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PRECISION MEASUREMENTS FROM VERY-LARGE SCALE AERIAL DIGITAL IMAGERY

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Abstract. Managers need measurements and resource managers need the length/width of a variety of items including that of animals, logs, streams, plant canopies, man-made objects, riparian habitat, vegetation patches and other things important in resource monitoring and land inspection. These types of measurements can now be easily and accurately obtained from very large scale aerial (VLSA) imagery having spatial resolutions as fine as 1 millimeter per pixel by using the three new software programs described here. VLSA images have small fields of view and are used for intermittent sampling across extensive landscapes. Pixel-coverage among images is influenced by small changes in airplane altitude above ground level (AGL) and orientation relative to the ground, as well as by changes in topography. These factors affect the object-to-camera distance used for image-resolution calculations. 'ImageMeasurement' offers a user-friendly interface for accounting for pixel-coverage variation among images by utilizing a database. 'LaserLOG' records and displays airplane altitude AGL measured from a high frequency laser rangefinder, and displays the vertical velocity. 'Merge' sorts through large amounts of data generated by LaserLOG and matches precise airplane altitudes with camera trigger times for input to the ImageMeasurement database. We discuss application of these tools, including error estimates. We found measurements from aerial images (collection resolution: 5–26 mm/pixel as projected on the ground) using *ImageMeasurement*, *LaserLOG*, and *Merge*, were accurate to centimeters with an error less than 10%. We recommend these software packages as a means for expanding the utility of aerial image data.

Keywords: aerial photography, image, measurement, measurement software, resolution, riparian measurements, stream width

1. Introduction

Resource managers often need measurements. Measurements of length or width (or both) may be needed for a variety of items or areas of interest including animals, logs, rocks, springs, streams, ponds, channels, meadows or riparian habitat, shrub or tree canopy diameters, vegetation patches, man-made objects, and other characteristics important to resource monitoring and land inspection. Usually an accurate assessment of these characteristics depends on multiple measurements (samples) systematically distributed over the population (management unit, plant community, reach of stream) being monitored. Conventionally, such measurements are made by crews working on the ground with tape measures because aerial imagery has lacked the resolution for accurate measurement of these types of features. Low and medium-resolution imagery acquired from high altitudes is not suitable for measurements requiring decimeter accuracy because the spatial resolutions prevent accurate viewing or placement of measurement points, or, small objects may be indistinct or even invisible. Ground sample distance (GSD) is a measure of the spatial resolution of an image and is defined as the linear dimension of a single pixel's projection on the ground (Comer *et al.*, 1998; ASPRS, 2004). Collection GSD refers to the spatial resolution as captured by a digital camera (Comer *et al.*, 1998). Recent advances in digital aerial imagery allow a spatial resolution as fine as 1.1 mm GSD (Booth *et al.*, 2004) – sufficient for sub-decimeter measurement accuracy. Here we present three software applications that capitalize on the potential to obtain accurate measurements from very large-scale aerial (VLSA) images.

Though discussed in-depth elsewhere (Booth *et al.*, 2003, 2004), to understand the utility of these software packages one must first understand how VLSA images are acquired. VLSA images have small fields of view and are used for intermittent sampling across extensive landscapes as opposed to continuous photographic coverage. We use a light airplane (225-kg empty weight, fixed wing, three-axis), a navigation and camera-triggering system, a digital camera, and a laser rangefinder. The navigation system is powered by Tracker[1] software (Track'Air B.V., Oldenzaal, The Netherlands) on a laptop computer interfaced with (1) a central navigation box ("TECI" box), (2) a WAAS-enabled geographic positioning system (GPS) unit, and (3) a small in-cockpit pilot display. Flight plans are written for a designated area and the GPS signal allows the navigation software to visually guide the pilot over pre-designated targets. When the pilot flies over a target, the navigation software sends a trigger pulse to the camera to acquire an image automatically, allowing the pilot to concentrate solely on flying the airplane.

