A Remote Sensing Strategy for Measuring Logging Road System Length from Small-Format Aerial Photography

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Abstract

Small-format aerial photographs (SFAP) can be acquired at a relatively low cost to obtain quantitative data for natural resource applications. A remote sensing strategy was developed for measuring logging road system length from SFAP. Aerial photography, digital image processing, and fieldwork procedures are described in sufficient detail for natural resource managers to acquire their own SFAP with only basic skills and equipment. An alternative field-based strategy was developed and used to evaluate time, costs, and relative accuracy of the remote sensing strategy. The field-based strategy was assumed to consistently produce more accurate measurements of road system length than did the remote sensing strategy. The remote sensing strategy was less expensive than the field-based strategy because logging road system length can be measured in a shorter amount of time. Error for the remote sensing strategy has an average of 11 percent and can be expected to range from 8 to 14 percent. Accuracy is limited by use of uncontrolled mosaics, lens distortion, tilt displacement, topographic displacement, and scale variation.

Introduction

Small-format aerial photography (SFAP) is becoming an increasingly popular alternative to commercial large-format aerial photography. The advantages of SFAP include the relatively low cost and flexibility of acquisition. SFAP is normally recommended when (1) existing large-format aerial photographs are not available and (2) for use as a supplement to large-format aerial photography (Willingham, 1959; Meyer, 1982). SFAP also has potential in quantitative applications such as measurements of bridges, timber sale layout, site preparation area, and road layout and monitoring (Ulliman, 1987). Digital image processing techniques can potentially facilitate the collection and improve the quality of measurements from SFAP.

This paper evaluates the accuracies that may be achieved in collecting quantitative data from SFAP. It also illustrates how to plan for successful SFAP collection and analysis, using a case study of the measurement of logging road system length from SFAP. Background information on SFAP, logging road systems, methods of measurement, potential of digitized SFAP, and the study sites is also provided. The methods of aerial photography, image processing, and field data collection are described. The time, costs, and relative accuracy of the measurements obtained are compared to conventional field methods for measuring logging roads.

Background

Small-Format Aerial Photography

SFAP is the most common format chosen by natural resource managers who acquire their own aerial photography (Ulliman, 1987). SFAP has the potential to become increasingly more attractive to natural resource managers as they are asked for increasingly sophisticated information without corresponding increases in their operating budgets (Meyer, 1982). Furthermore, SFAP can be acquired by natural resource managers even when it is not their primary responsibility, avoiding the cost of hiring an aerial photography contractor.

SFAP offers a relatively lower cost alternative for short, site specific, carefully timed, large-scale (i.e., 1:5000) photographic flights. Standard small format 35- and 70-mm cameras are considerably less expensive than metric small- and large-format cameras. It is also less expensive to mount a standard small-format camera on a light aircraft than it is to set up a metric large-format aerial survey camera in a larger size aircraft (Warner *et al.*, 1996). Cameras are sometimes hand-held, or placed in belly-mounts or custom-built in window mounts. Cessna aircraft are commonly used in acquiring SFAP and may be rented on an hourly basis. Aircraft rentals may be coordinated between the pilot and renter to take advantage of weather and other factors to obtain timely aerial photographic coverage. Color and color-infrared film is also easily obtained for standard 35-mm cameras.

Falkner (1995) has provided a useful summary of typical costs associated with aerial mapping using metric cameras. He suggests that the hourly rate for renting an aircraft with a mapping camera is higher than renting an aircraft with a

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standard camera. In addition, film costs increase if color is chosen over panchromatic film. Clearly, with small study sites, and study sites spread over a wide geographical area, SFAP is a very cheap method of acquiring data. It is important to realize that SFAP acquired with a standard camera will be less expensive than that acquired from a metric camera. Large study sites requiring many photos to image the entire area may possibly be more efficiently photographed with large-format cameras.

