An Evaluation of DEM Accuracy: Elevation, Slope, and Aspect

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Abstract

The accuracy of elevations, slopes, and aspects were evaluated for two DEMs of an area centered on Blacksburg, Virginia, in the southern Appalachian Mountains. The first was a U. S. Geological Survey (USGS) 7.5-minute quadrangle-based DEM with 30-metre postings, produced utilizing automated stereocorrelation of 1:40,000-scale leaf-off aerial photographs with a Gestalt Photomapper (GPM). The second DEM of the same area was produced from a SPOT panchromatic stereopair using a proprietary stereo-correlation technique developed by the STX corporation, among those used by SPOT Image Corp. for high resolution DEM production. DEM accuracy was assessed visually and through comparisons of DEM-derived to field-surveyed values for elevation, slope, and aspect.

While the GPM-derived USGS DEM appeared to provide a better representation of micro-topography, elevation errors for both the USGS-GPM and SPOT-STX DEMs averaged less than 6 metres and were not significantly different from zero, and both DEMs meet level 1 accuracy requirements. There were statistically significant errors in slopes and aspects derived from the SPOT-STX DEM, while slope and aspect errors for the USGS-GPM DEM were not significantly different from zero. There were significant, large correlations between slope and aspect and their respective errors. While this is one of few direct evaluations of DEM-derived slopes, aspects, and elevations, readers are cautioned that these results may not apply to different DEM generation methods or algorithms or to regions with differing terrain and vegetation conditions.

Introduction

Elevation, slope, and aspect are among the most important data in many natural resource spatial databases. Elevation data are often raster coded in a digital elevation model (DEM), where elevations relative to some datum are posted at regular intervals in X (often approximately east-west) and Y (often approximately north-south) directions. Due in part to the importance of these data and their derivatives in a wide variety of applications, the U.S. Geological Survey (USGS) has undertaken the production of 7.5-minute quad-based, high resolution (30-metre grid cell) DEM data for the contiguous 48 states. In addition, commercial vendors such as SPOT Image Corporation offer comparable products derived from satellite stereopairs.

The accuracy of these DEMs and their derived products are of crucial importance because errors in the base data will propagate through spatial analyses. This is particularly true in classification or other cartographic modeling applications where elevation, slope, and aspect are derived from DEMs and used with other spatial data (Spanner, 1983; Franklin *et al.*, 1986; Mason *et al.*, 1988; Moellering and Kimerling, 1990; Davis and Dozier, 1990; Quinn *et al.*, 1991; Green, 1992). Errors in elevation, slope, or aspect will often cause errors in the cartographic model outputs.

Unfortunately, there are few published reports on the accuracy of DEM-derived elevation, slope, and aspect. While the USGS has published accuracy specifications, the average elevation and distribution of errors are often not reported for individual quads. There are no accuracy standards and (to our knowledge) no simulation or empirical tests of USGS DEM slope and aspect accuracy. Although errors for elevation data generated from stereo SPOT have been reported (Vincent *et al.*, 1987; Gugan and Dowman, 1988; Rodriquez *et al.*, 1988; Vincent *et al.*, 1988; Swann *et al.*, 1988a; Swann *et al.*, 1988b; Day and Muller, 1988; Fukashima, 1988), there are few accuracy tests of SPOT-based DEM elevation, slope, and aspect (Sasowsky *et al.*, 1992). This paper presents a comparison of USGS and SPOT-derived DEM values to field measured elevation, slope, and aspect data.

