MONITORING ALPINE CLIMATE CHANGE IN THE BEARTOOTH MOUNTAINS OF THE CUSTER NATIONAL FOREST

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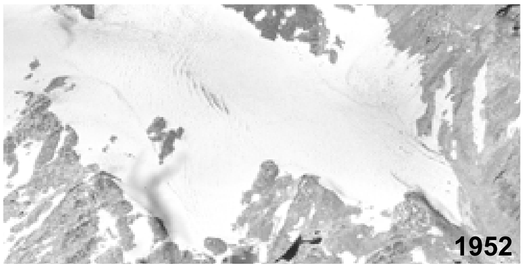

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Abstract

The U.S. Department of Agriculture, Forest Service's Remote Sensing Steering Committee awarded funding to investigate methods to measure and quantify the effects of climate change on alpine glaciers. Four glaciers within the Absaroka-Beartooth Mountains were selected for analysis. Five to nine dates of stereo photography, spanning the years from 1952 to 2003, were analyzed for each site. The photos were orthocorrected in Leica Photogrammetry Suite (LPS). However, digitizing the changing glacier boundaries from the orthocorrected imagery was surprisingly subjective and inexact. Still, the changing boundaries of these glaciers tell a compelling story about glacial retreat despite the inexactness of the interpretation. The LPS block files were also imported into ArcGIS Stereo Analyst to create 3-D profiles of the glacier surfaces. These profiles show dramatic ice loss at all four sites—thus, the surface profiles proved to be better indicators of glacier change than the boundary delineations. The methods used in this project can be a cost-effective means to monitor the effects of climate change on alpine glaciers.

Key Words

Remote Sensing, Stereo Analyst, aerial photography, climate change, glaciers, Beartooth Mountains, orthocorrection, Leica Photogrammetry Suite (LPS), thinning

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Background

The Earth's climate is warming, leading to smaller ice caps and glaciers. This loss has significant impact on the planet—not the least of which is a potentially catastrophic rise in sea level. The scientific community is focusing a good deal of attention on mapping and monitoring globally significant ice caps and ice fields.

Generating only slightly less interest are the tens of thousands of smaller alpine glaciers in mountainous areas around the globe. These alpine glaciers make critical contributions to local ecosystems and economies. They serve as reservoirs that release water in the summer and early fall when it is most needed. Glaciers cool the local environment, creating critical terrestrial microhabitats and cool the stream runoff producing critical aquatic habitats. The reduction and loss of these alpine glaciers will profoundly alter affected ecosystems and economies.

Figure 1—Alpine glaciers make critical contributions to local ecosystems, but they are severely threatened by our warming climate.

In 2008, the U.S. Department of Agriculture (USDA), Forest Service's Remote Sensing Steering Committee awarded funding to pursue a proposal submitted by the Custer National Forest to investigate methods to quantify the effects of climate change on the alpine glaciers of the Absaroka-Beartooth Mountains.

There have been a number of successful efforts to map alpine glaciers. Many of these have focused on spatial extent or planimetric *(X,Y)* mapping (Hoffman and others 2007). However, the decrease in ice depth, or elevation *(Z)*, can be far more significant than indicated by the reduction in ice surface area (Pochop and others 1990).

There are two general remote sensing methods to measure the *Z* dimension: 1) using stereo imagery, or 2) using an active return system such as radar or lidar. Lidar may prove to be the most effective method for current and future monitoring, but, since it is a new technology, there is currently no historical data. Radar data have been used to map ice elevation surfaces (Scheifer and others 2007); however, historical data sets are spotty, hard to come by, and virtually nonexistent prior to the mid-1980s.

Stereo imagery allows investigators to see and measure elevations and their differences. By definition, stereo imagery works by obtaining images of the same feature from two different vantage points. Some current satellite and airborne sensors can obtain digital stereo coverage—but, once again, these sensors are relatively new and don't provide an historic perspective.

The Forest Service has been systematically collecting stereo resource photography of all the lands it manages since the 1940s and, in some areas, as far back as the 1930s. Typically, photo acquisition repeats on a 5-to-10-year cycle. Programs such as the National High Altitude Photography (NHAP) program, the National Aerial Photography Program (NAPP), and the current National Agricultural Imagery Program (NAIP) greatly supplement the available dates of resource photography. In addition, the U.S. Geological Survey (USGS) is a terrific resource for additional special-project stereo photography. Thus, aerial photography is the best source of historical stereo imagery.