Measurements from standard SFAP are less accurate that those obtained from metric aerial photography. Factors such as a lack of lens calibration, an absence of film flattening devices, and the presence of lens distortion limit the metric qualities of SFAP (Faig, 1976; Ritchie and Meade, 1995; Warner *et al.*, 1996). Another issue is that SFAP is normally enlarged prior to analysis. The enlarging process has the potential to change image scale in an inconsistent manner, crop a portion of the image from the print, add additional distortion, and change tip and tilt in the photo (Needham and Smith, 1984). Standard cameras often have unknown, or partially known, interior orientation and do not allow for fiducial marks on photos (Faig, 1976). Thus, SFAP from standard cameras lacks metrical qualities and does not allow for use of highly accurate measuring techniques common to metric photogrammetry. On the other hand, the accuracy standards of metric cameras may exceed accuracy requirements needed to map soil and vegetation patterns for many applications (Warner and Fry, 1990).

Use of SFAP in Mapping and Measurement Applications

SFAP has been used for mapping and measurement applications in natural resource management. Direct photo measurements have been made on SFAP prints to obtain quantitative information such as estimates of tree height, crown width, and crown area (Hagan and Smith, 1986). Warner (1994) used space resection to compute ground coordinates and map waste sites. Although the resulting waste site map was not as accurate as what could have been produced from metric photography, he suggested that 3-m accuracy was acceptable for that particular end use (Warner, 1994).

Another option available is to produce digital images of SFAP. Lee and McKelvey (1984) produced digital images of 35-mm aerial photography in a wildlife application involving trumpeter swans. Lyon *et al.* (1986) also used video cameras to produce digital images of 35-mm photographs. Pixel counts of the video images were used to measure areas of wind erosion damage. Digital images can be enhanced and also analyzed in an environment that facilitates making measurements. Photo design and production software packages can provide low cost image processing and measurement capability from personal computer systems (Shiba, 1996). The accuracy of measurements made with photo design and production software depends on the resolution of the original photograph, distortions in the photograph, and the scanning resolution used to produce the photographic image (Rohde, 1995).

Logging Road Length

In this paper we illustrate how quantitative data on logging road system length may be obtained from SFAP. This research was part of a larger research project that investigated the area occupied by logging road systems and the corresponding potential for erosion. Logging road systems contribute the greatest potential for erosion on logged sites (Mitchell and Trimble, 1959; Kochenderfer, 1970; Patric, 1976; Swift, 1984). Erosion is minimal when forest litter remains intact on logged sites (Kochenderfer, 1970). Measuring logging road system area is the first step in determining the potential for erosion because it provides an estimate of the amount of exposed soil on logged sites. Logging road system length was needed to determine road system area and thus the surface area of exposed soil. Traditionally, logging road system lengths have been measured using a steel tape and staff compass (Kochenderfer, 1977). It was speculated that aerial photography might offer a more efficient alternative for measuring logging roads.

Other investigators have measured logging roads to estimate the amount of harvested area occupied by logging road systems, evaluate soil disturbance, and characterize haul road configuration. Baumgrass (1971) used a measuring wheel in a logging road alignment study. Horizontal distance was measured between road alignment stations located at the intersections of road centerlines, and the longest straight line distances between wheel tracks. In studies of soil disturbance, total transect length and length of disturbed soil have been measured along transects across logged sites (Aust *et al.*, 1993; Martin, 1988; Miller and Sirois, 1986).

Description of Study Sites

The study sites consisted of 30 logging operations in West Virginia Forest District 3 (Figure 1). Each logging operation was selected randomly from a master list of current logging operations in District 3. District 3 includes approximately 2.5 million forested acres in Lewis, Upshur, Randolph, Braxton, Webster, Pocahontas, Clay, and Nicholas Counties (DiGiovanni, 1990). These forests owe their origin to a reoccurring pattern of logging and fire (Clarkson, 1964). Moreover, they share common edaphic and topographic characteristics, making the environmental conditions broadly comparable among study sites (Core, 1966).