At present, our system uses a Canon EOS 1DS 11.1-megapixel SLR, RGB digital camera with various lenses (focal lengths of 100–840 mm). The camera is connected by IEEE-1394 cable ("firewire") and Canon Remote Capture software to a second laptop that is used to store up to 40 GB of digital data (Canon USA, Lake Success, NY, USA). Images are first saved as 4064 × 2704-pixel, ≈10 megabyte (MB) RAW TIFF files (which contain an array of image metadata) and are later converted to 24-bit, ≈12 MB, 4064 × 2704-pixel minimum-compression JPEG files.

The laser rangefinder is used as an altimeter to continuously read and record the plane's altitude above-ground-level (AGL) below 300 m. It displays this to the pilot on the screen of the laptop storing the images and is a useful tool for helping the pilot fly at a desired altitude AGL. The stored data are available for later correlation with images. Typical flight altitudes are 100–200 m AGL.

Knowing the exact airplane altitude AGL for each image allows the collection GSD (hereafter simply "GSD" except where display GSD is specified) to be calculated for each image. Once GSD is determined, image measurements can be converted to object measurements. Measuring imagery manually using common photo-editing software programs is labor-intensive, so a new program that combined the many steps of image loading, image measuring, pixel counting and conversion of pixels into metric units was developed to facilitate the process. To more accurately calculate GSD for images, new laser rangefinder software called 'LaserLOG' was developed. To facilitate correlation of photos with altitudes, 'Merge' was created. Here we present the details regarding development and testing of the new software.

2. Resolution and Scale

Scale has traditionally been a measure of the resolution of film-based aerial photography and is calculated as (Avery, 1968):

Scale = distance between two film points/distance between corresponding ground points

Scale = lens focal length/camera altitude AGL

In the first calculation, scale is based on the dimensions of the negative (negative scale). A similar calculation is used to define the scale of printed photographs (print scale or display resolution). A print cannot have a finer resolution (larger scale) than the original negative and that makes the negative scale the basis for comparisons among film-derived images. The digital sensor (diode array) is analogous to the film negative, and scale measurements can be similarly based on the dimensions of the sensor, or on altitude AGL and lens focal length. However, scale calculated either way is a poor indicator of digital image resolution because two digital sensors of equal area can have different numbers of diodes and diodes can vary in size, spacing and the way their output forms a pixel (picture element). Since the smallest discrete component of a digital image is the pixel, sensors with more pixels yield greater-resolution imagery (will show a smaller area of ground/pixel) – all other factors being equal – even though the calculated image scale will be the same for both. Therefore, the most meaningful way to compare digital images is by measuring the length of a single pixel's projection on the ground, the GSD (Comer, 1998; ASPRS, 2004).

The immediate product of a digital camera is a viewable image, not a negative. Digital images have display scales and resolutions that change depending on the dot-pitch of a monitor or the zoom factor used inside photo-editing software (Comer *et al.*, 1998). For this reason, display scales and resolution are not very meaningful for comparing the resolving power of digital images, and are typically used when examining printed images or after resizing images on a monitor. Thus it is most useful to compare image resolutions on the basis of collection GSD. We calculate digital image resolution as (derived from Comer *et al.*, 1998):

$$\mathrm{R} = (\mathrm{AW} * \mathrm{OD})/(\mathrm{FL} * \mathrm{IW})$$

where:

R = resolution in mm/pixel
AW = sensor array width in mm
OD = object distance and is the distance between the object photographed and the camera lens in mm
FL = lens focal length in mm
IW = image width in pixels

Note that the resolution calculation is a traditional scale-ratio equation with the added inputs of sensor array width and image width, whose quotient is the length of a single pixel's projection on the ground – the GSD. To bridge the gap between the traditional description of film image resolving power (scale) and digital image resolving power (collection resolution), we refer to images as "very-large scale" to indicate high resolving power, but recognize that they would more accurately be described as "very-high resolution" to indicate that each pixel has a small GSD.