Using photography to map elevations is not new, it provides the fundamental data to create the national series of 7.5 topographic quadrangles. However, traditional methods of deriving elevation information from photography are both specialized and cumbersome. Despite that fact, traditional photogrammetric techniques were used to measure the area and elevation changes of glacial surfaces in the Wind River Range in Wyoming (Pochop and others 1990). The project analysis was restricted to two dates of imagery and two sites—thus, making the effort more manageable.

A fortunate convergence of technologies and availability of data now allow anyone in the Forest Service to use historical aerial photography to map and measure changes in alpine glaciers. This project's objective was to develop a cost-effective procedure that demonstrates the efficacy of this approach.

Methods

The general methodology consisted of selecting suitable alpine-glacier sites, identifying and locating available stereo photography, scanning the photography or obtaining already-scanned imagery, orthocorrecting photography, delineating glacier boundaries, measuring ice elevations for each site and date, and analyzing the results of those measurements.

Selecting Suitable Alpine-Glacier Sites

Four alpine glacier sites within the Absaroka-Beartooth mountain range were selected for analysis: 1) the East Grasshopper Glacier, 2) the West Grasshopper Glacier[1], 3) the Castle Rock Glacier, and 4) the Rearguard Glacier. These four glaciers have different sizes, aspects, elevations, and locations.

Identifying and Locating Available Stereo Photography

The project used three sources of aerial photography: 1) the Aerial Photography Field Office (APFO), 2) the USGS Earth Resources Observation Systems (EROS) Data Center, and 3) existing prints from the Custer National Forest, Beartooth Ranger District.

The APFO has archived the original film for all USDA-contracted photo projects since 1955 (currently more than 50,000 rolls). Five dates of photography for each site were identified within the APFO holdings: 1951–52, 1971, early 1980s, early 1990s, and 2003. To facilitate selecting the correct photos, project personnel scanned the aerial-photo project flight-index map for each date, georeferenced each map, and overlaid it with the selected alpine-glacier sites in ArcGIS. This allowed easy identification of the film rolls and exposure numbers that corresponded to the four sites. Combining 4 study sites, 5 dates, and approximately 4 photos per date (ranging from 2 to 6), produced approximately 80 photos that were obtained from the APFO.

Because of the dramatic changes that appeared at Castle Rock Glacier, 4 more dates of imagery were obtained for this site from the USGS EROS Data Center (10 additional photos). These supplemental images resulted in 9 dates of stereo imagery: 1952, 1971, 1976, 1981, 1987, 1991, 1995, 1998, and 2003 and a total of approximately 90 individual photographs. Note: the most notable dates turned out to be the earliest and the latest—they gave the most complete summary of glacier change. The intervening seven dates were included to provide a more complete change record and investigate correlations with regional climate records.

One other date of photography was located and used—the Custer National Forest discovered aerial photo prints from the 1930s in its archives. However, this photography covered only one site—the Rearguard Glacier.

Scanning the Photography

The resource photography obtained from the APFO was originally acquired at nominal scales of 1:15,840 to 1:24,000. All of these resource photos were scanned at 700 dpi on a desktop scanner. This produced nominal pixel sizes ranging from 0.6 to 0.9 meters and an uncompressed file size of about 120 megabytes each. The photography that came from the USGS was smaller scale—ranging from nominal scales of 1:35,000 to 1:48,000. The USGS scanned these images on a photogrammetric scanner at approximately 1,800 dpi, resulting in nominal pixel sizes ranging from about 1.5 to 2 meters.

Orthocorrecting Photography

The photos were orthocorrected using ERDAS Imagine's Leica Photogrammetry Suite (LPS). LPS requires digital elevation models (DEMs) and reference imagery that cover the project area. LPS also requires camera reports[2] for each date of photography. Camera reports were created for any photographs that didn't have them.

Using LPS, we defined the photogrammetric orientation parameters for each set of stereo photos (each date and site). These definitions were saved in what LPS terms "block files." After preparing the block files, orthophoto mosaics were also created.

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[1] Despite having similar names, the East and West Grasshopper Glaciers are very different from each other—separated by more than 25 kilometers with many distinctive cirques and glaciers lying between them.

[2] Mapping cameras are periodically calibrated by the USGS Optical Sciences Lab. These reports provide precise measurements (to 0.001 mm) of the characteristics of each camera system including lens distortion, calibrated focal length, and fiducial measurements (fiducials are known locations on the film that become image control points in the orthocorrection process). Camera reports became a requirement for all mapping cameras in 1973 but are essentially nonexistent prior to that date.