Data and Methods

SPOT and USGS DEMs were obtained for the area included in the Blacksburg Virginia, USGS 7.5-minute quadrangle map. This quadrangle is characteristic of much of the upland southeast, with agriculture and urban land uses dominating valley bottoms and deciduous forests covering steeper areas. Terrain varied from 450 to 850 m in elevation within the study area. The USGS DEM was produced using a Gestalt Photomapper II and NHAP 1:40,000-scale, leaf-off, panchromatic aerial photographs. A 9- by 8-mm patch size was used (320 by 360 metres at scale), with 1600 points collected per patch (USGS, 1990). As is standard practice, no corrections were made for canopy height, and failed convergence points were manually entered on prompting. Level 1 accuracy was stipulated, indicating a vertical RMSE target of 7 metres and a maximum RMSE of 15 metres. Elevations were posted relative to the National Geodetic Vertical Datum of 1929 (NGVD29) with a 15-metre horizontal frequency. Postings were cast on to the Zone 17 Universal Transverse Mercator (UTM) Projection using the North American Datum of 1927 (NAD27), interpolated to a 30-metre resolution. The SPOT DEM was derived

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from a panchromatic stereopair with the first image acquired 18 October 1987 (incidence angle = −16.5 degrees, partially leaf-off) and the second acquired on 16 April 1988 (leaf-off, with a 17.2-degree incidence angle). The digital elevation model was produced by the STX Corporation using an image correlation algorithm (M. Bixler, pers. comm.), for which patch size and posting density are considered proprietary. Image quality was rated as excellent, and both days were cloud and haze-free. Elevation data were measured with reference to NGVD29, but were delivered cast to the Virginia South State Plane Coordinates with the NAD27 datum. These data were provided with a 10-metre horizontal resolution. They were then recast onto Zone 17 UTM coordinates with 30-metre cells using a nearest-neighbor sample. As with the USGS-GPM data (and again, as is standard practice), no corrections were made for canopy height. The two data sets were then clipped to the least-common geographic area covered by both. There was a 3.2-metre horizontal distance offset between cell centers for the two DEMs. Rather than introduce additional smoothing and possibly bias through a convolution re-sampling, these offset data were used for all subsequent analyses.

The following five methods were used to characterize data quality:

- A number of grey-level stretches were computed, DEMs displayed, and DEM quality assessed visually. This included reasonableness, conformance to general knowledge of terrain shape, and geomorphic consistency (e.g., connected stream channels, ridges).
- Digital and true elevations were compared. A total of 42 First-, Second-, or Third-order control points were located from a combination of National Geodetic Survey (NGS) information and from carrier-phase GPS surveys conducted by the consulting engineering firm Anderson and Associates, Incorporated. This sample size is within the region identified by Li (1991), in which DEM error variation approaches an asymptote. Points were selected for which horizontal and vertical locations were precisely known, i.e., at metre levels. Elevations were then extracted from these points from the respective DEMs, these elevations were compared to the field-surveyed values, and the error (field survey minus DEM elevation) was calculated.
- The elevation difference distribution was compiled for the two DEMs. SPOT-derived elevations were subtracted from USGS-reported elevations for each 30-metre cell in the coincident area, and the absolute value of the difference recorded. Statistical summaries were then calculated for this difference image.
- Slope and aspect were calculated for both DEMs using a third-order finite difference method (Horn, 1981). This finite difference method has been reported among those which most accurately determine slope (Skidmore, 1989). Calculated and field-measured values were then compared for the 28 field-sampled points. Field slope was measured with a hand-held clinometer to the nearest percent, and aspect was measured with a field compass to the nearest degree. Field sites were selected to have uniform slopes and aspects over at least 30 metres, and in most cases more than 50 metres. While this may have biased slope and aspect evaluations by potentially inflating accuracies for areas of complex terrain, it also limits the effects of horizontal registration error. Registration residuals are not commonly reported for commercially obtained DEMs, but are usually assumed to be less than the adopted cell size. Horizontal positions for the field-measured slope and aspect points were determined using differentially corrected GPS data, averaging at least 180 position fixes for each point. The horizontal RMSE for GPS positions averaged less than 3.4 metres.

Differences between the sample mean elevation, slope, and aspect were compared with t-tests (Ho: No difference between sample means for the SPOT-STX and USGS-GPM DEMs). In addition, paired-t tests were performed on a per-observation basis for elevation, slope, and aspect. Paired-difference tests are appropriate because the comparisons are not based on independent random samples for each treatment, but rather from meaningfully paired observations, i.e., SPOT and USGS data were analyzed for the same set of points (Steel and Torrie, 1980). Finally, Pearson's and Kendall Tau-b correlations and Hoeffding Dependence Coefficients were computed between true and reported values and true values and error magnitudes for elevation, slope, and aspect.

