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Assessing the Spatial Accuracy of Applanix DSS™ Model-301 Sensor Stereo Imagery using a Survey GPS Ground Control Network

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Abstract.—During the past decade, Geographic Information Systems (GISs) have become widely used in many disciplines and that has created demands for accurate high-resolution digital data, especially digital imagery. Photogrammetry has emerged as one of the most important disciplines employed in the collection of spatially related information for use in GIS databases, especially for terrestrial landscapes. This study assessed the horizontal and vertical accuracy of the Applanix Digital Sensor System (DSS™) 301 orthophotographs. The study area was located on the University of Arkansas at Monticello campus and included 950 acres. To assess the spatial accuracy of the DSS, 56 Ground Control Points (GCPs) were collected prior to image acquisition using Trimble Surveying grade 4700 Global Positioning Systems (GPS). The 28 stereo aerial photographs used to create the orthorectified mosaic were taken with the DSS™ 301, with approximately a 15.24 cm pixel spatial resolution. The average horizontal Root Mean Square Error (RMSE) for the DSS™ mosaic was 0.212 m using the GPS-aided Inertial Measurement Unit (IMU) and 0.194 m from the mosaic created using one GCP per photo with the IMU. The vertical RMSE was 0.371 m for the 2-meter DEM created from stereo imagery using only the IMU.

Key words:— Geographic Information Systems, high-resolution digital data, digital imagery, photogrammetry, Applanix Digital Sensor System (DSS™) 301 orthophotographs, global positioning systems, inertial measurement unit.

Introduction

Spatial information plays an important role in management, decision making, and planning. The use of Geographic Information Systems (GIS) can facilitate this process, and has evolved from primarily being a tool for description and representation to becoming a tool used for decision-making (Weih and Smith 1990). Because of this, it is important to develop GIS databases with current accurate data. The decrease in costs associated with increases in performance of computer technology continues to rapidly advance the use of GIS and digital photogrammetry across a wider user base.

Photogrammetry plays an important role in the collection of information for GIS databases. Photogrammetry has been described as the "art, science and technology of obtaining information and of making measurements from imagery" (McGlone et al. 2004). Digital photogrammetry deals with digital imagery rather than analog photographs. Only in recent years has the necessary hardware and software become available to solve problems posed by storing, retrieving, and manipulating large numbers of images. Digital Imagery has become the driving force behind aerial surveying, photogrammetry, and remote sensing technologies (Melihen 2006).

When discussing digital imagery it is important to note that it is not the same as more traditional aerial photographs. Photographs are recorded on film using lenses, while digital images are recorded electronically by lenses or a complex scanner system (Gibson and Power 2000, Lillesand et al. 2004). Digital images have many advantages over traditional photographs, making them the preferred source of remotely sensed data. Some of the advantages include:

- A digital camera system reduces expenses since the costs for film, film development and scanning can be eliminated.
- Digital images allow for a considerably larger spectral and radiometric resolution, leading to greater availability of information. This increases the number of applications that can benefit from this type of imagery and improves results.
- Digital information can be transmitted electronically at the speed of light (Irish 2003). This makes the data available for analysis by multiple people almost instantaneously and without shipping costs. There is no need to wait for processing of the photographs.
- Digital imagery can be reproduced with no loss of quality (information), while photography loses quality with each copy (Gibson 2000). This lowers the cost and increases distribution of data to users, making it available to more practitioners.
- Digital information opens up a multitude of mathematical manipulation options that would not be available with an analog photograph, allowing for information enhancements and extraction (Gibson and Power 2000).

One of the most used digital photometric products is the digital orthophotograph. A digital orthophotograph is a digital image with uniform scale created from a digital aerial photograph. Thus, a digital orthophotograph is equivalent to a planimetric map that shows images of features. The process of creating an orthophotograph requires two data sets: the parameters for analytical interior orientation (internal geometry, spatial position and orientation of camera when the image was acquired) and the land surface relief for the area of image acquisition that is often referred to as a digital elevation model (DEM). A DEM refers to the elevation of the Earth surface organized in the form of a matrix of digital data representing elevation values. This matrix is called a raster layer in a GIS (Li et al. 2004).