3. ImageMeasurement Software

ImageMeasurement can be used to measure between two points on any calibrated digital image and allows multiple measurements per image. A calibrated image is one whose GSD is known. Several software programs facilitate image measurements, but ImageMeasurement is unique because it integrates resolution data for every image in a multi-image data set from which measurements will be made. The source code is written in C# (Microsoft Corporation Redmond, WA, USA). A database allows a user to input a series of images and stores measurement values. A Microsoft Excel spreadsheet was chosen as the database because most people are familiar with Excel and can easily use it to input the required data fields and to manipulate the output data. The data to be entered in the spreadsheet include a name or code for each image and its GSD in units/pixel. ImageMeasurement provides output to the database in terms of what was measured (i.e. measured length or distance, zoom factor and internal scale). Up to 50 measurements can be made on each image. The program loads and resizes each image into a 'picturebox'. For example, an image may be 4064×2704 pixels with 15 mm GSD. The picturebox is sized at 924×614 which is roughly the same length-width ratio ($4064/2704 = 1.50$), so the image is reduced to fit into the smaller box and the image display resolution is adjusted accordingly (i.e. the display resolution is now 68.16 mm GSD). A user begins by left clicking at the edge of the object of interest, which creates a small yellow dot on the image. The X, Y mouse coordinates for this point are recorded. The user then left clicks at another point on the other side of the object of interest, creating a second yellow dot and a line joining it to the first. The distance of this line is calculated as the display GSD times the square root of $(X1 - X2)^2 + (Y1 - Y2)^2$. This data is then recorded in the database when the user clicks on 'Save'. Images with a different length-width ratio cause the picturebox to be resized to the same ratio as the image.

The program provides several 'zoom factors' (2X, 4X, 8X, and 16X). Whenever the user zooms (by right clicking on the desired area), the original image (not the resized image described above) is used to create the new zoom field. Note that the accuracy of any measurement is improved by zooming because the display GSD is reduced, allowing the user to see greater detail to more accurately select the measurement points. In the above example, the 1X display GSD is 68.16 mm. At 16X zoom, the display GSD is 4.26 mm. If a measurement point is off by one pixel, in the first case the error would be 68.16 mm, whereas in the second case it would be 4.26 mm (an improvement of 16X).

The program allows the user to make single or multiple measurements on an image. When in single measurement mode, the user can make multiple attempts to get the exact measurement desired, and then only the last measurement is recorded. In multiple measurement mode (up to 50/image), the last 50 measurements are all stored internally until the user saves them. In either case, the internal measurements can all be cleared by clicking on "Clear Lines" (Figure 1). A comment box allows the recording of a simple comment, up to 100 characters, to be added to the database in addition to the measurements made for each image.

One of the applications for which ImageMeasurement was conceived is the measurement of stream width and other measurable indicators in riparian areas. The ability to measure distances on an image for use in statistical analyses requires the establishment of standardized guidelines on how and where to make those measurements. The image window of ImageMeasurement can be overlaid with four intersecting red lines: one horizontal, one vertical, and two opposite diagonal, all intersecting at a single point in the image center (Figure 1). The primary sample-location line is the horizontal line. From left to right, the first point where the horizontal line intersects the center of the stream is the measurement point. The stream is measured perpendicular to stream flow, with the measurement line intersecting the sample-location line in mid-stream. If the horizontal (primary) sample-location line fails to intersect the center of the stream, then the vertical line acts as the secondary line when followed from top to bottom. The tertiary line, originating at the upper left corner, is used if the secondary line fails to intersect. The quaternary line, starting at the lower left corner of the image, is used as needed. If none of the four lines intersect the stream center and the user feels a measurement should be made from the image, then a random point can be chosen. In no case will a measurement line be used that does not first intersect dry land. Streams, riparian corridors, riffle areas, pools, dry beds, gravel bars and willow canopy can all be measured using the same guidelines. Alternatively, if more than one measurement point per image