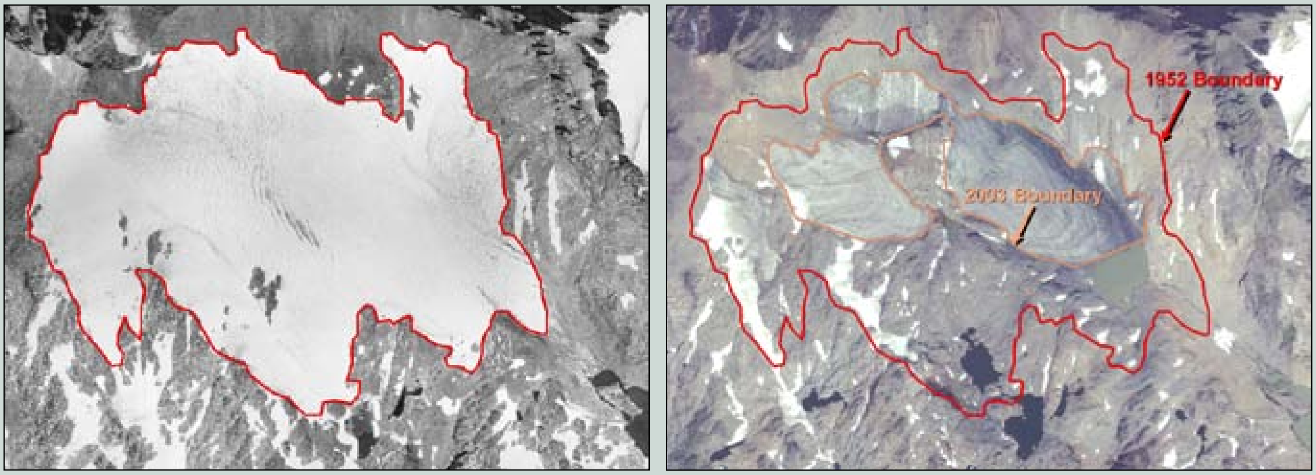

Figure 2—On the left is the Castle Rock Glacier in 1952, with its boundaries outlined in red. On the right is the Castle Rock Glacier in 2003, with its present boundaries outlined in gold along with the 1952 boundary in red. The shrinkage is dramatic—especially when considering the additional loss in depth.

Delineating Glacier Boundaries

The nine orthophoto mosaics of the Castle Rock Glacier were used to digitize the approximate glacier boundary for each date. This seemingly simple task was actually quite difficult and inexact. The main glacier surface was always easy to identify; however, it sometimes seamlessly graded into seasonal snowfields, rock glacier, and rock outcrops that made the boundary very indistinct. Digitizing the glacier boundary for the other sites was not attempted because the distinction between the obvious glacier surface and surrounding surfaces was even less apparent than it was in the Castle Rock Glacier. Despite the difficulties this technique encountered with the Castle Rock Glacier, clear trends revealed significant shrinking over the 51 years captured by this imagery (figure 2).

Measuring Ice Elevations

Each LPS block file was imported into ArcGIS Stereo Analyst. Then a line that approximated the major axis of the glacier was digitized for each site. For each date of stereo imagery, a set of 3-D points along the axis (± 5 meters horizontally) of the glacier was digitized. These were saved as Environmental Systems Research Institute (ESRI) shapefiles with *Z* values. The 3-D points required identifying the same exact feature on the stereo pair in Stereo Analyst and manually adjusting the parallax to define its elevation before digitizing the point. Automated (image-to-image correlation) methods did not work well for two reasons: 1) the amount of parallax in this steep mountainous terrain is extreme, and 2) often there were very few distinct features on the snowy glacier surfaces that allowed image-to-image matching. For each date, 40 to 80 3-D points were digitized along the major axis of the glacier.

By using the 3-D analyst tools in ArcToolbox, the 3-D point shapefiles were exported to comma-delimited ASCII text files with *UTM X, UTM Y*, and elevation values in meters above mean sea level. These text files were imported into an Excel spreadsheet for analysis.

Analyzing the Data

Once the data were gathered and prepared, the analysis was fairly direct. It consisted of simply plotting the ice-surface elevations so they could be compared, computing the differences in surface elevation between dates, and deriving summary statistics from the difference calculations.