A digital orthophotograph is created using analytical aerotriangulation. Analytical aerotriangulation is the process of determining numerically the X, Y, and Z ground coordinates of individual points based on image coordinate measurements (Wolf and Dewitt 2000). Analytical aerotriangulation orientation parameters can be measured directly (camera interior orientation and ground control measurements) or indirectly (global positioning system and airborne inertial navigation system). Both processes can create a DEM from stereo imagery. This study assesses the spatial accuracy of orthophotographs and a DEM created from Applanix Digital Sensor System (DSS™) Model-301 Sensor imagery, which is important to GIS and remote sensing practitioners.

Materials and Methods

Applanix DSS™ Model-301 System.—The DSS is a fully digital system with a GPS-aided Inertial Measurement Unit (IMU) that enables fast DEM and orthophoto production with commercial off-the-shelf software like Imagine® Leica Photogrammetry Suite® (LPS). The GPS/IMU measurements are used to determine camera position and altitude for each frame so this eliminates the need for collecting ground control points (GCP) for image referencing. The DSS™ Model-301 is equipped with a charge-coupled device (CCD) that has a 9 μm (micron) pixel size and consists of a 4K by 4K digital array (Mostafa 2004). The setup and functionality of the DSS enables the production of high quality, rectified/orthorectified, natural color (RGB)/color infrared (CIR) imagery. Figure 1 shows the digital sensor system in a Cessna 182 (DSS).

Study Area and Image Acquisition.—The study area was at the University of Arkansas at Monticello (UAM) and consisted of approximately 950 acres. The aerial images were taken at approximately 914.4 m above the ground, producing a resolution of 15.24 cm square pixel. The 28 individual exposures were taken in natural color (RGB) in the morning on February 18th, 2005. The weather during photo acquisition consisted of high, thin clouds. The overcast was actually beneficial because it decreased the amount of contrast between the shaded and unshaded areas in the images. There was approximately 30% sidelap and 60% endlap on each of the four flight-lines of 7 photographs. Each individual aerial photograph covers approximately 40.46 hectares. The average ground speed of the airplane during photo acquisition was 185 km per hour.

Ground Control Network Collection.—To assess the accuracy of the DSS, GCPs had to be collected. The GCPs were collected with a survey grade dual frequency Trimble 4700 GPS. The setup of the GPS unit at each GCP was conducted in the exact same manner. The rod that held the GPS antenna was set on the head of a cotton picker spindle that was nailed into the ground, the GPS antenna was placed 1.999 m above the ground surface and the GPS data were collected for more than 2 hours for each GCP.

Field data were sent to the National Geodetic Survey (NGS) Online Positioning Users Service (OPUS) at www.ngs.noaa.gov/OPUS to be differentially corrected. The results were returned from NGS and included information on the RMSE for each GCP and its corrected geographic location. The overall RMSE ranged from 0.010 to 0.032 m with a mean of 0.016 m in the horizontal and from 0.005 to 0.878 m with a mean of 0.094 m for the ellipsoid height (vertical). A total of 56 GCPs was collected in the study area for 28 aerial images. Figure 2 shows the distribution of the GCPs. The GCPs were placed on distinct features such as a sidewalk corner that could be easily

Fig. 1. Applanix DSS™ Model-301 System in a Cessna 182.

Fig. 2. Distribution of the Ground Control Points (GCPs) in the study area.

detected on the aerial image. In areas with no distinguishable features, large Xs made from ribbon and/or strips of cardboard were placed on the GCP so that the center of the X marked the GCP's location. Every image had at least one GCP. Figure 3 shows GCP number 37 with the GPS unit setup.