Results and Discussion

Both DEMs contain most of the dominant terrain features in the study area (Figures 1a and 1b). Major mountains in the northern and south-central portion of the study area are recognizable, as is a deep valley on the eastern edge. The USGS-GPM DEM shows more detail and in some respects a more "realistic" representation than the SPOT-STX DEM in that features such as fine resolution drainage channels and small mountain side valleys are more evident, and there is less apparently random variation.

Both DEMs exhibited negative mean errors, under-reporting elevations on average for the 42 test points used in this study (Table 1). Data from the USGS-GPM DEM showed a slightly larger mean signed and unsigned bias than the SPOT-STX data, although the mean difference and paired difference error were not statistically significant (Tables 1 and 2, t-test $p>0.1$). The USGS-GPM DEM did show a smaller error range for elevation data, from −12 to +7 metres, versus −12 to +18 metres for the SPOT-STX DEM (Table 1, Figures 2a and 2b). Elevation errors for both DEMs were approximately evenly distributed about the mean, although large positive outliers were more frequent for the SPOT DEM data (Figure 2b). Surface regressions revealed no trends in signed error; however, there were significant relationships between X and Y horizontal position and unsigned error (F-test, $p<0.05$). Error magnitudes were largest in the southern and eastern portions of both DEMs, the areas of the highest and lowest elevations, respectively, in the study area.

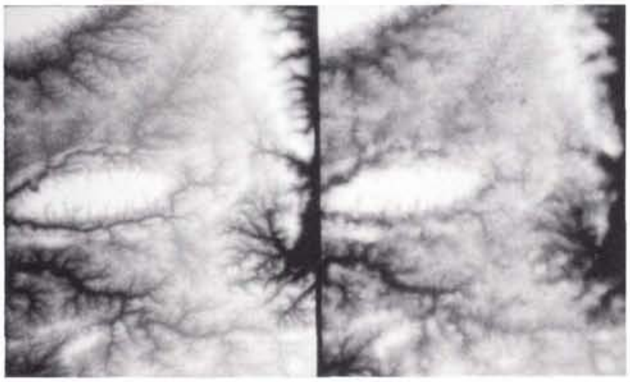

Figure 1. Gray-scale display of USGS (left) and SPOT (right) DEMs for the Blacksburg, Virginia USGS quadrangle map. Sharper, finer-scaled topographic features are visible on the USGS DEM.

TABLE 1. ERROR STATISTICS FOR ELEVATION, SLOPE, AND ASPECT FOR THE SPOT AND USGS DEMS. ERRORS ARE THE FIELD-MEASURED MINUS DEM-DERIVED VALUES FOR EACH PARAMETER.

	Mean Signed Error	Mean Unsigned Error	Minimum Error	Maximum Error	Std. Error (n=42 for elevation) (n=28 for slope)
ELEVATION(m)					
SPOT	−3.6	4.5	−12.0	18.0	0.93
USGS	−4.2	5.1	−12.0	7.0	0.83
SLOPE (%)					
SPOT	3.0	4.6	−12.4	7.9	0.9
USGS	1.5	2.2	−4.1	7.9	0.5
ASPECT (deg.)					
SPOT	8.0	32.7	−77.2	123.6	8.2
USGS	−2.6	8.6	−23.7	34.5	2.3

TABLE 2. PAIRED DIFFERENCE STATISTICS FOR ELEVATION, SLOPE, AND ASPECT. THE PAIRED DIFFERENCE IS THE USGS-GPM ERROR (GROUND-MEASURED) MINUS THE SPOT-STX ERROR (GROUND MINUS MEASURED) FOR EACH POINT. THERE WERE 42 OBSERVATIONS FOR ELEVATION, AND 28 EACH FOR SLOPE AND ASPECT.