● CrossHair
○ Vertical
○ Horizontal

Point 1
59 X1
295 Y1

Point 2
84 X2
315 Y2

Distance
2703.29 Units

Zoom
○ 2X
● 4X
○ 8X
○ 16X

No. Meas
● Single Meas
○ Multiple Meas

KEY 45
Current Image E:\Nevada\2004\2004 Stream Survey\Nelson\nv_streams_0452_RJ.JPG
Enter Measurement Comment Here
Meas Made = 1
Area Shown (WXH) = 77850.680 Units X 51844.162 Units
Scale = 84.437 Units/Pixel

Figure 1. ImageMeasurement 1.0 screenshot showing a large scale aerial image of a stream in Wyoming. The image was acquired from 217.4 m above ground level using a Canon 1DS with 100 mm F/2.8 lens. Resolution for this image is 84.437 mm ground sample distance. Red crosshair-pattern gridlines are placed over the image and the point where the primary sample-location line intersects the center of the stream is used as the center of the yellow measurement line, which is placed perpendicular to stream flow. This stream has been measured at 2.703 m. The inlay shows the ability to zoom in for measurements, here shown at 4X. Other features of the software shown are the ability to apply vertical and horizontal line grids, the image footprint dimensions, the optional text comment box, different zoom level options and the toggle between single and multiple measurement modes.

is desired, a user may apply overlays of 20 equidistant vertical or horizontal lines, and measure the stream at any stream intersection with a line.

4. LaserLOG Software

An accurate measurement from ImageMeasurement is dependent on the accuracy of the GSD calculation. Pixel-coverage is determined by three main factors: camera lens focal length, camera sensor size and altitude AGL. Altitude-above-sea-level (ASL) readings from a WAAS-enabled Geographic Positioning System unit on the airplane are recorded at the instance of camera trigger but have a possible error of ±7 m. Besides GPS instrument error, error is also introduced by the need to subtract ground elevation (from USGS digital elevation models) from GPS-altitude

ASL values to derive altitude AGL. The GPS-derived-altitude AGL is the same as the distance from camera lens to photograph center *only* when the airplane is in straight and level flight. Pitch and roll regularly affect the light-airplane platform. Early attempts to utilize GPS altitudes for ImageMeasurement produced widely-variable results. A more accurate measure of the lens-to-photograph-center distance was available from a Riegl LD90-VHS laser rangefinder (Riegl USA, Orlando, FL, USA) mounted parallel to the camera lens on the aircraft. Via a serial DB-9 cable, the laser rangefinder sent data to an onboard laptop computer at about 100 readings/second (average interval is 10.8 milliseconds). Software supplied with the instrument (LaserWin 3, Riegl USA) allowed either display of this data for the pilot or storage in a text file, but not both simultaneously. Moreover, the laser data was not time-stamped. LaserLOG was developed to address these shortcomings. The source code was written with Visual Basic 6. Using LaserLOG, the data sent from the laser rangefinder is time stamped to the nearest millisecond and written to a comma-delimited text file at 90 readings/second and displayed to the pilot on the laptop screen, in either meters or feet, at about 3 readings/second. Vertical velocity in meters/minute is calculated from every 30th laser reading, showing changes in this value about 3 times/second, in red if the velocity is negative, or in green if positive. This allows the pilot to see how the terrain is changing even when a variometer may not signal an ASL change.

The text file generated during a flight can be appended during a later flight, so that each job need have only a single laser log even if it covers multiple days (date is also recorded in the time stamp). Large amounts of data are saved to the text file: 324,000 altitude readings/hour + 32,400 vertical velocity readings/hour. However, since it is saved in a simple text format, the data consumes only ≈6 MB/hour, compared to a single digital image which consumes ≈10 MB.

A potential source of error in the time stamp for LaserLOG is that the Windows operating system may be busy with another task when LaserLOG attempts to write a value. This could cause milliseconds delay in the time stamp reading. To determine altitude change between consecutive readings in the laser log and to determine the maximum deviation between the image trigger time and the LaserLOG write time, the altitude change and write-time deviation between consecutive readings was analyzed for one test flight.