Comparing the profiles of different dates required converting each *X,Y* position of each profile to a distance from a single, fixed *X,Y* position, which was located just beyond the toe of the terminal moraine. Again, to facilitate comparison, an Excel add-in interpolated values so that every distance value from the fixed *X,Y* position at the toe of the glacier had a corresponding ice-surface elevation value for all dates of imagery (figure 3).

Errors can enter this procedure at nearly every step; however, on two occasions, the entire process (for a site and date) was repeated and produced nearly identical results. This correlation indicated the high precision of the measurements. In spite of the measurement accuracy however, a bias could not be ruled out. An elevation bias could have resulted from allowing the LPS program to solve the block-file triangulations by giving too much latitude to the *Z* component. Fortunately, that bias was easily corrected by adding a constant to each profile that made the initial part (which was on bare ground—except in 1952,

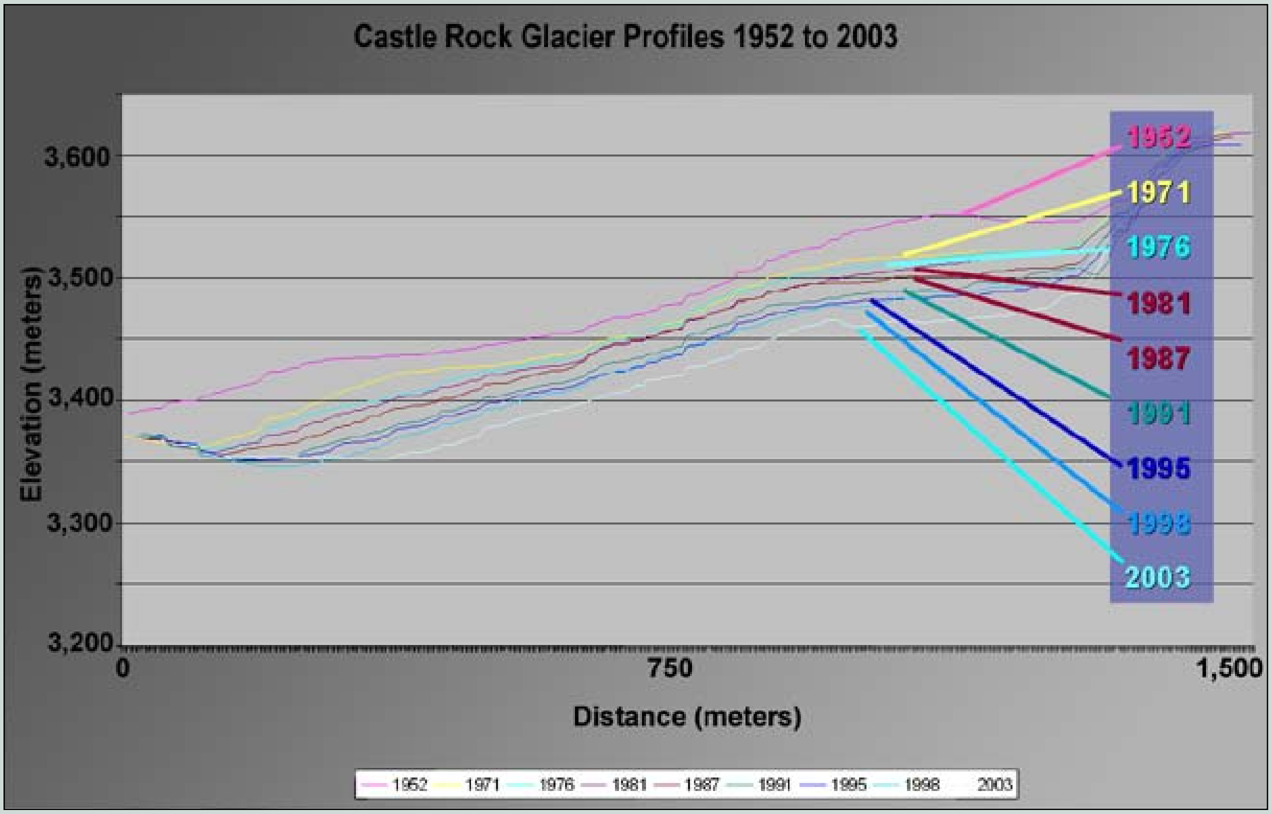

Figure 3—Surface profiles along the major axis of the glacier for each date of imagery. The surface profiles decrease after each time interval.

