate to the resolution of the underlying DEM. The FA is notable in that it makes a viewshed and an image simultaneously – there is no need to preprocess a DEM first to find visible pixels.

In the following example let us assume, without loss of generality:

- The y axis is the view axis (the direction the camera is looking).
- There is a hill shading model of the same resolution as the DEM available (e.g., the Hillshade Model in Figure 6).
- The camera inclination and rotation is zero degrees.



Let us further assume that the desired VP is going to be 10,000 pixels wide. The FA considers 10,000 rays emanating forward from the camera viewpoint. Taken together the rays will trace out the FoV angle as they move across the DEM. In building the Virtual Photo the FA considers each ray separately with each ray corresponding to one vertical column in the VP.

For a given ray moving forward through the DEM, we are clearly moving away from the camera viewpoint at an angle within the FoV. We move one  $y$  unit at a time, stop at each  $x$  intercept (in this case the  $y$ -axis is the *major axis*, and the  $x$ -axis the *minor axis*), get the elevation at that point with linear interpolation along  $x$ , and then calculate the height  $v$  of the corresponding 2D pixel in the Virtual Photo.

If and only if  $v$  is higher than any previously calculated height, it is visible, and is drawn on the VP using a corresponding linear interpolation applied to the shading model. We proceed along through the DEM until we are off the DEM, or have reached a predefined maximum depth away from the viewpoint. (For the LiM project this might be 30 kilometres or 15,000 DEM pixels.) Now, all higher image pixels in the current column of the VP (aka the *vertical scan line*) are coloured "sky".

Note that when we have found a new visible pixel, we have also identified a location in the viewshed. Since there is an interpolation along  $x$  (with an integral  $y$ ), we define two adjacent DEM pixels as viewshed pixels. For example, if a newly visible 3D pixel is (5.7, 38, 1456 metres), then pixels (5,38) and (6,38) are categorized as within the viewshed. This is accurate to the resolution of the DEM itself.

More work is needed when a newly drawn pixel in the VP leaves undrawn pixels beneath it. Generally speaking, this can happen in the foreground, and at very steep inclines (e.g., cliffs). This situation is easily and deftly handled by interpolating along the  $y$  direction, between the last shading value calculated for this scan line, and the current one, using these calculations to fill in the undrawn image pixels on the VP.

**Appendix A: Visualizing the Forward Algorithm** presents a discussion of the finer points of the FA. Two fully explained diagrams illustrate how the FA moves information from the DEM and hillshade model onto the Virtual Photo.

### 3.3.2 Aligning the VP and actual photo

Once created the VP must be aligned with the actual image in IAT. The VP is the digital artifact that ties the aligned actual photo back to the DEM. Exploiting this relationship allows IAT to generate a georeferenced viewshed of the overlay. For the LiM project the goal was to design and build a web-based process to create georeferenced viewsheds of the land cover masks. MLP researchers *were successful in reaching this goal*. Land cover viewshed masks were created based on images from 1895, 1897, 1916, and 1940. An example from an 1897 image is given in **section 3.0** of this report: **Applying the IAT end-to-end workflow**. Examples from all 17 images can be found online at the Mountain Legacy [IAT Project website](#).

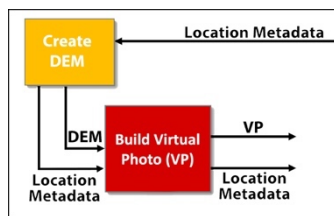
In other photo georeferencing systems (i.e. [WSL- Monoplotting Tool](#) or [Pic2Map](#)) the use of an oblique image (the "human-eye" photo) and an orthogonal ("birds-eye") view from above of the same landscape are required – see for



example Bozzini et al.,[6], Stockdale et al.,[7] and [8], and Marco et al.,[9]. In preferring to stay with the oblique photographs as much as possible, IAT takes a different approach. One that reimagines early work in the field – for example the ideas of Aschenwald et al.,[10] around georectification of high oblique images, Guth and Craven’s [11] use of Digital Elevation Models (DEM) to register oblique images, and Corripio’s [12] “virtual photograph” development. As well, we look to current work – like that of Guillet et al.,[13] on camera calibration – to move forward. Not only does our preference to work within the context of the oblique images match MLP’s philosophy of “letting the photographs speak”, but the user doesn’t have to make the context switch from oblique to orthogonal and back again for every pair of control points selected. Variations in terrain, ridge lines, and horizons are more readily apparent. And, while it is not there yet, IAT shows promise for automatically detecting control points between the VP and actual photo, perhaps using a form of edge and vertex detection. This would allow for automation in what is a somewhat time-intensive process - no matter the system used.

Once the accuracy of the VP to the actual image has been established, georeferencing the viewshed can proceed. This process is described in the next section.

### 3.4 CREATE A GEOREFERENCED VIEWSHED PROCESS



Creating a georeferenced viewshed builds on the relationship formed when an image is aligned with its corresponding Virtual Photo (VP). An aligned image/VP pair has a one-to-one correlation at the pixel level between the image and the VP. And, since the VP has a mathematical correlation to the DEM that was used in its creation, that same correlation can now be thought of as applying to the image.

One of the objectives of the Landscapes in Motion project was to see if MLP researchers could generate a georeferenced viewshed based on the land cover masks from historic images. The georeferencing component of IAT was able to successfully demonstrate this. Figure 7 below illustrates the process using one of A.O. Wheeler’s original 1897 “Irrigation Survey” photographs and a 2014 repeat image from the ["South Quirk" 1897/2014 image pair](#).

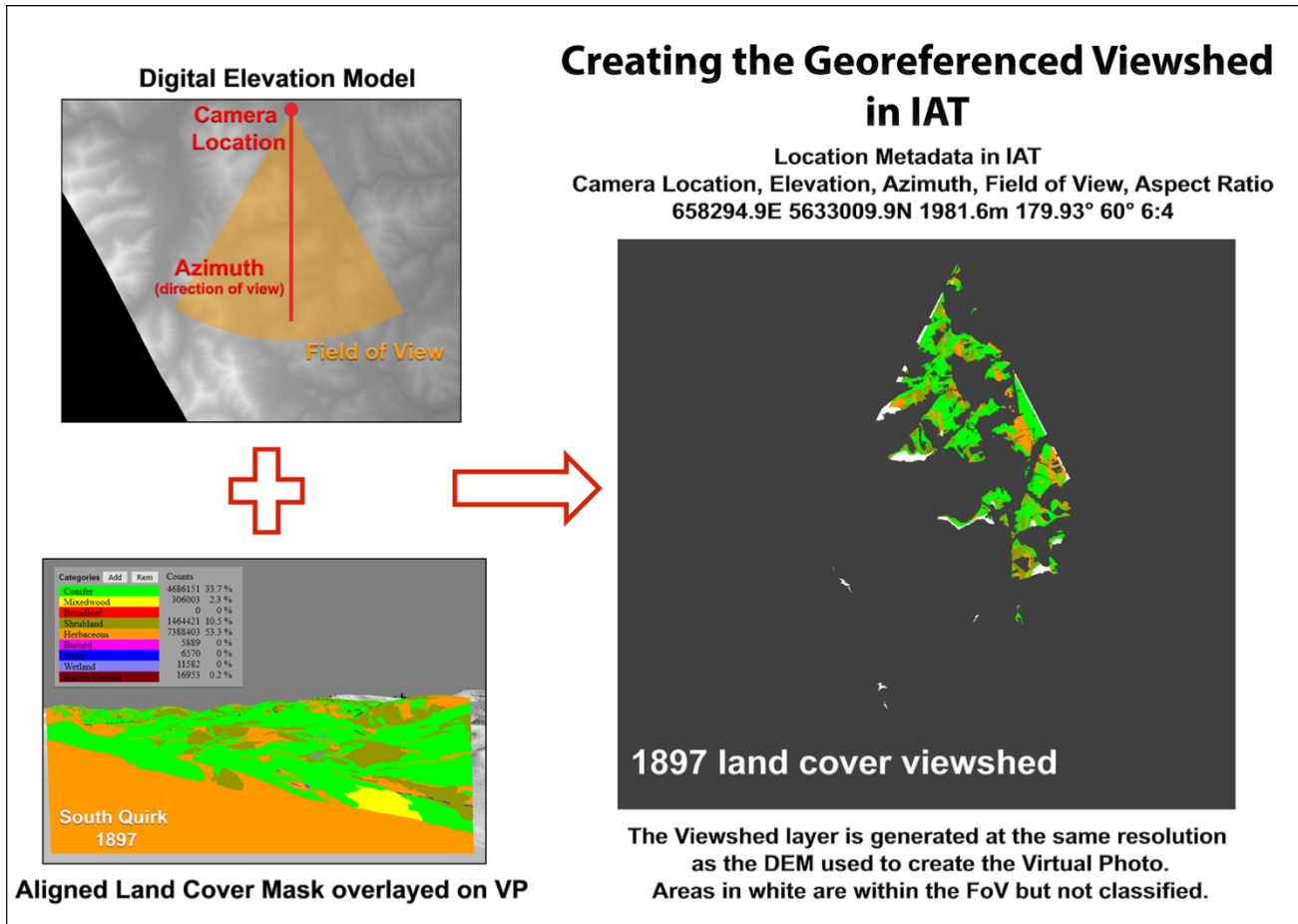
The viewshed generation process turns on the one-to-one pixel relationship between the aligned land cover mask of a given image and its corresponding VP. The algorithm used in IAT to generate the viewshed uses two established information layers to create the resulting viewshed:

- The land cover mask aligned with the VP;
- The DEM used to create the VP;

All of the camera and location information used to create the VP is also included when building the viewshed. Indeed, the same Forward Algorithm (FA) that was used to create the VP is used to create the viewshed. The FA looks “forward” along rays emanating from the camera location – one ray for every column of pixels in the VP. Leveraging the relationship between the VP and aligned mask allows the “forward” ray to look at the corresponding RGB pixel colour for a given location on the mask. The ray then “paints” that colour onto the correct pixel in the viewshed layer.



Because the VP and its corresponding land cover mask are finer in resolution than the DEM, every pixel in the DEM that would be visible in the VP is covered by at least one pixel in the land cover mask. Therefore, the rays in the Forward Algorithm are going to paint every pixel in the viewshed at least once, and many of the pixels - in the foreground especially - will be painted multiple times. In this way the viewshed fully captures the continuity of mask and its underlying VP: if a given pixel is visible in the VP and classified in the land cover mask, it will be visible on the viewshed at the resolution of the DEM.



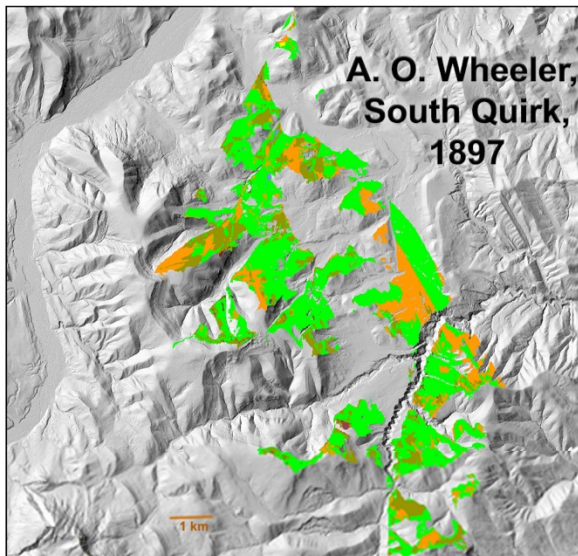
**FIGURE 7: THE VIEWSHED LAYER IS GENERATED IN THE GEOREFERENCING COMPONENT OF IAT. IT IS BUILT USING THE FORWARD ALGORITHM WHICH DETERMINES THE COLOUR OF A PIXEL IN THE LAND COVER MASK, ITS CORRESPONDING LOCATION ON THE DEM, AND "PAINTS" IT ONTO THE VIEWSHED IN THE CORRECT LOCATION. THE RESULT IS A GEOREFERENCED VIEWSHED OF A LAND COVER WHICH, IN THIS EXAMPLE, DATES BACK OVER 120 YEARS TO 1897.**

Since the resolution of the DEM is known – in the case of the LiM project it is 2 metres – the actual area in square metres / hectares of each land cover class represented on the viewshed can be calculated in IAT. Opening the viewshed in IAT and running an analysis on pixels per class gives the total number of pixels in each class. Multiply the class totals by four (in this case) and the area in square metres is returned. Figure 8 demonstrates this by comparing South Quirk viewsheds from 1897 and 2014.

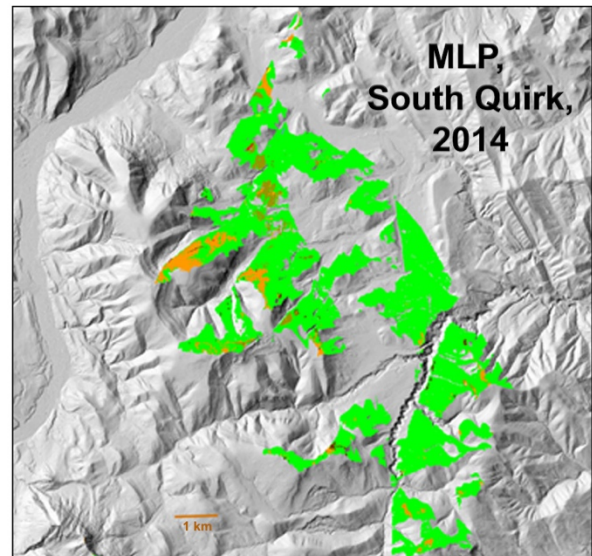


## Land Cover Quantification using viewsheds created with the georeferencing component of IAT

Location Metadata in IAT  
Camera Location, Elevation, Azimuth, Field of View, Aspect Ratio  
658294.9E 5633009.9N 1981.6m 179.93° 60° 6:4



Class	Area in hectares
Conifer	1404
Herbaceous	425



Class	Area in hectares
Conifer	2035
Herbaceous	135

**FIGURE 8: IAT GENERATES A VIEWSHED AT THE SAME RESOLUTION AS THE UNDERLYING DEM. IN THIS EXAMPLE FROM SW ALBERTA THE DEM IS AT 2 METRE RESOLUTION, THUS 4 SQUARE METRES PER PIXEL. CONSIDER THE 1897 VIEWSHED – IAT REPORTS 3,510,198 PIXELS IN THE CONIFER CLASS. THIS IS APPROXIMATELY 1404 HECTARES (3,510,198 PIXELS X 4 SQ METRES PER PIXEL / 10,000).**

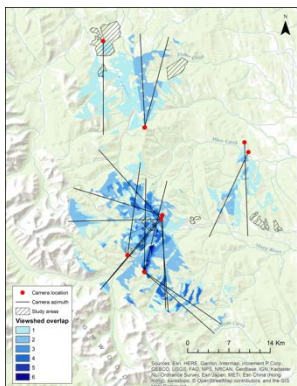
In the Figure 8 example WSL-monoplotting as well as IAT alignment was used to determine the camera location. The monoplotting technique yielded a mean locational error of 3.5 metres. The location determined in IAT was within this mean error. Since minimizing locational error in a way that best leverages the IAT alignment process is one of the challenges the development team is working on now, it was decided to use the monoplotting-derived location for this example – even though either could have been used.