	Mean	Maximum	Minimum	Standard Error
Elevation (m)	−0.55	12	−15	0.95
Slope (%)	−1.48*	15	−9	0.91
Aspect (deg.)	−36.9**	178	−163	19.3

*p = 0.06
**p = 0.11

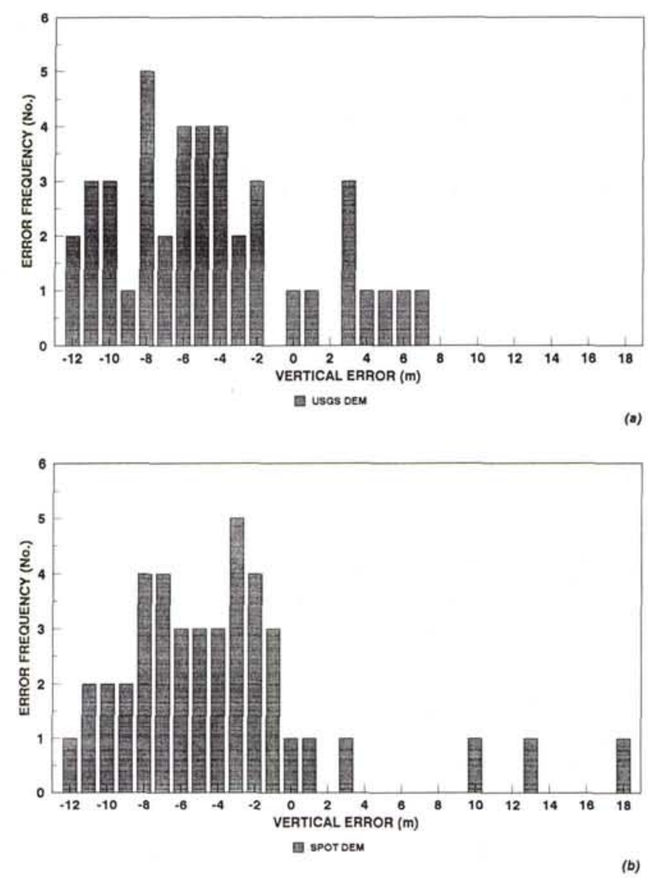

Figure 2. Vertical elevation error frequencies for the USGS (a) and SPOT (b) DEMs. Errors are the difference between ground-measured and DEM-reported elevations, in metres.

There was a wide range of elevation differences in the difference image (Figure 3). The two DEMs reported the same value for only 3.5 percent of the cells in the study area, and differences of up to 82 metres were observed. Approximately 63 percent of the differences were 10 metres or less, and 90 percent were less than 22 metres. Inspection of the difference images indicated the largest discrepancies occurred in high-relief forested areas. Image correlation algorithms often exhibit poorest fit and hence lowest accuracies in forested regions (Theodossiou and Dowman, 1990); this may be responsible for the divergence in this instance.

While analyses indicate that there are few statistical or practical differences between elevations in the USGS and SPOT DEMs, and that both are within reported accuracy bounds, there were large and significant differences between slopes and aspects derived from these two data sources. Signed mean slopes were 1.5 percent and 3 percent above true values for the USGS-GPM and SPOT-STX DEMs, respectively (Table 1). While the average slope error for the USGS-GPM DEM was not significantly different from 0, the SPOT-STX average slope error was significantly different in a one-tailed t-test. Unsigned errors averaged 2.2 percent (USGS) and 4.6 percent (SPOT). SPOT-based slope errors were distributed more uniformly over a larger range than the slope errors for the USGS-GPM DEM (Figures 4a and 4b). The mean slope error of the 28 sampled points was not significantly different according to the t-test ($p>0.05$); however, paired-difference errors were significant (Table 2, $p<0.1$).