5. Merge Software

The first step in measuring images is to match each image with an altitude so that GSD can be calculated. A flight produces three large data sets: image files (camera), airplane altitude AGL (laser rangefinder) and a photo index report (Tracker). The photo index report is a comma-delimited text file and includes several fields such as actual GPS airplane position at photo trigger, GPS altitude ASL, trigger time to the nearest millisecond (from PC clock), and other user-defined fields. Tracker runs on a dedicated laptop with a network connection to a second laptop that stores the image and laser rangefinder data.

LaserLOG records 90 altitude AGL readings/second and Windows file-creation times are recorded to the nearest second. The file-creation time can be as much as a minute behind the actual photo trigger because of the time required for camera files ($\approx$10 MB) to transfer to the laptop. Windows does not assign a file creation time until the entire file is present, thus, file-creation times are at least 4 seconds behind the actual photo trigger. Under ideal circumstances, a RAW TIFF image requires about 4 seconds to transfer and save. When images are taken at less-than-4-second intervals, a new image is acquired and queued up in the camera buffer (which can hold 10 images) before the first image is fully transferred. Thus, successive images are increasingly delayed and some images may require as much as a minute to transfer.

To obtain an accurate match of each image with its altitude, the photo trigger time (the time the trigger pulse was sent by Tracker) recorded in the photo index report is compared with the laser log. This requires the respective laptops be time-synchronized to the millisecond (done using the net time command in the DOS command prompt with the two laptops connected with a network line). We assume the camera requires at least a millisecond to respond and open the shutter, but the time delay is negligible, as is the exposure time (shutter speed = 1/4000th second).

The next difficulty was matching a trigger time, a LaserLOG altitude AGL reading, and an image file. This is what Merge was designed to simplify. Merge was written using the C# programming language. The required inputs for Merge are the photo index report, the laser log and any image from the directory where all images are stored. Merge outputs a new text photo index report having the same base filename appended with "_W_LASERLOGDATA" that includes the closest time-matched altitude AGL reading for each trigger time, as well as the closest post-trigger time-matched image filenames. In addition, a delta time between each match is given so a user can check to ensure that all matches are within a tolerable time window. Merge notifies the user of how many altitudes and image files were successfully matched with trigger times. Merge also allows a user to select the camera type and lens, and it will automatically create an Excel database with image resolution values ready for immediate use in ImageMeasurement.

6. Accuracy Assessment Methods

6.1. GROUND-BASED TEST

A building door, 1.15 m wide, was photographed 20 times each from 100, 200 and 300 m using the Canon EOS 1DS camera with a 100 mm F/2.8 lens. Distance from camera to door was measured using a 100 m tape measure. Door width was measured directly with a tape measure at twenty different random locations from top to bottom. An Excel database with image filename and scale was created using Merge.

ImageMeasurement with the database loaded into memory was then used to measure door width at one randomly-selected location in each image. A zoom factor of 8x was used for the 100 m set, while the 200 and 300 m sets were examined at 16x. Operator error at zoom levels 8x and 16x were assessed using the built-in accuracy assessment tool that requires a user to measure the distance between two known points on the screen.

6.2. AERIAL TEST

A 1-km section of south-north oriented front-roll irrigation wheel line was photographed at 9 locations using the same camera and lens as above. Each resulting image contained at least one wheel. All nine positions were photographed from target altitudes of 50, 100 and 150 m AGL. The diameter of each wheel was measured directly on the ground, as was the diameter of the central pipe. The flight was conducted near mid-day when the sun was at approximately full apogee to avoid shadow effects. LaserLOG was used to record laser rangefinder data during the flight. Merge was used to match image trigger times with laser log data and image filenames. ImageMeasurement was used to measure wheel diameter and pipe diameter. Since LaserLOG recorded the camera lens-to-photograph center distance, but the objects being measured (diameter of the wheel and central pipe) were known to be raised above the ground 0.72 m, each laser altitude reading was reduced by this amount to more accurately calculate GSD. Four of the 9 targets were missed in the 50 m AGL flight line (the image did not capture any segment of the irrigation line), thus n = 5 at 50 m and n = 9 at 100 and 150 m. A zoom factor of 8X was used for all image measurements in ImageMeasurement. Data from both tests were analyzed using one-way ANOVA with Tukey's HSD mean separation test as well as correlation comparisons.