Methods

A remote sensing strategy was developed to measure logging road system length from SFAP. This strategy included airphoto acquisition, digital image processing, and fieldwork. Airphoto procedures included flight planning and photo acquisition. Image processing consisted of scanning, interpreting, and measuring digitized airphotos. Fieldwork for the remote sensing strategy included (1) plotting boundaries of logged sites on 7.5-minute quadrangle sheets and (2) measuring ground distances used in determining equivalent image scales. A separate field-based strategy for measuring logging road system length was also developed to compare the costs and relative accuracy of the remote sensing strategy. Field-

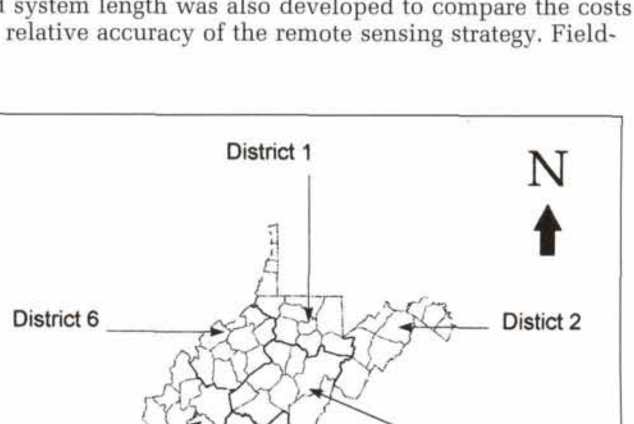

Figure 1. The six West Virginia Forest Districts, including District 3.

work for remote sensing strategy and field-based strategy are discussed in the fieldwork section.

Aerial Photography

Flight Planning

Flight planning was conducted to obtain complete photographic coverage of harvested sites. A specific flight plan was drawn up for each harvested site. The flight planning variables included flight lines, flying heights, altitude, end lap, intervalometer settings, weather, site order, and time. Two trial flights were performed to test planning assumptions and decisions prior to the three final flights.

The primary purpose of Trial Flight 1 was to determine if logging roads could be identified and measured from 35-mm photography. The aircraft and camera characteristics are listed in Table 1. The test site consisted of several recent timber sales on the West Virginia University Forest which were photographed following leaf out in May, 1995. Landmarks such as forest road intersections were shown to provide opportunities to determine photo scale. Results from Trial Flight 1 indicated that logging road lengths could be obtained from aerial photography using standard 35-mm color film.

A method was then developed to estimate the optimum flying height, altitude, and intervalometer setting for each site. The assumptions and methods were evaluated in Trial Flight 2, flown in November, 1995. Five flight planning variables were considered. First, flight lines were located so that the longest (36-mm) side of the negative was parallel to the narrowest dimension of the logged site (Figure 2). Second, flying height was determined graphically with a homemade flying height template (see Appendix). The minimum flying height was added to the lowest site elevation to determine altitude of aircraft. Third, photographs were end lapped along the direction of the flight line using an intervalometer. Intervalometer settings were calculated by methods described by Paine (1981). Fourth, weather criteria were developed for percent cloud cover above aircraft, ceiling, and winds aloft. These criteria were used as guidelines for choosing days suitable for photo acquisition. Finally, site order for photographic flights was determined by plotting all logged sites on the Cincinnati Sectional Aeronautical Chart and estimating total time for each flight.

Photo Acquisition

The general photo acquisition procedure involved aerial navigation to the general vicinity of harvested sites, location, visual identification of the harvested sites, orientation of the plane to the flight line, and camera operation. Of the 30 planned sites, 20 were successfully photographed. Funding for aircraft rental and pilot services was not available for the remaining ten sites. Over the three final flights, a total of 12 hours were spent in the air.

The photo acquisition procedure included five steps. First, the plane was flown to the general vicinity of the site. Aerial navigation to the general vicinity of the harvested site was by a Loran unit (Trial Flight 2 and Final Flight 1) and a Global Positioning System (GPS) unit (Final Flights 2 and 3). Second, landmarks such as roads, bridges, houses, and ponds were used to locate each harvested site. Following landmarks to each harvested site was essential because differential correction was not available for accurate GPS navigation. Third, each site was visually identified by matching the harvested area to its plot on the 7.5-minute quadrangle maps. Fourth, the plane was oriented to the flight line. A series of 90-degree turns were made to view the site from all sides. A final 90-degree turn was made to orient the plane with the flight line. Teamwork between the pilot and camera operator was essential to successful photo acquisition during these flights. Fifth, the camera operator adjusted intervalometer settings, started, and stopped the camera.