Aspect errors were more variable and more divergent. Mean signed and unsigned errors for aspect derived from the SPOT-STX DEM were 8 and 32.7 degrees, while they were -2.6 and 8.6 degrees for aspects derived from the USGS DEM. Substantially larger aspect errors were observed over a much broader range for the SPOT DEM, when compared to those for the USGS DEM (Figures 5a and 5b). Mean values were not significantly different because positive and negative errors tended to balance each other. However, the USGS-derived

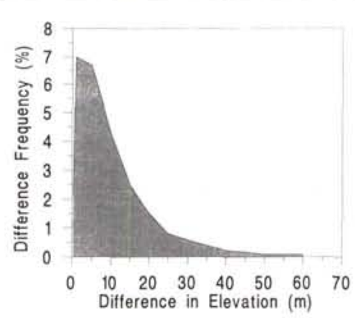

Figure 3. Frequency histogram for the DEM difference image, defined as the cell-by-cell unsigned difference between the USGS and SPOT DEMS.

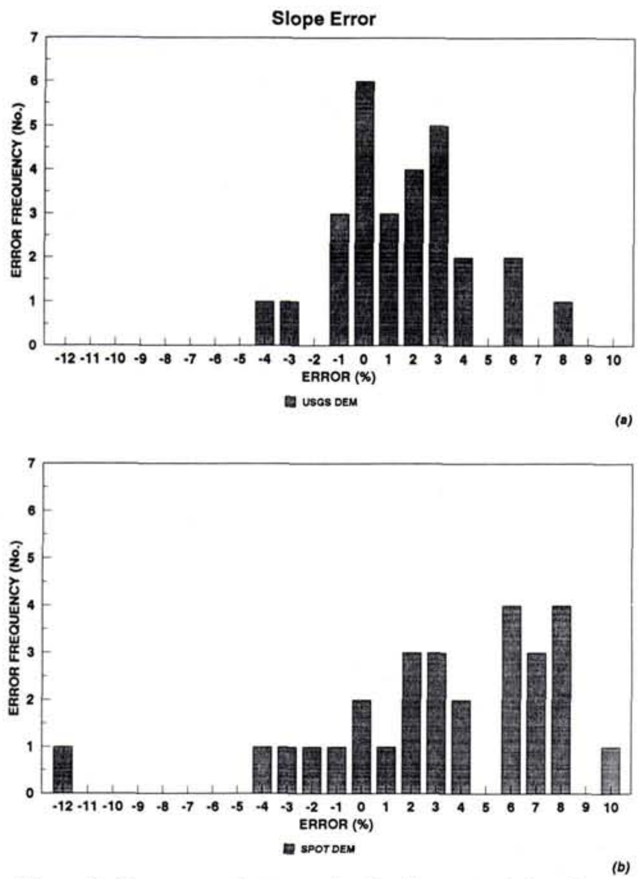

Figure 4. Slope error frequencies for the USGS (a) and SPOT (b) DEMs. Ground slope was measured in percent, and DEM slope was calculated with a third-order finite-difference method.