7. Accuracy Assessment Results and Discussion

7.1. GROUND-BASED TEST

Comparing direct and image-derived measurements of door width indicates that the software works well in a controlled setting. The door width was 1.146 m ($n = 20$). Door width was measured from 100, 200 and 300 m imagery as 1.134, 1.133 and 1.139 m, using ImageMeasurement. 100 m imagery GSD was 8.8 mm, and the ImageMeasurement value differed from the direct measurement by 12 mm, which is about the GSD of 1.4 pixels ($P < 0.01$, $n = 20$). Images taken from 200 and 300 m AGL had GSDs of 18 and 26 mm. Measurements from 200 m imagery differed from the direct measurement by less than the GSD (13 mm), meaning that the difference was contained in less than a pixel, and therefore could not be seen ($P < 0.01$, $n = 20$). The maximum difference between measurements was 1.1%, occurring between the 200 m data set and the direct measurement. Mean width from 100 m imagery was 1.0% lower ($P < 0.01$, $n = 20$) than the direct measurement, but mean width from 300 m imagery was not significantly different from the direct measurement ($P > 0.05$, $n = 20$). Confidence intervals for each set of images ($n = 20$) were under 15 mm (1.3%). To make one measurement/image from the 60 images in the set required 15 minutes.

Human vision and dexterity in placing measurement points on the digital image play a role in error control. Operator error at various zoom levels shows that error is highest for 2X zoom (±12 mm) (Table I). However, the error assessment utility only measures how well an operator can click on 2 well-defined points. In actual data collection, object edges may be less well-defined and an additional image-dependent error is created when the operator cannot clearly see feature edges. Together, these two factors comprise total operator error.

7.2. AERIAL TEST

Aerial images had GSDs ranging from 5–13 mm, depending on altitude AGL. ImageMeasurement-derived values of the 127 mm pipe ranged from 113 to 154 mm (Table II). The highest 95% CI from any altitude set was 15 mm (11.8%), the same as in the door-width test. Thus, precision was the same from a stationary camera platform as from a moving platform. Measurements from 50 m ($n = 5$) and 100 m ($n = 9$) imagery did not differ significantly from the actual value ($P > 0.05$), but measurements from 150 m imagery did ($P < 0.001$, $n = 9$), being 16 mm (12.6%) greater than the actual value (Table II). Despite this, altitude AGL was not correlated to measurement value ($R^2 = 0.3101$, $n = 23$).

The direct measurement of wheel diameter was 1.435 m ($n = 9$) and ImageMeasurement values ranged from 1.371 to 1.489 m, a range of 0.118 m or 8% of the

TABLE I
Measured operator error at all available zoom factors ($n = 10$). Error was assessed using the integrated accuracy assessment utility which requires a user to click on two predefined cross hairs. Deviation from the targets is measured in terms of resolution units to determine real error

Zoom level	Mean error (mm)	95% CI (mm)
2x	11.7	13.6
4x	9.3	9.6
8x	3.7	4.1
16x	1.5	1.9

TABLE II

Front-roll irrigation line pipe and wheel measurements made with ImageMeasurement from imagery obtained from different altitudes above ground level (AGL). $n = 5$ for 50 m image set, $n = 9$ for all other sets

Altitude AGL (m)	Average pipe (mm)[a]	Difference (mm)	% Difference
50	131	*NS*	
100	132	*NS*	
150	143	16	12.6
	Average wheel (m)[b]		
50	1.442	*NS*	
100	1.431	*NS*	
150	1.450	*NS*	

[a] Actual Size = 127 mm.

[b] Actual Size = 1.435 m.

total diameter. Measurements from all altitudes showed no mean difference from the actual diameter ($P = 0.4993$, $n = 5$–9; Table II). Maximum 95% confidence interval was 0.94 m, or around 6.5% of the total, for the 50 m set ($n = 5$). Again, no relationship was seen between altitude AGL and measurement value ($R^2 = 0.01863$, $n = 23$).