## 4. APPLYING THE IAT END-TO-END WORKFLOW

In conjunction with the Fire Regime Team, Mountain Legacy's Visual Applications Team selected 17 images for an initial test of the Image Analysis Toolkit end-to-end workflow. These images are from five areas overlooking the upper Elbow and Sheep River drainages in SW Alberta. The areas are as follows:

- Along the south ridge of Mt. Quirk looking southwards over Quirk Creek. Identified as South Quirk in the historical surveys;
- On the summit of All Smoke Mountain looking northwards over the Mt. Quirk area toward the Elbow River;
- In the Mt. Hoffman area looking northwards over the Sheep River valley, and looking eastward toward Mt. Dyson and the Blue Ridge;
- On Missing Link Mountain looking westward over the Sheep River valley towards Mt. Ware in the north and Mt. Hoffman in the south;
- On a ridge above Ware Creek looking southward over Ware and Death Valley Creeks. Identified as Sinnot in the historical surveys.



The map shown here ( a copy of Figure 2) links to [an interactive map](#) showing the study images, approximate Field of View (FoV), the stations associated with the images, and links back to the MLP Explorer website that hosts the historic photos and their repeats.

The images of interest are all historic photos from the following time spans:

- Four from 1895 – Arthur O. Wheeler, Canadian Irrigation Survey (CIS).
- One from 1897 – A. O. Wheeler, CIS.
- Five from 1916 – David A. Nichols, Palliser-Kananaskis Survey.
- Seven from 1940 – Rutherford J. Parlee, Dyson Creek area survey.

### 4.1 LAND COVER CLASSIFICATIONS USED ON THE LIM PROJECT

Our test of the Image Analysis Toolkit for the LIM project begins with determining the stations and images of interest. Then the land cover classifications to be used with the images are developed. The Visual Applications Team worked closely with the Fire Regime Team to determine both. The following land cover classes were decided upon:

- **Coniferous forest:** Greater than 75% of the area in coniferous trees;
- **Broadleaf forest:** Greater than 75% broadleaf trees;
- **Mixedwood forest:** 26 – 75% broadleaf with the rest largely coniferous trees and/or shrubs;
- **Shrubs:** Greater than 25% shrub cover, less than 6% trees of any type;
- **Herbaceous:** Vegetated with less than 25% shrub cover and less than 6% tree cover of any type;
- **Burned:** Clear evidence of burned timber on the landscape – includes snags, fallen or standing timber on any other class (e.g. burned snags in a herbaceous meadow, burned snags in a wetland, fallen logs in shrubs, etc.);
- **Water:** 6% or greater standing or flowing water;



- **Wetland:** Wet, swampy, aquatic moisture regime;
- **Barren ground:** Sand, soil, rock;

For the three forest land covers (Coniferous, Broadleaf, Mixedwood) two further classification schemes were devised – Density, and Height.

**Height** was set at approximately four metres:

= 4 m was deemed “high”; <4m was deemed low.

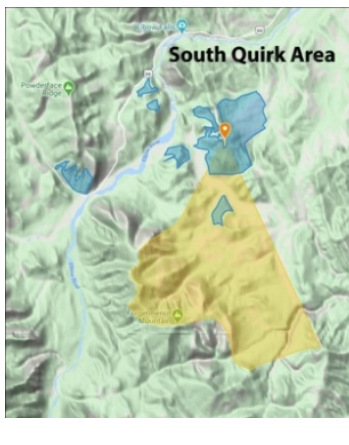
**Density** was set as follows:

10 – 30%; >30 – 50%; >50 – 70%; >70%.

The height and density classes were new to our workflow. In previous studies using segmented and classified oblique images only land cover classes were determined, not particular features of these classes. An ecologist working in IAT did this by hand – a detailed and time-consuming task. We acknowledge that automated and semi-automated classification algorithms, which would significantly speed up this task, already exist. However, via multiple prior tests, MLP researchers have assessed that existing algorithms do not work well with the historic black-and-white photographs [14]. We are cautiously optimistic that emerging research by members of our research group using DeepLab artificial intelligence approaches will improve results relative to current classification software and holds promise in automating some or all of this task.

## 4.2 THE SOUTH QUIRK EXAMPLE

One station in the South Quirk area was selected for in-depth study: Arthur O. Wheeler’s 1897 South Quirk Station, part of the Canadian Irrigation Survey. The image selected is W97-14-7 (Library and Archives Canada ecopy # e0082922187).



The station sits at N50.8271° W114.75233° (UTM Zone 11: 658294.9E 5633009.9N). The camera azimuth (direction it is pointing) is 179.93°. The Field of View is between 50 and 60°.

The figures below illustrate the full gamut of digital assets produced at the image level for this study:

- Figure 10 – is the historic photo.
- Figure 11 – the vegetation land cover mask and class percentages.
- Figure 12 – 14 – the conifer cover with height and density overlays.
- Figure 15 – the georectified viewshed.

All of the digital assets from this image and the other 17 can be downloaded from the [Resources](#) page or the [Locations](#) page online at Mountain Legacy’s IAT website.





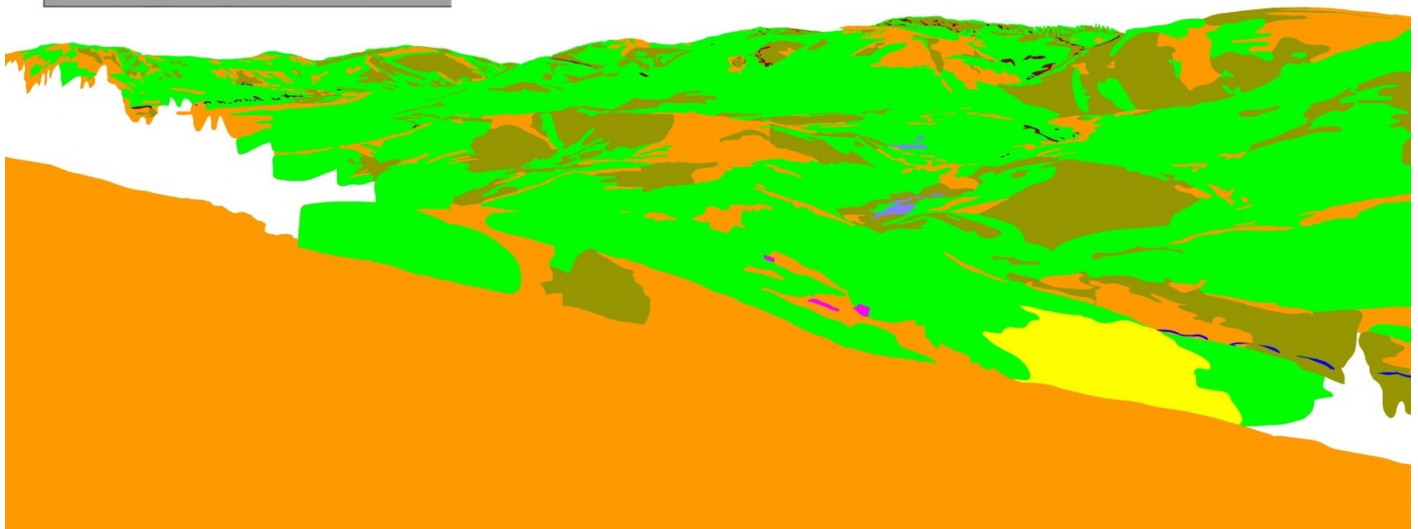
**FIGURE 10: IMG WH97-14-7 (LAC/BAC ECOPY # E008292187)**

VISIT [EXPLORE.MOUNTAINLEGACY.CA](http://EXPLORE.MOUNTAINLEGACY.CA) TO SEE THE REPEAT OF THIS IMAGE AND OTHERS FROM THE AREA.