TABLE 1. AIRCRAFT AND CAMERA CHARACTERISTICS USED FOR TRIAL FLIGHT 1.

Characteristic	Description
Aircraft	Cessna 172
Aircraft Camera Mount	None
Camera	Standard, 35-mm, single lens reflex (SLR)
Lens	50 mm
Lens Filter	Skylight

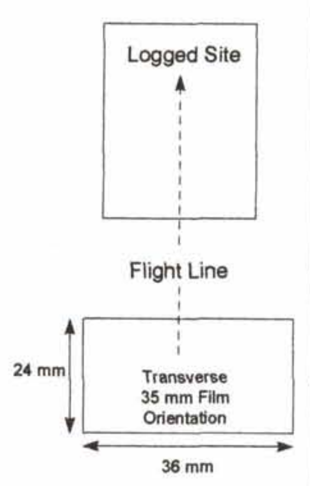

Figure 2. Schematic showing relationship between 36-mm side of negative and narrowest dimension of logged site.

Equipment

A camera mount, automatic camera with a motor drive, and an intervalometer were needed (Table 2). One of the most difficult tasks was locating an aircraft equipped with a belly camera mount. After some searching, a contractor in a neighboring state was able to provide a Cessna C-150 aircraft and an aluminum camera mount.

The orientation of the camera in the camera mount determined the photo-coordinate axes. The camera mount oriented the camera in the transverse mode (Warner *et al.*, 1996). The 36-mm side of the negative was defined as the photo *y* axis as it was most perpendicular to the flight direction. The 24-mm side of the negative was defined as the photo *x* axis as it was most closely parallel to the flight direction (Figure 2).

Digital Image Processing

The digital image processing component of the remote sensing procedures employed a photo design and production software package for scanning uncontrolled mosaics, determining image scale, and image interpretation. A computer aided drafting (CAD) software package was employed to measure logging road length. Procedures for image scanning, scale determination, and interpretation are explained separately from measurement procedures.

Scanning, determining image scale, and image interpretation involved four steps. First, end-lapped color photo-

TABLE 2. AIRCRAFT, CAMERA, AND LENS CHARACTERISTICS FOR TRIAL FLIGHT 2 AND FINAL FLIGHTS 1, 2, AND 3.

Characteristic	Description
Aircraft	Cessna C-150
Aircraft Camera Mount	Custom made, aluminum construction, no leveling mechanism, mounted on floor of cockpit
Camera	Standard, 35-mm, SLR, automatic exposure settings used
Lens	35- to 70-mm zoom lens, Approximate focal length = 35 mm, focus set at ∞
Lens Filter	Skylight
Intervalometer	Attached to camera
Film	ASA 100

graphs were assembled into uncontrolled mosaics of each harvested site according to methods described by Paine (1981). Second, the uncontrolled mosaics were scanned into the photo design and production software using a color image scanner. To minimize file size, images were scanned in grayscale at a resolution of 150 dots per inch (DPI), cropped, and saved as Joint Photographic Expert Group (JPEG) files in the low image quality option. Third, average equivalent scales were calculated for each image using ground distances and corresponding image distances by methods adopted from Paine (1981). The photo design and production software provided a tool for measuring line length. Fourth, image interpretation was conducted in the photo design and production software as it provided close-up views of images. Close-up views of images were unattainable from direct photo interpretation of uncontrolled mosaics. The locations of logging roads were delineated with the photo design and production software.

Measuring

Although the photo manipulation software could be used to measure road length, it was very tedious because logging roads can only be measured one segment at a time. A computer-aided drafting package was selected to measure road system length because entire roads can be measured at once. Six steps were involved in the measuring process. First, actual widths and heights of images were obtained in inches. These measurements were then multiplied by the average image scale, converting them to real world units in feet. This step is necessary because the CAD operations are conducted in real world units. Second, design files were created with the CAD software. Third, rectangular blocks were created in each design file. Block dimensions corresponded to image dimensions in real world units of feet. Fourth, JPEG images of each site were then imported into their own unique blocks. Image degradation associated with importing JPEG images did not allow for adequate image interpretation with the CAD software. Thus, image interpretation needed to be conducted with the photo manipulation software. Delineating the roads with the photo manipulation software allowed them to be visible, when JPEG images were imported into blocks. Fifth, new lines were drafted over the delineated roads with the CAD program. Finally, logging road length was determined by measuring the length of each computer drafted line. Measuring CAD lines was efficient because lengths of entire roads could be determined with a single measurement. All road length measurements were later converted to meters.