Image Processing and Orthorectification.—The DSS collects imagery in a 12-bit format but most software programs are not compatible with 12-bit imagery. The first step to processing the imagery was to use the DSS Mission View software to convert the 12-bit imagery to 8-bit imagery. The second step was to extract the GPS and all other navigational data for each image using POSPac™ software. This data includes geographic position, roll, tilt, pitch and GPS location of each image. Following the extraction of navigational data, the GPS coordinates were differentially corrected. This step utilizes the Spatial Analysis Laboratory (SAL) Surveying NGS Continuously Operating Reference Station (CORS) base station at UAM.

Leica Photogrammetry Suite (LPS) 8.7 software was used for the image orthorectification and mosaic processes. The LPS uses a self-calibrating bundle block adjustment method in its triangulation process (Leica Geosystems 2003). However, to othorectify the imagery, an elevation data model must be used in the process. Two different DEMs were used in this study.

Three orthorectified mosaics were created in this study; method 1 used the DSS GPS-aided IMU, with no GCPs and the 30-meter United States Geological Survey (USGS) DEM; the second mosaic method used the DSS GPS-aided IMU with 1 GCP per image and the USGS 30-meter DEM; and the third mosaic method used DSS GPS-aided IMU with a 2-meter DEM created from the DSS's stereo pairs. The first and second

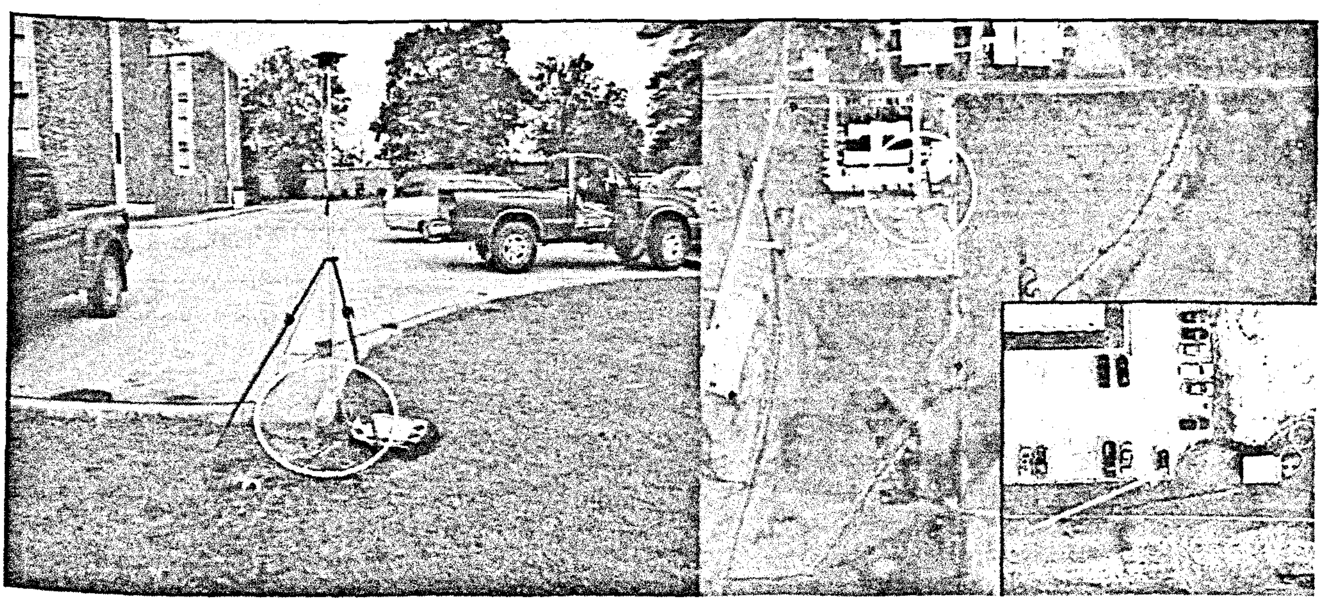

Fig. 3. Ground Control Point #37.

mosaics allowed an assessment of accuracy differences between an orthorectification using no GCPs, with GPS-aided IMU and the GPS-aided IMU, with one GCP per image.