## South Quirk, 1897: A. O. Wheeler, Img W97-14-7 Vegetation classification with pixel counts and percentages / class

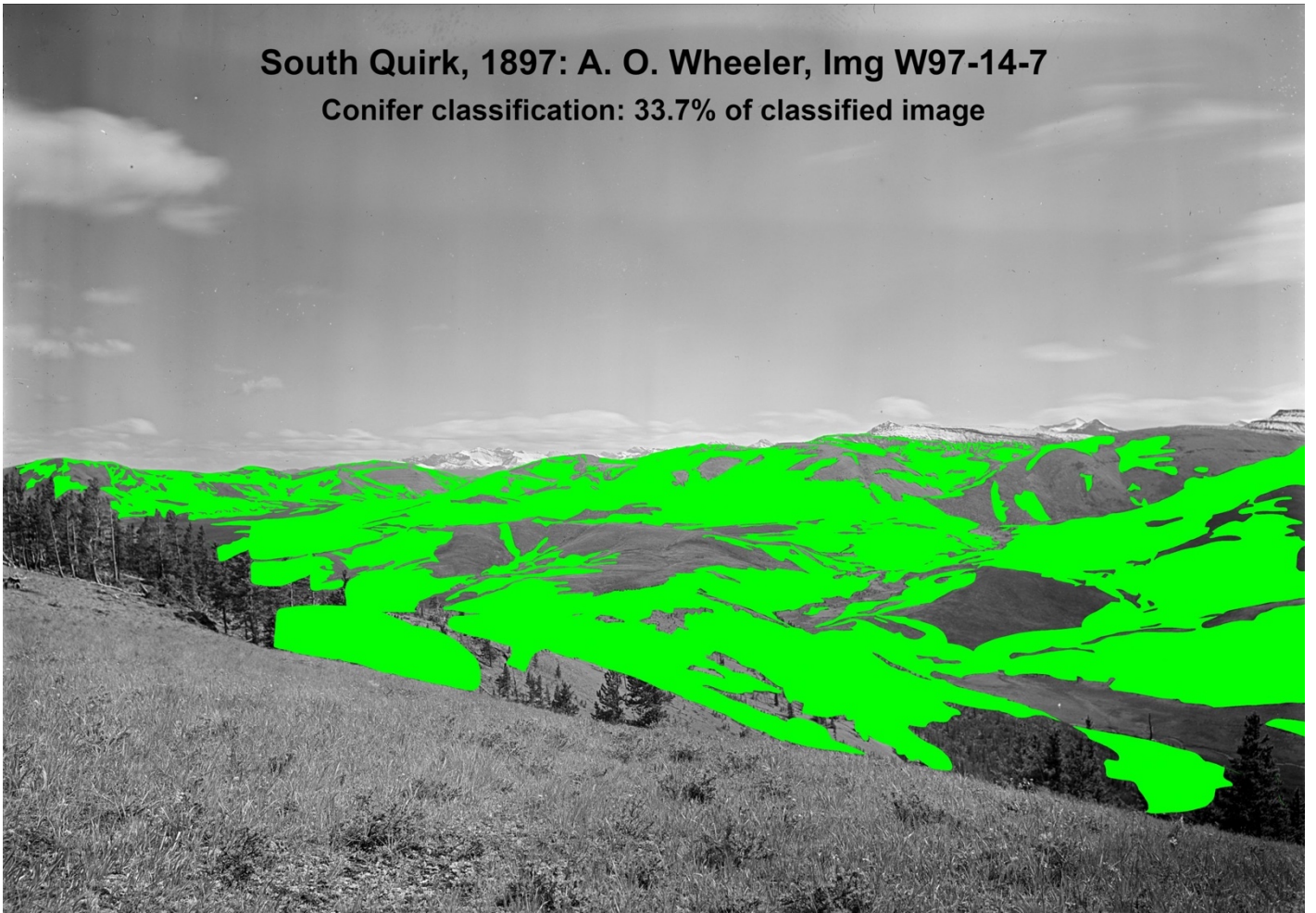
Categories	Add	Rem	Counts
Conifer			4686151 33.7 %
Mixedwood			306003 2.2 %
Broadleaf			0 0 %
Shrubland			1464421 10.5 %
Herbaceous			7388403 53.2 %
Burned			5889 0 %
Water			6570 0 %
Wetland			11582 0 %
Barren Ground			16953 0.1 %



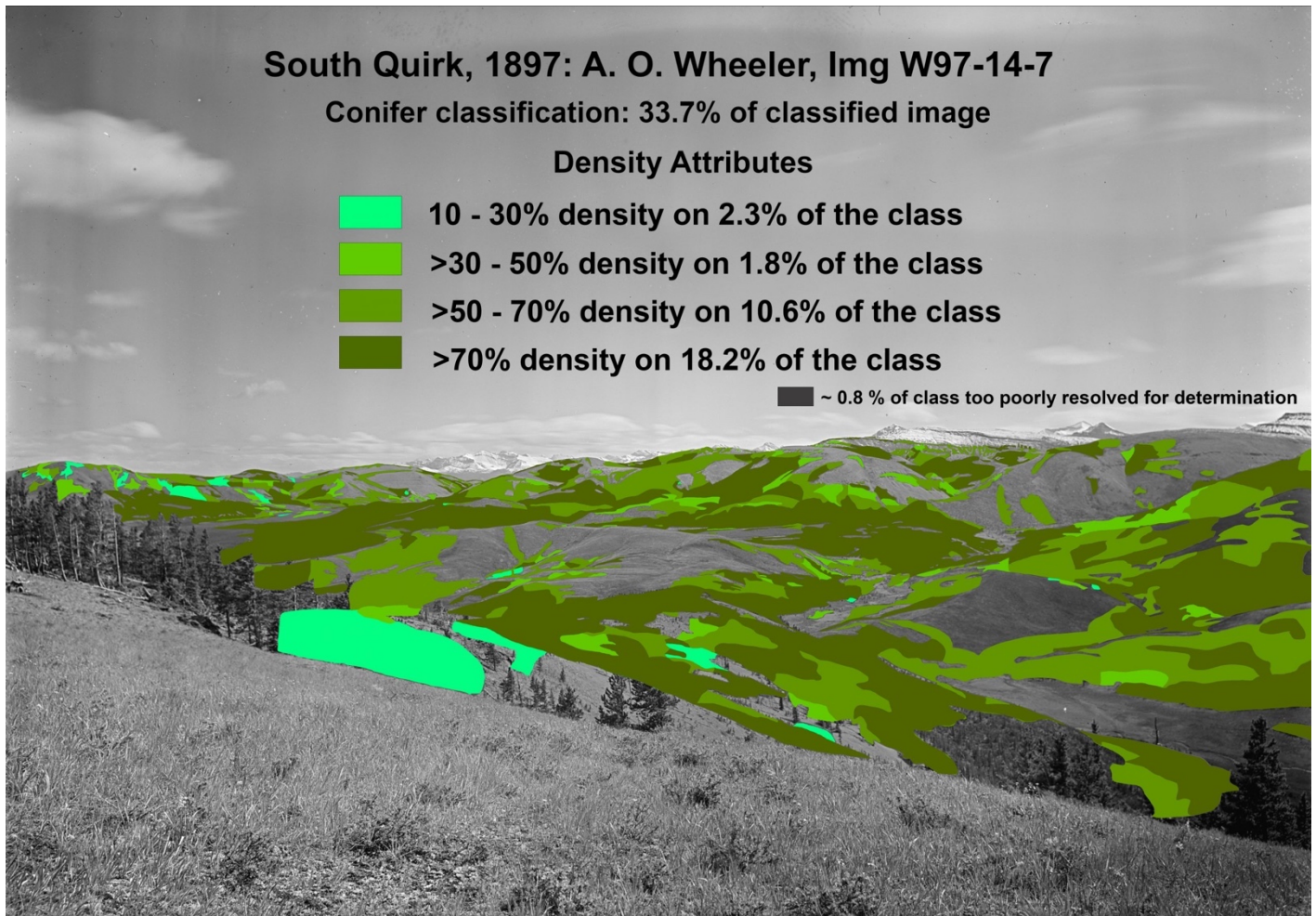
*FIGURE 11: VEGETATION CLASSIFICATION MASK APPLIED TO A. O. WHEELER'S 1897 IMAGE. IN THIS CLASSIFICATION THE HERBACEOUS CLASS IS OVER-REPRESENTED BECAUSE IT FILLS THE AREA IMMEDIATELY IN FRONT OF THE CAMERA. THIS "FOREGROUND EFFECT" WILL DISAPPEAR IN THE GEOREFERENCED VIEWSHED.*