Fieldwork

Fieldwork was conducted to support the remote sensing strategy for measuring logging road system length, as well as to provide an independent estimate of logging road system length. Fieldwork for the remote sensing strategy was conducted before photo acquisition. Boundaries of all harvested sites were plotted on U.S. Geological Survey (USGS) 7.5-minute quadrangle map sheets, and ground distances were measured for determination of photo scales. All measurements were made with a fiberglass tape, rounded to the nearest foot, and converted to meters. Features used in determining photo scale ground distances included landings, ponds, fences, and powerline rights of way. To account for scale variations associated with mountainous topography, ground distances were stratified by elevation whenever possible. It was assumed that an average scale based on high and low elevations on each harvested site would help minimize scale variation associated with topography.

After photo acquisition, the field-based strategy was used to measure logging road system length. A hand-held survey laser served as the measuring device. Eighteen of the 20 photographed sites were re-visited because two landowners would not give permission for an additional site visit. Haul and skid roads were divided into the longest possible straight-line segments, and survey stations were located on the roadbed surface.

The field measurements for road lengths were performed by a two-person crew. The first crew member kept field notes and marked survey stations with spray paint. The second crew member operated the survey laser. A custom reflector, taped to the back of an aluminum clipboard, was used as the target for the survey laser. The reflector was held over each survey station, while another crew member held the survey laser over the previous survey station. The survey laser was aimed at the reflector target as horizontal distance measurements were taken. If tall slash or vegetation interfered with measurements, a foliage eliminating filter was attached to the survey laser. The uncontrolled mosaics greatly assisted in the field measurements because it was much easier to keep track of which roads had been measured and which had not.

Results and Discussion

Accuracy

The accuracy of the remote sensing strategy was evaluated by constructing a 95 percent confidence interval on the mean percent error in road system length between the remote sensing and field based methods. The confidence interval was calculated using a t-distribution with $\alpha = 0.05$ and 17 degrees of freedom. Although there is error associated with the field-based system, it was assumed to be closer to the true value of road system length. The difference between computer and field-based road lengths was therefore assumed to be the error associated with the remote sensing strategy. Percent errors (PE) were calculated for each harvested site according the to the following formula:

$$\mathrm{PE} = \frac{\text{(Absolute value of difference in road system length)}}{\text{(Field road system length)}} * 100\%.$$

The remotely sensed and field-based road lengths, absolute values of difference in road system length, and percent errors are listed in Table 3. Percent errors ranged from 3 to 24 percent (Table 3). The mean percent error was 11 percent. Results from the confidence interval suggested that users of the remote sensing strategy could expect 8 to 14 percent error 95 percent of the time. These results are not comparable to metric photogrammetry. Several factors may explain this. First, measurements were made from roads traced on images of uncontrolled mosaics, which are a major source of error (Paine, 1981). Second, by using a standard camera, the metrical qualities of the photographs were limited by lens distortion, lack of a film flattening device, and lack of forward motion compensation. The principal point of each photo and

TABLE 3. DIFFERENCES BETWEEN REMOTELY SENSED AND FIELD-BASED ROAD SYSTEM LENGTHS, ABSOLUTE VALUES OF DIFFERENCE IN ROAD SYSTEM LENGTH, AND PERCENT ERRORS BY SITE.

Site	Computer Length (m)	Field Length (m)	Abs. Val. Of Diff. (m)	PE (%)
1	1188	1297	109	8
3	1848	2446	598	24
4	2451	2606	155	6
5	3100	3318	218	7
6	631	551	80	15
7	2148	1852	296	16
8	6203	5740	463	8
9	2449	2641	192	7
10	609	520	89	17
11	748	791	43	5
13	434	485	51	11
23	822	737	85	12
24	1401	1239	162	13
25	2030	2107	77	4
26	857	785	72	9
27	501	485	16	3
28	2023	1691	332	20
30	2494	2216	278	13

TABLE 4. THE TOTAL APPROXIMATE COSTS OF MEASURING LOGGING ROAD SYSTEM LENGTH USING THE REMOTE SENSING STRATEGY ON 18 LOGGED SITES.