Identification of GCP on Image Mosaics.—To access the geometric accuracy of the imagery, the field GCPs locations needed to be identified on the imagery. This was done manually by creating a point vector layer using ArcGIS 9.0. In an effort to eliminate interpretation error, all the GCPs were identified 10 different times. The average of the 10 coordinates for each GCP was used as the mosaic image coordinate for accuracy assessments. This was done for all three mosaics.

Creation of the 2-meter DEM.—The 2-meter DEM was created using LPS automated terrain extraction (ATE) from stereo imagery and LPS terrain editor. Stereoscopic parallax provides the basis for determining elevation points from the stereo imagery. The DEM is generated by the software using the following steps.

- Interesting features (points) are determined in the stereo overlap regions in one stereo image that are unique from its neighboring pixels.
- The adjacent stereo image of the pair is searched to find the same interesting feature. A correlation coefficient is calculated for each possible match and the point with the highest correlation is selected for the match.
- Once the feature is identified in matching stereo images, the GCP and the associated elevation value are determined considering both interior and exterior orientation parameters.
- This is performed for all stereo image pairs generating a set of mass points (X, Y, Z).
- The DEM is generated by interpolating the mass points.

The mass points were examined in terrain editor in 3D to identify any errors. For example, blunders such as a hill in the middle of a football field. These erroneous mass points were deleted. Mass points over buildings were also deleted since the study focuses on ground elevation.

Data Analyses.—All of the DEM datasets were projected, if required, to the Universal Transverse Mercator (UTM), Zone 15, North American Datum (NAD) of 1983, GRS80 ellipsoid for comparisons. All processed GPS GCPs were reprojected using the same parameters. The GCP X and Y locations with their elevation were obtained from survey grade GPS and processed by NGS. This data was considered to represent true location and elevation values throughout this study.

The image horizontal locations (X and Y) and the DEM elevation values were subtracted from the GCP to determine if the location and elevation differences were different from zero and if the parameter overestimated (negative) or underestimated (positive) the true value. To make inferences about the magnitude of location and elevation differences, the absolute difference (AD) was determined by using the absolute value of the differences. The Root Mean Square Error (RMSE) was calculated for all the X, Y, and Z parameters using equations 1 through 3, respective. The total RMSE is calculated using equation 4.

$$\mathrm{RMSE}_X = \sqrt{\frac{1}{n_X}\sum_{i=1}^{n_X}(\mathrm{GCP}_{Xi} - \mathrm{Image\ Point}_{Xi})^2} \qquad \text{Equation 1}$$

$$\mathrm{RMSE}_Y = \sqrt{\frac{1}{n_Y}\sum_{i=1}^{n_Y}(\mathrm{GCP}_{Yi} - \mathrm{Image\ Point}_{Yi})^2} \qquad \text{Equation 2}$$

$$\mathrm{RMSE}_Z = \sqrt{\frac{1}{n_Z}\sum_{i=1}^{n_Z}(\mathrm{GCP}_{Zi} - \mathrm{DEM\ Elevation}_{Zi})^2} \qquad \text{Equation 3}$$

$$\mathrm{RMSE}_T = \sqrt{RMSE_X^2 + RMSE_Y^2} \qquad \text{Equation 4}$$

The RMSE evaluates the distance between the true location or elevation (GCPs) and the estimated location or elevation from the imagery. Higher RMSE means less accuracy.

Results and Discussion

Method 3, which used DSS imagery processed with the GPS-aided Inertial Measurement Unit (IMU) information and the 2-meter DEM created from the DSS stereo imagery produced the most accurate orthorectified image mosaic in this study. The total RMSE for this method was 0.186 meters (Table 1) with an east-west RMSE of 0.131 meters and a north-south RMSE of 0.132 meters (Table 2). This method required the most analysis time of all the methods due to the need to develop the 2-meter DEM. The absolute mean difference between the GCP elevation and the 2-meter DEM created from the stereo imagery was 0.287 meters, with a RMSE of 0.131 meters as shown in Table 3. The DEM difference ranged from -0.819 to 0.683 meters.