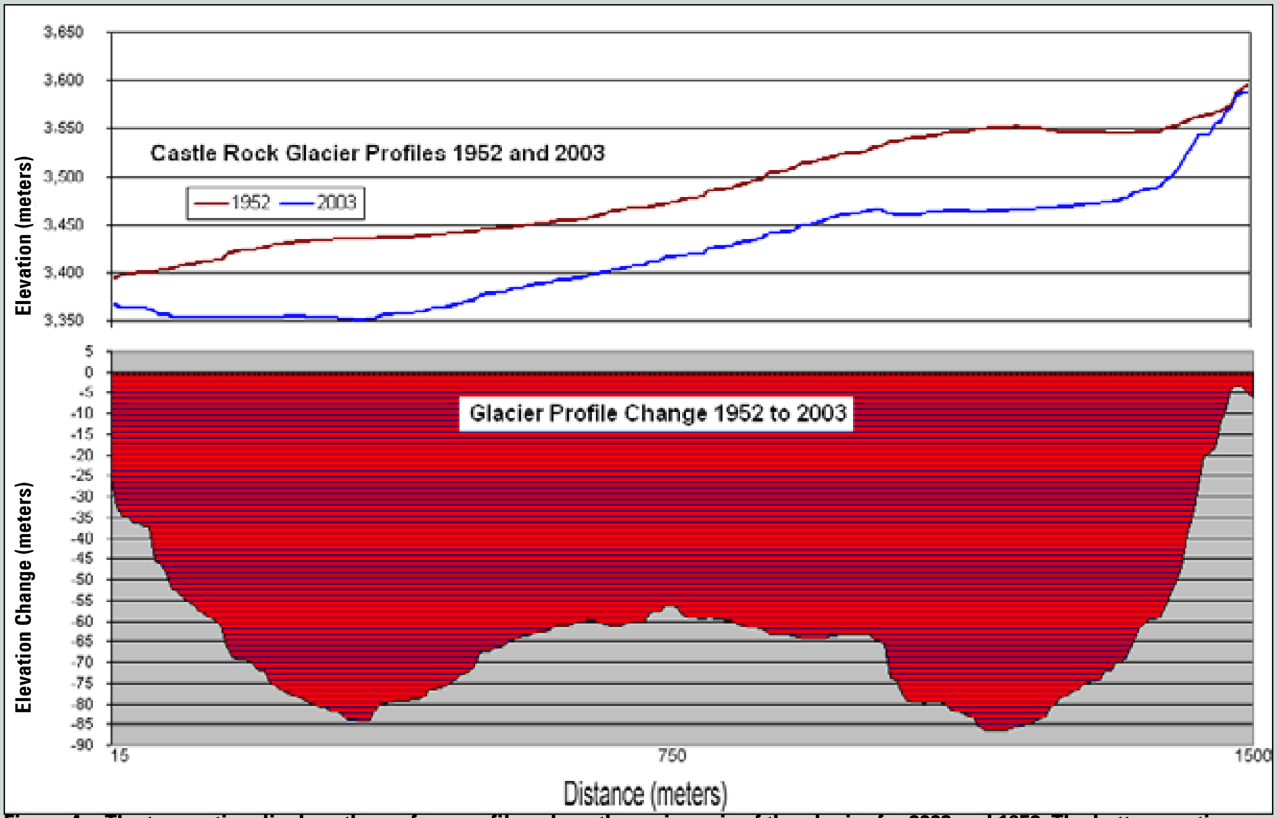

Figure 4—The top portion displays the surface profiles along the major axis of the glacier for 2003 and 1952. The bottom portion graphically shows the loss of ice along the profile between the two dates. In 51 years, the average ice loss has been more than 60 meters.

Table 1—Summary of Castle Rock Glacier surface ice-loss rates

Mean Surface Ice-Loss Rates (m/yr)—Castle Rock Glacier								
1952 to 1971	1971 to 1976	1976 to 1981	1981 to 1987	1987 to 1991	1991 to 1995	1995 to 1998	1998 to 2003	Overall
-1.06	-0.93	-0.89	-0.95	-2.55	-1.06	-0.28	-2.47	-1.26

Table 2—Summary of surface ice-loss rates at other glaciers

Mean Surface Ice-Loss Rates (m/yr)—Other Glaciers					
	1952 to 1971	1971 to 1987	1987 to 1995	1995 to 2003	Overall
E. Grasshopper Glacier	-0.60	-0.04	1.07	-1.55	-0.31
W. Grasshopper Glacier	0.10	0.14	-0.88	-0.33	-0.11
Rearguard Glacier	0.01	-0.16	-0.16	-0.79	-0.20

Table 3—Amount of incoming solar insolation for the Castle Rock and East Grasshopper Glaciers

Direct + Diffuse Mean Incoming Solar Insolation (watt hours per square meter)		
Day	Castle Rock Glacier	East Grasshopper Glacier
Summer Solstice	7,768	6,338
Spring/Fall Equinox	4,565	3,114
Winter Solstice	1,188	602

when it was snow covered) match the true elevation of that area.