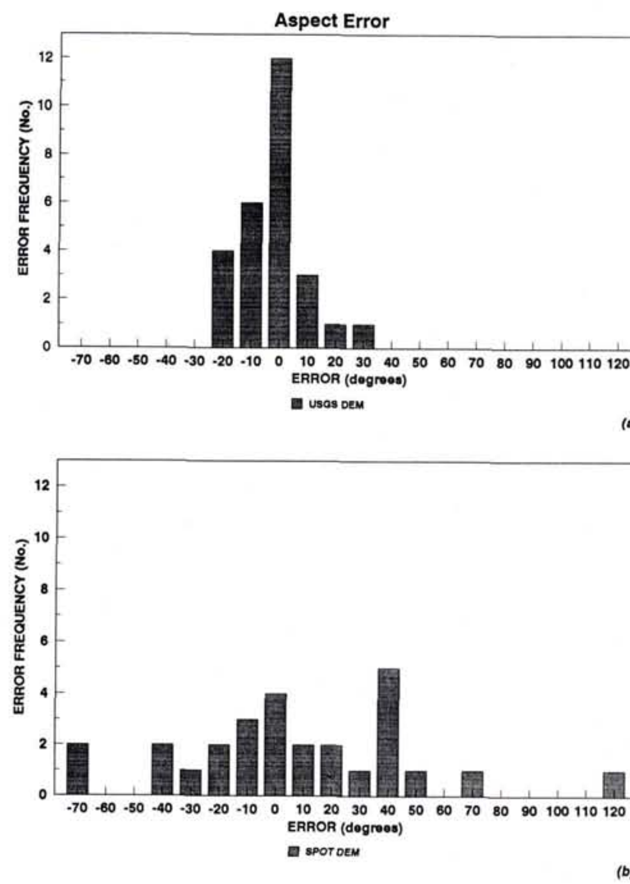

Figure 5. Aspect error frequencies for the USGS (a) and SPOT (b) DEMs. Ground aspect was measured in degrees, and DEM aspect was calculated with a third-order finite-difference method.

TABLE 3. CORRELATION STATISTICS BETWEEN GROUND-MEASURED AND DEM-DERIVED ELEVATIONS. SIGNIFICANCES OF THE CORRELATION (PROBILITY OF FALSELY REJECTING THE NO-CORRELATION NULL HYPOTHESIS) ARE IN PARENTHESES.

	USGS Elevation	SPOT Elevation	USGS El. Error	SPOT El. Error
Pearson's	0.99	0.98	0.08	0.39
	(0.00)	(0.00)	(0.63)	(0.01)
Kendal Tau b	0.88	0.88	−0.04	0.16
	(0.00)	(0.00)	(0.73)	(0.14)
Hoeffding	0.64	0.64	0.00	0.00
	(0.00)	(0.00)	(0.68)	(0.34)

TABLE 4. CORRELATION MEASURES BETWEEN GROUND-MEASURED AND DEM-DERIVED SLOPES. SIGNIFICANCES OF THE CORRELATION (PROBILITY OF FALSELY REJECTING THE NO-CORRELATION NULL HYPOTHESIS) ARE IN PARENTHESES.

	USGS Slope	SPOT Slope	USGS Sl. Error	SPOT Sl. Error
Pearson's	0.87	0.66	0.56	0.27
	(0.00)	(0.00)	(0.00)	(0.00)
Kendall Tau b	0.69	0.45	0.32	0.31
	(0.00)	(0.00)	(0.02)	(0.03)
Hoeffding	0.33	0.10	0.02	0.04
	(0.00)	(0.00)	(0.08)	(0.04)

slopes and aspects were significantly more accurate when measured on a per-point basis, reflected in the significant paired-difference tests (Table 2).

Correlation analyses agree with the above observations, and identify some inter-relationships among elevation, slope, aspect, and errors. First, true elevations are associated with those included in both DEMs (Table 3) as measured by Pearson's, Kendall Tau-b, and Hoeffding metrics. In addition, there was a weakly significant ($p \leq 0.10$ in only one of three cases) positive relationship between elevation and elevation error for the SPOT-STX DEM, indicating a slight tendency for larger errors at higher elevations. There were large, significant correlations between true and both USGS- and SPOT-derived slopes (Table 4), and, furthermore, there were strong relationships between true slope and slope errors ($p<0.10$ in five of six tests). Thus, slope errors tended to increase for steeper slopes. Finally, there were large, statistically significant correlations between true aspect and USGS- and SPOT-de-

TABLE 5. CORRELATION MEASURES BETWEEN GROUND-MEASURED AND DEM-DERIVED ASPECTS. SIGNIFICANCES OF THE CORRELATION (PROBILITY OF FALSELY REJECTING THE NO-CORRELATION NULL HYPOTHESIS) ARE IN PARENTHESES.

	USGS Aspect	SPOT Aspect	USGS Error	SPOT Error
Pearson's	0.99 (0.00)	0.91 (0.00)	−0.02 (0.93)	0.20 (0.31)
Kendall Tau b	0.93 (0.00)	0.68 (0.00)	−0.00 (0.95)	0.11 (0.39)
Hoeffding	0.76 (0.00)	0.36 (0.00)	0.13 (0.16)	−0.01 (0.69)

rived aspect ($p<0.01$ for all metrics), but there was no relationship between true aspect and aspect error for either DEM (Table 5).