The range of altitude change between consecutive readings in the laser log prior to the trigger times of the 23 images (10 previous readings/image, for $n = 230$) used in the above analysis was 0–7 mm, with an average consecutive reading change of 1.7 mm. The maximum deviation between the image trigger time and the LaserLOG write time was 0.029 seconds. Since LaserLOG optimally records one reading every 0.01 seconds, this maximum delay of 0.029 seconds might result in an average error of 5.1 mm in the altitude reading, or an extreme maximum error of ±21 mm in the altitude AGL used to calculate GSD. This is lower than the laser rangefinder's accuracy of ±25 mm when measuring altitude AGL, and thus is not an important source of error.

7.3. SOURCES OF ERROR

Good agreement between direct measurements and measurements made from aerial photographs is notable given all the sources of potential error. In addition to the human dexterity and vision-associated error discussed above, airplane pitch and roll alter GSD to some degree. If the laser is reflected at a point other than the measured object, as when the object or area of interest is not in center of the image, then the distance between the camera lens and the object may be different from the laser measurement. An airplane roll of 20° results in a somewhat oblique photograph that can cause as much as a 9% error in GSD using a 100 mm lens. A 5° roll alters the GSD by 4%. Calm weather and pilot skill can be relied on to keep roll and pitch low, but cannot eliminate it. Use of a gyroscopic camera mount, such as described by Prado *et al.* (2003), keeps the camera lens axis at nadir and reduces or eliminates error due to changing airplane position relative to gravity. However, it can not compensate for variation in ground topography which can result in differences between laser measurements and object-to-lens distances that are similar to what occurs when the airplane deviates from straight and level flight.

Another factor affecting GSD and therefore the accuracy of image measurements is the curvature of the lens, which creates radial distortion. This is a source of error that can be measured and is of little consequence with long lenses. Wide angle lenses have pronounced lens curvature, causing a large increase in edge pixel GSD relative to center, but telephoto lenses have little curvature – the difference in GSD of edge pixels relative to the center pixel drops off logarithmically with longer focal lengths (Figure 2). Telecentric lenses are specially designed to eliminate radial distortion by shaping the lens so that light does not pass through the lens at an angle. These lenses are more expensive than curved-glass lenses, and are only capable of imaging an object 0.75× the size of the lens diameter. Alternatively, an image can be orthorectified to correct for radial distortion, but this introduces a complex mathematical correction that may not be needed for the applications we

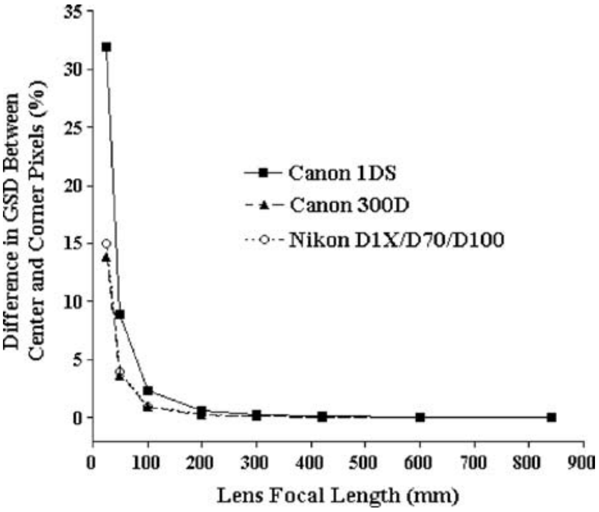

Figure 2. Percent difference between corner and center pixel ground sample distance (GSD). Due to lens curvature, shorter lenses produce more edge distortion than longer lenses, hence, edge pixels in images taken with shorter lenses cover larger areas, relative to center, than if shot with a longer lens. Smaller sensor size, such as in the 300D and Nikon models, reduce the distortion by rendering each lens effectively longer (by 36 mm/sensor width). This graph shows, for example, that any image taken with the 300D using a 25 mm actual focal length results in corner pixels that have actual ground coverage 15% larger than the center pixel.

envision where an error of 2% or less is acceptable in the interests of speedy and simplified data processing.