South Quirk, 1897: A. O. Wheeler, Img W97-14-7  
Conifer classification: 33.7% of classified image



**FIGURE 12: THE CONIFER CLASS OVERLAID ON THE IMAGE. CONIFERS MAKE UP 33.7% OF THE CLASSIFIED IMAGE. PORTIONS OF THE IMAGE COULD NOT BE CLASSIFIED BECAUSE THEY WERE OBSCURED OR NOT RESOLVABLE.**




**FIGURE 13: CONIFER CLASS DENSITY. PERCENTAGES FOR EACH DENSITY CLASS ARE BASED ON 33.7% OF THE IMAGE UNDER THE CONIFER CLASS.**





South Quirk, 1897: A. O. Wheeler, Img W97-14-7

Conifer classification: 33.7% of classified image

Height Attributes

 Short (< 4 metres ) on 25.1% of the class

 Tall on 8.0% of the class

 ~ 0.6 % of class too poorly resolved for determination

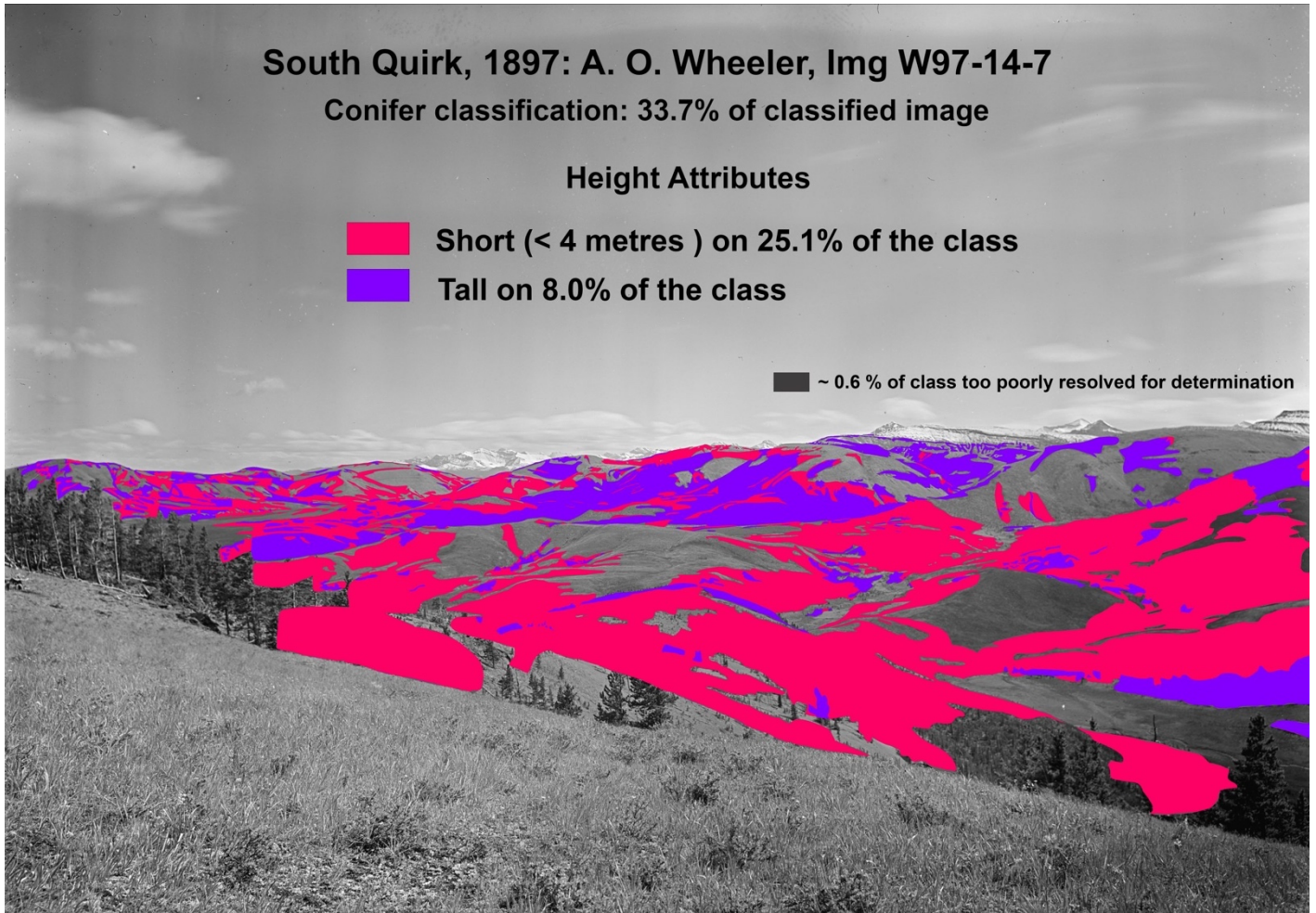


FIGURE 14: CONIFER CLASS HEIGHT. PERCENTAGES FOR THE TWO HEIGHT CLASSES ARE BASED ON 33.7% OF THE IMAGE UNDER THE CONIFER CLASS.