Activity	Hourly Rate	Total Time (hrs)	Total Cost ($)
Fieldwork (1 Person)	15.00	90	1350.00
Flight planning	15.00	40	600.00
Aircraft rental and pilot services	75.00	12	900.00
Camera			500.00
Camera operator	15.00	12	180.00
Scanner			500.00[1] (250.00)
Photo manipulation software			300.00
CAD Software			4000.00[2] (500.00)
Digital Image Processing	15.00	40	600.00
Total			8930.00[3] (5180.00)

[1] A table top scanner can be acquired for approximately $250.

[2] Similar but less expensive CAD programs may be able to perform the same function.

[3] Substituting less expensive items may reduce the total cost of the remote sensing strategy.

exact lens focal length were unknown, making measurements other than from tracing impossible (Warner *et al.*, 1996). The camera mount did not have a stabilizing device. Therefore, tilt displacement was easily introduced. Finally, mountainous topography in West Virginia resulted in topographic displacement as well as scale variation in the photos.

Being able to achieve measurements within 8 to 14 percent of those obtained with the field-based system seems to be adequate for determining logging road length. Logging road length is needed to determine forest road system area and the corresponding potential for erosion. Eight to 14 percent error should allow investigators to ascertain whether a high or low potential for erosion exists. Moreover, logging roads in West Virginia are often non-engineered. Their shapes are often irregular and lack exactness. Metric measurements may be more than is needed to determine whether their is a high or low potential for erosion.

Time and Approximate Costs

Time and costs were directly related and are therefore discussed together. Approximate total costs were compared between the remote sensing and field-based strategies. The following cost items were included for the remote sensing strategies: fieldwork (one person), aircraft rental and pilot services, camera, camera operation, scanner, software, image interpretation, processing, measurement, and fieldwork performed by one person (Table 4). Fieldwork performed with a two-person crew and cost of survey laser were included for the field-based system (Table 5). The total approximate costs of the remote sensing strategy appear to be substantially less than those for the field-based strategy. The cost of the survey laser is the greatest factor in the high cost of the field-based strategy. Furthermore, two people are needed to perform the field work. In contrast, the field work for the remote sensing strategy can be completed by one person.

There is potential to further reduce the costs of both strategies by substituting equipment with similar products that are less expensive (Tables 4 and 5). For instance, the survey laser and CAD program might be substituted with similar but less expensive products. By substituting similar products, the total costs of the remote sensing and field-based strategies were estimated at $5180 and $6700, respectively.

Although not employed in this study, GPS offers an alternative strategy for obtaining length. There are GPS units available that offer positional accuracy in the 2- to 5-meter range after post processing. The correction files required for post processing are becoming readily available for downloading from the Internet. With appropriate receivers, and the acquisition of broadcast services, the need for post processing to perform differential correction is eliminated. However, GPS reception can be limited in forests, reducing the effectiveness of this technology.

Conclusion and Recommendations

In this study, remote sensing strategy has been developed to measure logging road system length using SFAP. Quantitative data on logging road system length have been obtained from SFAP. Logging road system length was measured because of its importance in evaluating the potential for erosion on logged sites. As part of a larger research project, it was intended to use length data to determine area. Logging road system area could then be used to develop information on the potential for soil erosion from logging operations.

Flight planning is a very important because it is needed to obtain complete photographic coverage of harvested sites. Road length measurements cannot be made without complete photographic coverage. Results indicated that remotely sensed measurements will be within 11 percent of field-based measurements on the average. Error can be expected to range between 8 and 14 percent. Accuracy is probably limited by the use of uncontrolled mosaics, the presence of lens distortion, tilt and topographic displacement, and scale variations. The accuracy attained with the remote sensing strat-

TABLE 5. THE TOTAL APPROXIMATE COSTS OF MEASURING LOGGING ROAD SYSTEM LENGTH USING THE FIELD-BASED STRATEGY ON 18 LOGGED SITES.