Using the Canon 1DS, which has a sensor the same size as a 35 mm frame, relative GSD difference between the center pixel and the 4 corner pixels is 2.28% with a 100 mm lens, but only 0.58% with a 200 mm lens. All pixels in between center and the corners are distorted to some degree less than the corner pixels, so the corner pixels represent the worst radial distortion in the entire image. Digital cameras with correction (magnification) factors above 1 show less radial distortion relative to other cameras with identical lenses, since their field of view is limited by a smaller sensor size (Figure 2). Thus, using a 100 mm lens the Nikon D1X, D70 or D100 (correction factor = 1.52) shows a relative GSD difference of 1.001% while the Canon 300D (correction factor = 1.6) shows a relative difference of 0.925%. For any of the cameras listed above to achieve measurements, without correction for radial distortion, with a 1.0% or less error, the lens must have an effective focal length (lens focal length times camera correction factor) greater than 147 mm. These calculations assume the surface being imaged is flat, and perpendicular to the camera lens axis. This is rarely true as the ground is seldom flat, and an aerial camera lens axis is seldom in perfect perpendicular alignment with the ground. This results in edge distortions that are not equal in all four corners of an image, depending on the degree of obliqueness in camera orientation (Figure 3). Our results show consistently-accurate, image-derived measurements. However, our aerial test was conducted over flat terrain on a fair-weather day. As we have noted, weather and topography have the potential to increase error by increasing the variability in camera lens-to-object distance within each image. These important sources of

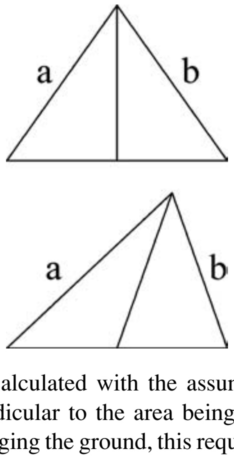

Figure 3. Image edge distortion is calculated with the assumption that the area being imaged is flat, and that the lens axis is perpendicular to the area being imaged. In the top two-dimensional representation of an aerial camera imaging the ground, this requirement is fulfilled, so a = b, and edge distortion is equal on both sides of the image. In the lower figure, the lens axis is not perpendicular to the area being imaged, so a > b, and edge distortion will be greater on the left side of the image than on the right. In reality, this effect is present in three dimensions, linked to the independent roll and pitch movements of the airplane.

error and error from placement of measuring points on an image are assumed to be random and therefore compensating. Therefore, overall accuracy should be increased when values are averaged over a large number of samples representing a distinct population. Thus, multiple samples of features like sagebrush canopy diameter in a management area, or full-bank stream-channel width in a given reach of a stream, are likely to be measured with acceptable accuracy and at a much reduced cost compared to values and distribution that can be obtained by ground crews.

8. Conclusions

Natural resource monitoring is severely hampered by ground access and by the costs associated with using ground crews to measure resource features. We conclude that many of these measurements can now be obtained from systematic aerial sampling that produces calibrated aerial digital images. Image resolution must be consistent with the desired measurement accuracy. ImageMeasurement software uses a database approach to facilitate precision measurements from images in a simple, straightforward way that increases the accuracy of GSD calculations for each image in multi-image data sets. It also speeds actual measurements and we found we could make one measurement/image and complete four images a minute. Because it takes longer to load an image than to make a measurement, making multiple measurements per image would increase the rate at which measurements could be made. Using imagery with a 5–26 mm GSD, one can measure features accurate to centimeters with an error less than 10% when LaserLOG is used to record and display the essential precision-measured altitude AGL at the time of image triggering. Merge greatly assists the matching of trigger times with altitudes and image filenames to bring all components together in a manageable way. Applications for the software have been tailored to riparian-area measurements needed in land management, but obviously may be of use to any project whose goal is to accurately measure physical features from aerial imagery.

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