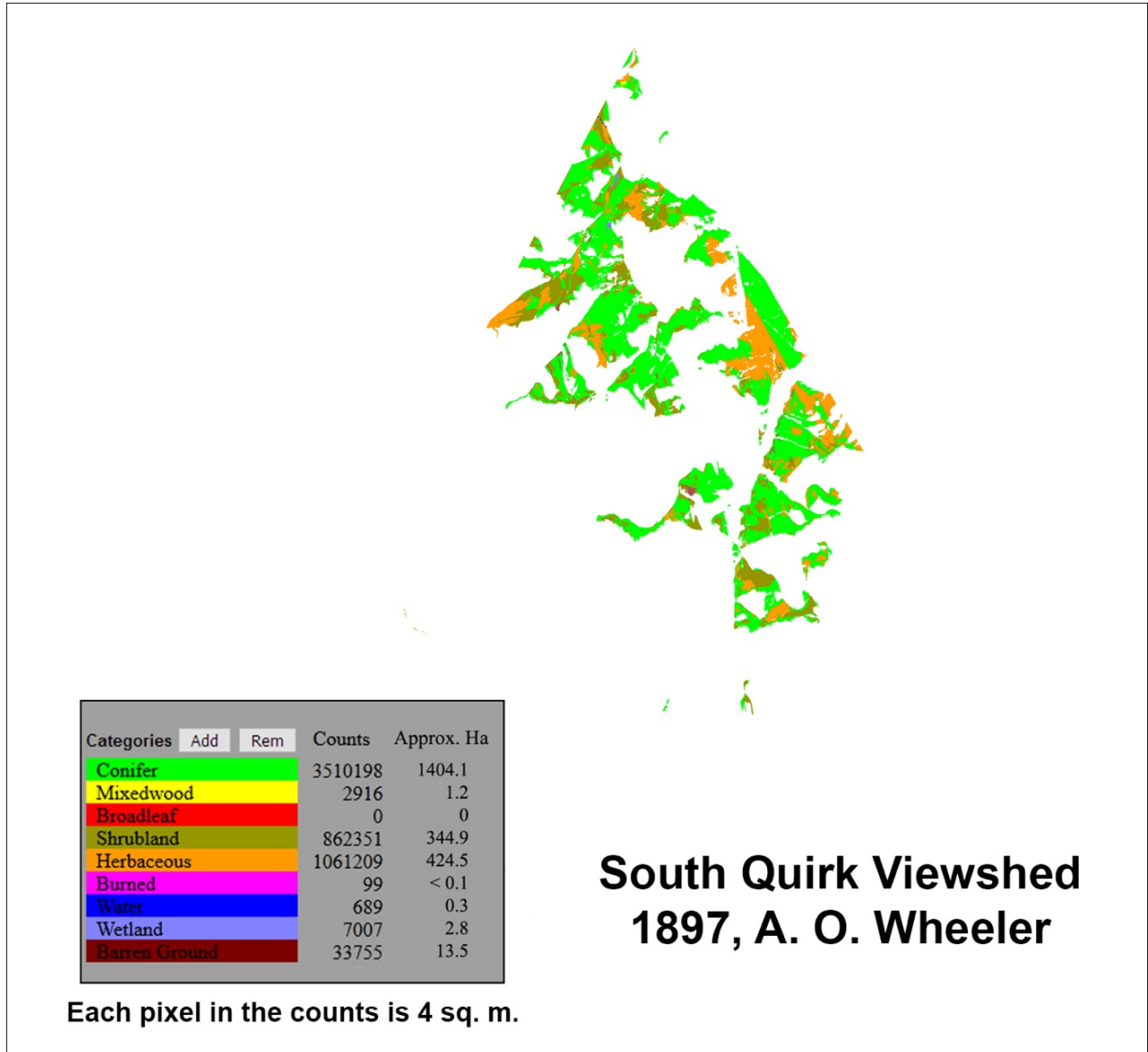


FIGURE 15: VIEWSHED OF THE 1897 VEGETATION CLASSIFICATION MASK WITH ASSOCIATED PIXEL COUNTS. THIS IS A VISUAL REPRESENTATION ONLY – THE FULL-SIZED GEOREFERENCED VIEWSHED CAN BE [DOWNLOADED HERE](#).



## 5. NEXT STEPS

One of the promising opportunities with the Image Analysis Toolkit is the ability to integrate spatial information from historic photographs with spatial information from other sources. Georeferenced viewshed masks can be loaded into GIS programs to analyze with other data. For instance, landscape information derived from historic and modern photographs can now be added to a timeline of spatial data including dendrochronology samples, burn perimeters, air photos and satellite imagery. This can extend the timeline back by many years as the historical photos reach far back in time. Collaboration between the Visual Applications Team and the Fire Regime Team examined images that reached back to 1895.

While there is still development needed on a number of fronts, we are confident in characterizing IAT as a modular, flexible, and comprehensive means for analysing oblique photographs. IAT shines as an end-to-end application for handling a variety of tasks critical to interpreting and analysing oblique photographs: aligning, virtualizing, classifying, and rectifying. The vast oblique images collections of the Mountain Legacy Project demanded a toolkit that would comprise all of these elements and allow a seamless and accurate workflow. The rectification process in IAT accomplishes similar functions to the WSL-Monoplot software for georectifying images, but allows for finer-grained analysis of classified features. To summarize, the IAT has several advantages over existing software for working with oblique images:

- An integrated set of tools for a seamless workflow.
- Scales to the finest resolution of both Digital Elevation Models and oblique photographs.
- Supports segmentation and classification of “human-eye” view oblique images.
- Increased accuracy associated with oblique images in regions of significant vertical relief.
- Interoperability with a wide variety of orthographic and oblique image data to create more complete timelines.
- Modularity of tools, which allow for continued development, improvement, and additions.
- Freely available for researchers to use with the MLP collection, or their own imagery.

It was a conscious decision to develop IAT in an HTML5/Javascript environment, which allows for portability and wide access to the software. As a research team we are committed to making our work widely accessible for others to use both in association with the Mountain Legacy Project and in other oblique photo applications. We are also exploring pathways to making the IAT work effectively with the open source R Project for Statistical Computing and the QGIS open source spatial analysis package.

As identified in section 3.1, Artificial Intelligence classification is another area full of promise for future research. The very large size of the MLP collection: over 120,000 historic photographs (16,000 at UVic alone – the rest with long-standing research partners) and almost 9000 modern repeats. The ability to automate the classification process in a precise and reliable way would open the door to leverage this immense dataset. Thousands of classified historic images, georeferenced using the Image Analysis Toolkit presented in this report, could lead to estimates of land cover

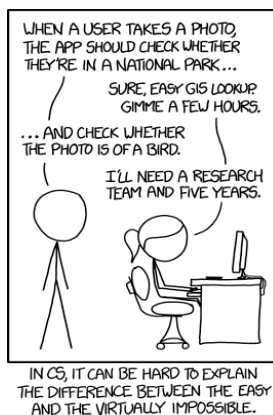


from a century ago across the Alberta Rockies and foothills. Progress in developing an automated classification tool for IAT is encouraging.

A crucial next step for MLP researchers will be to evaluate the accuracy of the georeferencing viewshed process. There are multiple points along the process at which error could be introduced or propagate, such as the creation of the DEM, interpolation in the creation of the Virtual Photo and viewshed, alignment between historic/modern photos and the VP, and classification of the historic/modern photos. The alignment tool does already contain a metric for error (RMSE), but robust accuracy assessment of the whole process remains to be done.

Our work here is based on the premise of knowing camera location, based on MLP repeat photography field work and measurements. The perspective transformations used in the alignment tool adequately compensate for discrepancies in camera attitude (the Euler angles azimuth, inclination and rotation) and the principal point of the subject photo (true image centre). However, we came to realize that camera location is not always sufficiently accurately known. We recognize the need to incorporate sophisticated camera calibration methods based on photogrammetry mathematics, such as used in Bozzini et al., [6], and this lies near the top of our next priorities. It may be possible to devise a georeferencing scheme involving both camera calibration and our existing alignment techniques.

The opportunity to continue collaboration with the Fire Regime and Spatial Modelling teams, and with other research and applications teams, is most welcome. Working with researchers who understand the significance of what the photographs – especially the historic images – show is invaluable. Image processing, computer vision, scene detection and recognition – all are difficult problems in computer science.



*"In the 60s, Marvin Minsky assigned a couple of undergrads to spend the summer programming a computer to use a camera to identify objects in a scene. He figured they'd have the problem solved by the end of the summer. Half a century later, we're still working on it.."*

([xkcd](#) website)

Working with an interdisciplinary team, especially in the computer science realm, helps to make difficult problems like image processing more tractable. Without the collaboration and resources of the LiM project the Image Analysis Toolkit would not be as far advanced as it is today.