Activity	Hourly Rate	Total Time (hrs)	Total ($)
Fieldwork (Crew Member 1)	15.00	90	1350.00
Fieldwork (Crew Member 2)	15.00	90	1350.00
Survey laser			10750.00[4] (4000.00)
Total			13450.00[5] (6700.00)

[4] The survey laser may be substituted with a laser range finder with compass and inclinometer.

[5] Substituting a less expensive measuring device for the survey laser may reduce total cost.

egy is adequate for the erosion evaluation application discussed in this paper.

The total approximate cost of this remote sensing strategy was less than for the field-based strategy for determining logging road system length. Time is a key factor in determining costs. The amount of flying time and fieldwork increases the cost of the remote sensing strategy. Likewise, increased fieldwork increases the cost of the field-based strategy. GPS warrants consideration because the costs of GPS units are comparable to the costs of the remote sensing strategy and offer high accuracy. Like field-based measurements, GPS does not have the advantage of the overview of the site provided by SFAP.

The remote sensing strategy involved fieldwork, 35-mm aerial photography, digital image processing, and computer aided drafting. The equipment and materials employed by this remote sensing strategy are all readily obtainable. The procedures can be followed by natural resource managers to acquire their own SFAP without an aerial photography contractor. Photo planning and image processing aspects of this system may be conducted by other scientists to process raster images for export into image processing or geographic information system (GIS) software.

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Appendix

A simple flying height template was constructed as a graphical method for determining the minimum flying height needed to obtain complete photographic coverage of harvested sites along the photo *y* axis (Figure A1). This template

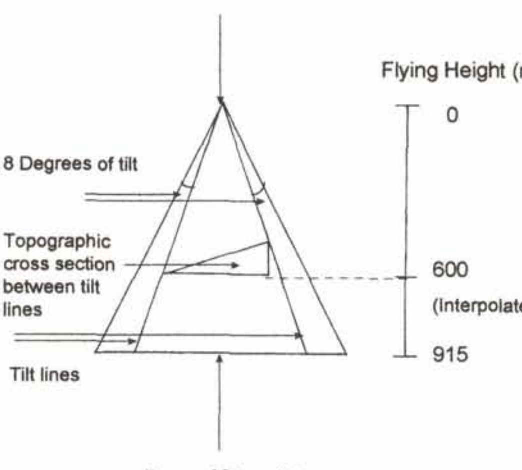

Figure A1. Schematic depicting flying height template with cross section between tilt lines and an interpolated flying height.

was found to be a useful aid in mission planning and can be constructed easily.

The template was drawn to scale on paper and fastened to cardboard for support. The template was used in conjunction with cross sections of harvested sites. The template and cross sections were drawn to scale in real world units. The flying height template was an isosceles triangle with a base that represented the photographic coverage along the photo y axis, obtained with a flying height of 915 meters, a lens with approximate focal length of 35 mm, and an approximate focal plane of 36 mm along the photo y axis. When constructing this template, width of photographic coverage (base of the template) was calculated as follows:

$$\text{Coverage Width} = \frac{(\text{Focal plane in mm}) \times (\text{Flying height in meters})}{(\text{Focal length in mm})}.$$

Cross sections of entire or isolated portions of harvested sites were constructed for use with the flying height template. These cross sections depicted the lowest and highest site elevations as well as widths of harvested sites perpendicular to their flight lines (Figure A1). The cross section was moved towards the apex of the template to determine the lowest possible flying height that would yield complete photographic coverage along the photo y axis. Flying height was interpolated based on the location of the cross section relative to the apex of the template.

A safety factor was used to increase flying heights beyond their minimum values. Tilt was the major consideration in developing the safety factor. The tilt lines on the interior of the flying height template increased flying heights so that ± 8 degrees of tilt could be experienced while maintaining complete photographic coverage (Figure A1). In addition, an extra 60 meters was added to each side of each cross section, increasing the required width of photographic coverage. The flying height (including safety factor) was added to the lowest site elevation to obtain aircraft altitudes above the National Geodetic Vertical Datum of 1929.