Method 1 was the most efficient method, based on the least analysis time. This mosaic was created with DSS imagery processed with the IMU information and orthorectified using the 30-meter DEM. The mosaic created had a total RMSE of 0.212 meters (Table 1) with an east-west RMSE of 0.156 meters and north-south RMSE of 0.144 meters (Table 4).

The mosaic created by method 2 from DSS imagery and processed using the IMU information with one GCP per image and the 30-meter DEM had a total RMSE of 0.194 meters (Table 1), an east-west RMSE of 0.118 m and a north-south RMSE of 0.126 m (Table 5). The accuracy of this method was tested using 23 GCPs since the other GCPs were used in processing the imagery to create the mosaic. The use of one GCP per image improved the RMSE by 0.018 m.

The mosaics created using the imagery collected with the Applanix Digital Sensor System (DSS™) 301 were all accurate to within 0.5 m for any GCP with an absolute difference mean of 0.14 m in the worst cases. Based on this study, positional accuracies of less than 0.369 m can be expected using any of the methods for areas with similar terrain.

Sanchez and Hudnut (2004) had an RMSE of 1.475 m in the east-west direction and 0.331 in the north-south direction, with a total RMSE of 1.511 m for seven GCPs in a study done in San Bernardino County, California using similar techniques as this study. Their vertical RMSE was 1.029 m for the approximately 15.24 cm pixel spatial resolution imagery. Their study found larger horizontal and vertical errors, which could be due to the rough terrain of the study area and the small sample size compared to this study.

This study also showed that positional accuracies are affected by DEM resolutions and accuracies. As the resolution and accuracies of DEMs increase the positional accuracies of orthorectified imagery created using these DEMs will increase.

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Table 1. Accuracy of the Applanix Digital Sensor System (DSS™) Model-301 Sensor mosaic

Mosaic creation Methods	Number GCPs	Total RMSE meters
(1) IMU and 30-meter DEM	53	0.212
(2) IMU and 1 GCP with 30-meter DEM	23	0.194
(3) IMU and 2-meter DEM	48	0.186

Table 2. Horizontal accuracy in meters of the Applanix Digital Sensor System (DSS™) Model-301 Sensor mosaic with no ground control points (GCP) using a 2-meter DEM

	X (East-West)	Y (North – South)
Number of GCP Points	48	48
Mean difference	0.037	0.015
Difference Range	-0.172 to 0.369	-0.231 to 0.332
RMSE	0.131	0.132
AD Mean	0.104	0.111
AD Range	0.003 to 0.369	0.011 to 0.332
AD Standard Deviation	0.079	0.073

Table 3. Vertical accuracy in meters of the 2-meter DEM create from Applanix Digital Sensor System (DSS™) Model-301 Sensor using stereo pairs

Number of GCP Points	49
Mean difference[1]	-0.07
Difference Range	-0.819 to 0.683
RMSE	0.131
AD Mean	0.287
AD Range	0.007 to 0.819
AD Standard Deviation	0.242

[1]Surveyed GCP elevation – Created Image DEM elevation

Table 4. Horizontal accuracy in meters of the Applanix Digital Sensor System (DSS™) Model-301 Sensor mosaic with no ground control points (GCP) using a 30-meter DEM

	X (East-West)	Y (North – South)
Number of GCP Points	53	53
Mean difference	0.011	0.011
Difference Range	-0.449 to 0.438	-0.254 to 0.334
RMSE	0.156	0.144
AD Mean	0.116	0.119
AD Range	0.002 to 0.449	0.010 to 0.334
AD Standard Deviation	0.105	0.082

Table 5. Horizontal accuracy in meters of the Applanix Digital Sensor System (DSS™) Model-301 Sensor mosaic with one ground control point (GCP) per image using a 30- meter DEM

	X (East-West)	Y (North – South)
Number of GCP Points	23	23
Mean difference	-0.014	0.001
Difference Range	-0.301 to 0.169	-0.191 to 0.235
RMSE	0.118	0.126
AD Mean	0.09	0.112
AD Range	0.001 to 0.301	0.019 to 0.235
AD Standard Deviation	0.077	0.059