Results and Discussion

The project revealed a dramatic decrease in ice depths—especially in the case of the Castle Rock Glacier, which lost an average of 60 meters of ice in the 51 years from 1952 to 2003 (figure 4). This amounts to an average surface loss of 1.2 meters of ice per year. However, this rate has been far from consistent. The periods from 1987 to 1991 and 1995 to 2003 showed mean ice losses of 2.5 meters per year (well above the average), while the period between 1995 and 1998 revealed a mean loss of only 0.3 meters per year (well below the average). Results for the Castle Rock Glacier are summarized in table 1.

The other sites exhibited less dramatic ice losses (table 2). The East Grasshopper Glacier lost an average of just over 16 meters of ice in the 51 years from 1952 to 2003, averaging 0.3 meters per year.

The Castle Rock Glacier has a south-southeastern exposure. Its profile (for all dates) was measured over 1,500 meters of horizontal distance with an elevation ranging from 3,400 to 3,620 meters. By contrast, the East Grasshopper Glacier has a northeastern exposure, a 2,700-meter profile distance, and elevations ranging from 2,900 to 3,500 meters. It seems that the northeastern exposure of the East Grasshopper Glacier allows it to be longer and lower than the southern exposure of the Castle Rock Glacier. The incoming solar radiation for the Castle Rock Glacier is much higher than the East Grasshopper Glacier (table 3).

The character of the two glaciers is quite different as well. The East Grasshopper Glacier exhibits a very indistinct gradation from an ice/snow surface at the upper elevations to rock glacier and then moraine at the lower elevations. By contrast, the Castle Rock Glacier has a very distinct snow and ice surface—with little or no transition to rock glacier or moraine conditions. The exposure and characteristics of the East Grasshopper Glacier may be attenuating the effects of global warming compared with the Castle Rock Glacier. Alternatively, because the East Grasshopper Glacier has a far larger rock component, the loss of ice may simply be less evident. The inconsistency between these two glaciers indicates that it may be unwise to extrapolate ice-loss values to other glaciers in the Beartooth Mountains—much less other mountain ranges—without further study.

Costs

With several caveats, the approximate total cost for one date of imagery at a typical glacial site is $2,120.00. As already detailed, the tasks include identifying and locating available stereo photography, scanning the photography or finding already-scanned images, orthocorrecting the photography, measuring ice elevations for each site and date, and analyzing the results of those measurements. There are several ways of accomplishing many of these tasks, and consequently costs can be quite variable. To keep things simple, assume one glacier site for one date—requiring four photographs for complete stereo coverage. Here is the estimated breakdown:

- Identifying and locating available stereo photography (assumes access to flight-index maps)—6 hours
- Scanning the images—6 hours
- Orthocorrecting the photography (including finding or making a camera report and downloading the DEMs and reference imagery)—12 hours
- Measuring ice elevations (includes importing the LPS block file and setting up the stereo model in ArcGIS Stereo Analyst, creating the shapefile, digitizing 3-D points, and exporting the shapefile to an *X,Y,Z* text file)—8 hours
- Analyzing the data (includes importing the *X,Y,Z* text file, preparing the data for comparisons, and plotting the results)—8 hours

Thus, the total labor time is approximately 40 hours at $50 an hour or $2,120.00). This estimate assumes that the personnel have the required software, expertise, and familiarity with the procedures and that there are no unforeseen problems. The data have a relatively insignificant cost: four photos at $30 apiece is $120, bringing the total cost to $2,240.00.

Conclusions

This project demonstrated that current technology and methodology can effectively monitor changes in glacial areas and ice volumes related to climate change. The technology to measure changes in alpine glaciers accurately is widespread within the Forest Service—however, using these technologies effectively may entail a significant learning curve.

The methodology in this project provided the desired information and was cost effective; costs can be even lower if fewer dates of imagery are used in the analysis. This project used nine dates of stereo imagery for the Castle Rock Glacier and five dates for the other three glaciers. However, important glacial-change information can be garnered by comparing any two dates of imagery—especially if they are the earliest date and the latest date available.

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