The association of steep slopes with slope errors may be due to several factors. First, terrain is generally more varied and rugged on the steeper mountainsides. Hence, point estimates derived from area samples, particularly for aspect and to a lesser extent slope, may not agree well with true values. This may be particularly true for the SPOT-derived DEM tested herein, although specific posting densities are not known. This is not likely to be a major source of error in this instance for the USGS DEM, because GPM posting density (between 9 and 15 metres) is significantly higher than terrain/slope break density around the field-measured points.

Second, larger errors are expected over forested terrain for both technologies used to derive the DEMs, due to lower posting density. Stereo-correlations are more difficult in forest canopy, due in part to a lack of clearly defined features such as roads, buildings, or vegetation boundaries. On average, fewer points meet threshold correlation criteria, and posting densities tend to be lower. With the GPM, failed convergence is flagged, and elevations are manually posted for the location. The satellite data provide at best a 10-m posting density, and in practice are likely to provide a sparser density of points. Interpolation between postings will smooth microtopography and have a greater impact on slope and aspect in these areas. Actual posting densities over the wooded, steep terrain are not available in this case for the SPOT-STX DEM (nor are they generally available for most commercial products). These factors are likely the probable cause of the correlations between true slope and DEM-derived slope and aspect errors. Land-use patterns in the study area result in a preponderance of forest on higher elevations and steeper slopes; conversely, most flat, low elevation areas are cleared. Thus, larger errors, particularly for slope and aspect, should be expected for the forested steeper slopes.

Canopy bias may be another error source. No adjustment for canopy height was performed in either method, given that imagery was targeted for leaf-off conditions with predominantly deciduous forests. The USGS-GPM data were produced using leaf-off photographs. However, the first SPOT image was taken in mid-October, with partial leaf-on conditions, and was matched with a leaf-off image taken approximately six months later. While this mis-match did not appear to cause significant elevation errors (as noted above, there were no significant differences in mean elevation accuracy, and only weak correlations between elevation and elevation error), this may have increased local variability and, hence, degraded slope and aspect accuracy.

Finally, there may be more error in the field measurement of slope and aspect in forested terrain. As anyone with field experience can testify, slope and aspect estimation is considerably more difficult in forested areas due to stem obstruction, understory vegetation, and other factors. Although not likely a large impact in the present study, this may have resulted in slightly more variation in ground-measured slope and aspect, and hence contributed to the positive association between error magnitudes and slope.

Conclusions

This paper represents a limited test of DEMs produced utilizing two digital stereocorrelation methods, and, as such, extrapolations should be conducted with extreme caution. However, this work adds to the scant body of literature describing the slope, aspect, and elevation error properties of widely-used USGS DEMs, and provides some information on an early commercially produced, satellite-based DEM method.

In summary, we draw the following conclusions from this work:

- The mean elevation errors of the two analyzed DEMs are statistically indistinguishable from zero, and both DEMs meet the RMSE accuracy target established by the U. S. Geological Survey for 7.5-minute DEMs. Elevation errors were weakly correlated with elevation for the SPOT-derived DEM, and were not correlated with elevation for the USGS-GPM DEM.
- There are statistically significant errors in slopes derived from the SPOT-STX DEM. Although intermediate slope errors were observed for the USGS-GPM DEM, they were not significantly different from zero, but they were significantly different from SPOT-derived slopes.
- There were significant, positive correlations between slope errors and slope, resulting in larger errors on steeper slopes for both DEMs. Because nearly all slopes in this study were forested, this is likely due at least in part to difficulties in stereo-correlation in forested terrain.
- Large aspect errors were derived for SPOT-derived DEMs, and moderate aspect errors were observed on USGS-GPM DEMs. USGS-GPM aspect errors were significantly smaller than those for SPOT-based values. Aspect errors were uncorrelated with aspect for both SPOT-STX and USGS-GPM data.

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