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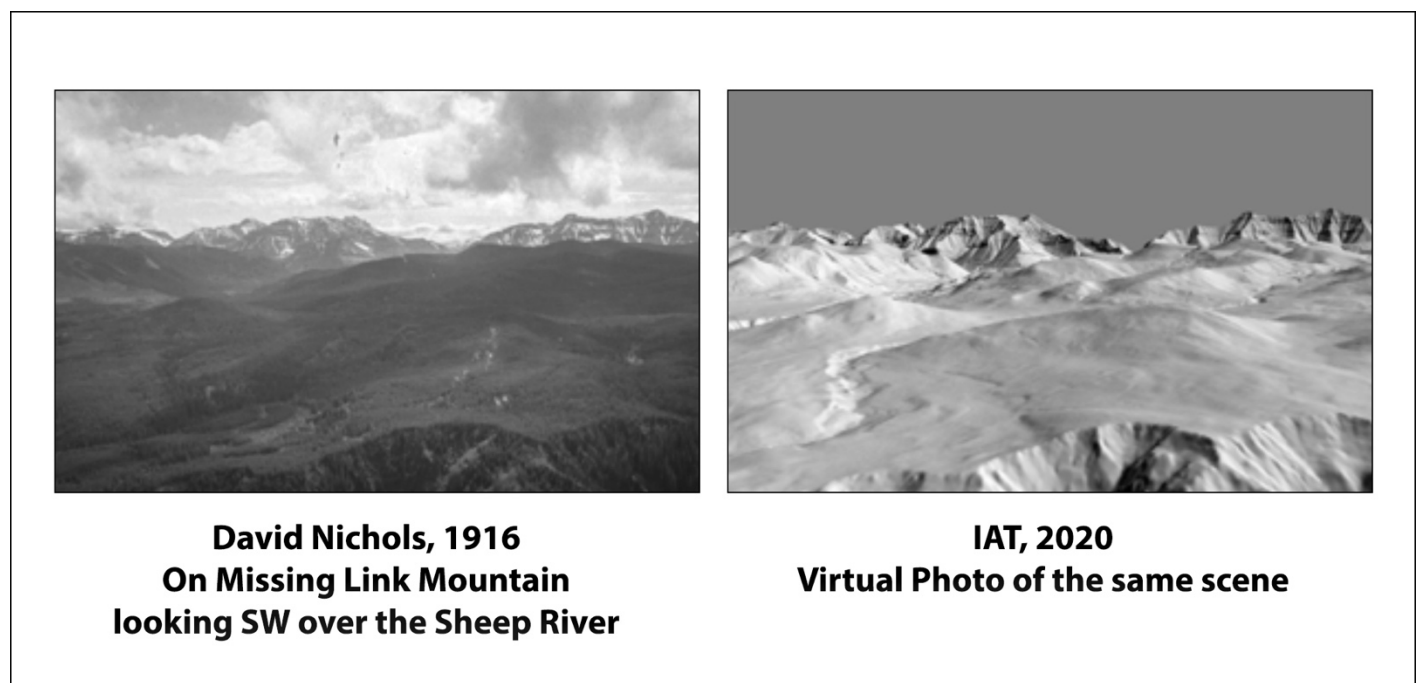
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## APPENDIX A: VISUALIZING THE FORWARD ALGORITHM

Although we are all immersed in the three-dimensional world around us, describing that world so it makes sense – especially inside a computer program – is not an easy task. Consider the following problem: we wish to create an accurate, computer generated shaded relief “virtual” photo of a landscape scene depicted in a photograph. The camera information (e.g. location, FoV, azimuth, elevation) is known. A DEM and corresponding hillshade model of the area encompassed by the photo is available.

A straightforward enough problem description, and, for IAT the resulting “Virtual” Photo looks to be easily produced. But, as with many things, the devil is in the details, and so we present here a deeper explanation of the way this problem is approached in MLP’s Image Analysis Toolkit. We call it the Forward Algorithm (FA) and, as displayed in Figure 16 below, it produces an accurate Virtual Photograph (VP) of the scene displayed in the actual photograph.



*FIGURE 16: AN EXAMPLE OF A VIRTUAL PHOTO MATCH WITH THE ACTUAL PHOTO IT IS MEANT TO REPRESENT*

This VP is conceptually based on rays emanating forward from the camera viewpoint. Taken together the rays will trace out the camera’s FoV angle as they move across the DEM. In building the Virtual Photo the FA considers each ray separately with each ray corresponding to one vertical column in the VP.

Figures 17 and 18 presented below, along with accompanying discussion, illustrate some of the finer points of the Forward Algorithm.



## WORKING WITH THE DEM: AN OVERHEAD VIEW

Figure 17 is an overhead view of a view triangle superimposed on a DEM. This particular triangle has the interesting property of crossing one of the four 45 degree offset lines that separate major axes. In this case, the azimuth is 124 degrees, and the field-of-view is 60 degrees. Two view rays are shown. **Ray 1** is an example where the major axis is  $x$ . The forward algorithm visits DEM points **a** through **i** (and on), each one pixel apart along  $x$ . All rays in the upper shaded portion of the view triangle are treated similarly. **Ray 2** has a major axis of  $y$ , so DEM points **A** through **H** (and on) are each one pixel apart along  $y$ . All rays in the lower shaded portion of the view triangle are treated similarly.

Note that if we treated **Ray 1** similarly to **Ray 2** – that is, with major axis  $y$  - we would be looking at actual DEM values only one third as often. For example, instead of visiting points **c**, **d**, **e** and **f**, we would instead visit only **c** and **f**. This shows the importance of choosing the correct major axis for each ray, rather than globally for an entire view triangle. Perspective projections only allow for images less than 180 degrees field-of-view, so a changeover from one major axis to another occurs at most twice.

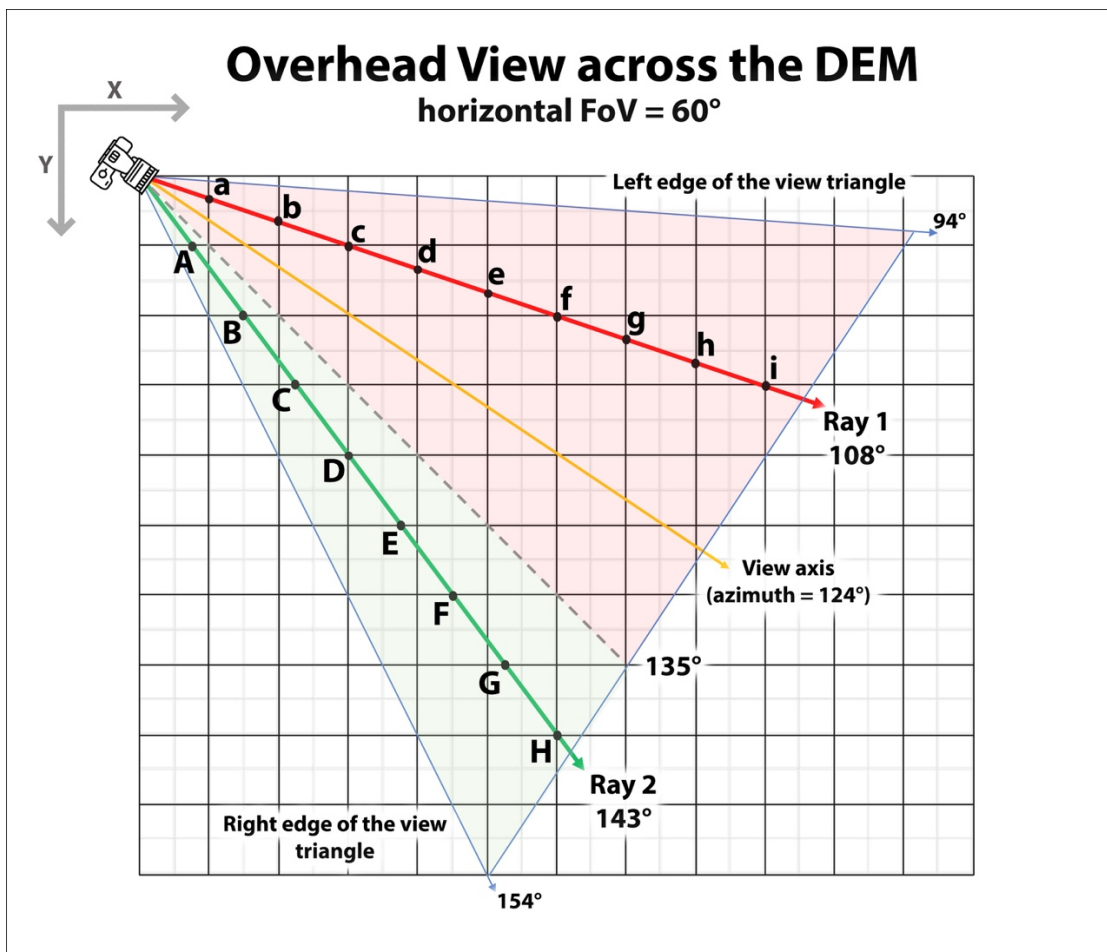


FIGURE 17: OVERHEAD VIEW OF THE DEM WITH THE VIEW TRIANGLE OVERLAID.



## BUILDING THE VIRTUAL PHOTO: A SIDE-ON VIEW OF RAY 1

Figure 18 shows a side view corresponding to **Ray 1** of Figure 17. The main triangle here is 60 degrees, but because the drawing is in a plane and not orthogonal to 3D space as defined by the DEM and its elevations, the actual vertical field-of-view of the Virtual Photo is somewhat less than 60 degrees. Points **a** through **i** are shown on a cutaway mountainous landscape. Some of these points get projected onto the corresponding vertical column in the picture plane of the Virtual Photo. In particular, points (**c,d,e,f,h**) all get drawn on the picture plane. But these pixels are often separated by large gaps. This is where the vertical interpolation of the Forward Algorithm comes in. The shade value of a pixel (e.g., shading 90 for point **h**) comes from a hillshade model corresponding to the DEM.

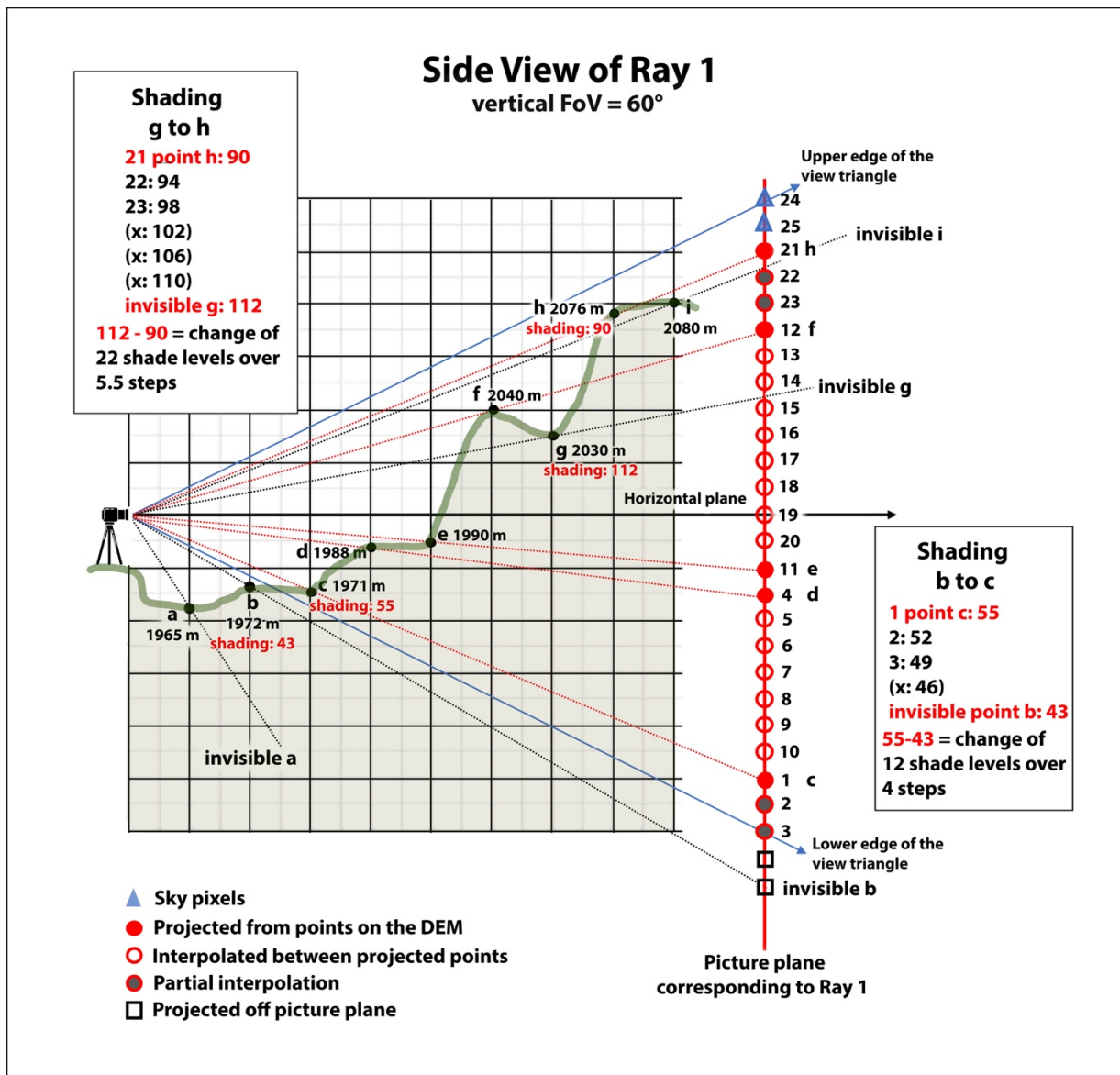


FIGURE 18: DRAWING RAY 1 ON THE PICTURE PLANE OF THE VIRTUAL PHOTO.



Let's see what happens as we move *forward* from the camera. In Figure 18, all 25 vertical column points on the picture plane, which must be all filled in, have a number corresponding to the order in which they are drawn. Point **a** gets projected below the picture plane, so is ignored. Point **b** is also too low. But note here that these two points are in the overall 360 degree viewshed of the viewpoint, although not in the viewshed as limited by the camera view.

Point **c** now projects onto the picture plane, so its pixel gets drawn. But there are two pixels under **c** that did not get drawn, so they get shade values defined by an interpolation function based on pixel values from **b** and **c**. Note that only 2 additional pixels are drawn, even though the function is defined over a delta of 4. Next, point **d** is projected higher than the last drawn pixel **c**, so its pixel is drawn, and 6 more pixels filling the gap are drawn too, based on a new interpolation function.

The next pixel, corresponding to point **e**, is by far the most common case. It is projected to position 11, right above position 4 (i.e., the highest previous pixel drawn). In this case, no extra interpolation work is done. With point **f**, a big jump up a cliff, many intervening pixels are filled in. Point **g** marks a new situation. Because its position is *lower*, it is not in the viewshed, and therefore not drawn on the picture plane. However, when we reach point **h**, its projection is higher than that of **f**, so it is drawn as pixel 21. Again, we have a steep cliff's worth of pixels to fill in, but note that their shade values are based on an interpolation between where **g** would have projected, and **h**. If the delta is 5.5 picture plane pixels, and the shade values of **g** and **h** are 112 and 90 respectively, pixels 22 and 23 get values 94 and 98 as shown.  $((112-90)/5.5=4)$ .

Note that if the FA were not quite so clever and interpolated from the last *visible* point **f**, we would not see the effect of the steep cliff being somehow behind **f**. Instead it would look like a continuous slope connecting **f** and **h**.

Finally, we reach point **i**. In this example we'll assume all subsequent projected pixels (not "sky" pixels) are lower than pixel 21. Point **i** itself projects lower than pixel 21, so it is not in the viewshed. We include point **i** here to remind hillwalkers of their nemesis - the False Peak. (Note that the elevation of point **i** is higher than that of **h**, but remains invisible until one reaches the vicinity of **h**.)

Once we have concluded processing all DEM points along **Ray 1**, verifying that there are no high points, we are nearly done, and complete the vertical column by filling in pixels 24 and 25 with colour/shade "sky". It is time to move to the next ray.