

# Spatial Descriptions and Comparisons of Intermap IFSAR and USGS DEM Errors

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**[Abstract]** This paper reports two groups of GIS- and field-based experiments that were designed to describe and compare DEM data errors in a spatially explicit fashion. Two USGS map quadrangles in the Santa Monica Mountains, CA, and three small watersheds within these quadrangles were used for these experiments. USGS 10 m DEMs and Intermap 5 m IFSAR (interferometric synthetic aperture radar) DTMs were used for the experiments. A third data set, GPS ground measurements of the elevations in the above-mentioned watersheds, was used as “ground-truth” data. The first group of the experiments focused on (1) characterizing the differences between the two DEMs; and (2) identifying and describing possible correlations between the difference grid and landscape factors. The second group of experiments aimed to (1) estimate the magnitudes and patterns of absolute errors in the DEMs with the help of field measurements, (2) evaluate the correlations between DEM errors and landscape factors, and (3) detect possible systematic errors existing in the two DEMs. The results provide new insights about the spatial character of errors in SAR DEMs and the relative merits of these DEMs compared to longstanding DEMs provided by the USGS.

## 1. Introduction

Non-random, structured (or autocorrelated), and interconnected distributions of environmental attributes, including terrain attributes, may facilitate estimation of unknown environmental patterns from known patterns (e.g. Burrough et al. 2001) or from known point values (e.g. Hutchinson 1998, McBratney et al. 1992) by use of tools such as geostatistics, terrain analysis, landform classification, etc. (Burrough and McDonnell 1998, Wilson and Burrough 1999).

Terrain information is crucial in these environmental modeling activities for at least five reasons.

First, landforms pose significant control and influence on many topo- to meso-scale environmental processes (Wilson and Gallant 2000). Second, compared with many other environmental attributes (e.g. climate, ground water and subsurface soil), terrain attributes are relatively easy and cheap to measure accurately. Third, while other environmental data may often be unavailable or may not exist at desired spatial locations, resolutions and accuracies

(Wilson and Gallant 1998), digital terrain data are usually available over large areas at fine spatial resolutions (e.g. IFSAR and LIDAR technology makes it possible to collect elevation data at 1-2 m resolutions). Fourth, Digital Elevation Models (DEMs) represent the best existing depiction of the spatial continuity – a major challenge for environmental modeling – of our physical environment. Fifth, high resolution DEMs offer the possibility of performing distributed environmental modeling at these fine scales and resolutions. Nevertheless, these advantages rely on high quality input data since the validity of all terrain-based environmental modeling, as well as the quality of subsequent environmental decision-making, will vary with the magnitude and distribution of errors in terrain information (e.g. Burrough and McDonnell 1998, p. 244-7; Heuvelink 1998; Florinsky 2002).

Yet model quality is often difficult to assess due to insufficient knowledge of DEM uncertainties and errors. Perhaps one of the biggest frustrations is that current descriptions of DEM accuracy are aggregated or averaged spatially while the distributions of DEM errors are usually not known. For example, most available DEMs use RMSE (root mean square error) to report DEM errors over a large area (such as a USGS map quadrangle). However, it is usually the terrain shape at a much finer scale/resolution, rather than individual or averaged elevation values, that matters most to topo- and meso-scale environmental processes (Hutchinson and Gallant 2000, Wilson and Gallant 2000). The difficulty lies in the fact that, even with a small RMSE and mean error, terrain shape may still be severely distorted by local errors in DEMs. Table 1 lists four scenarios showing that mean error and RMSE of DEMs cannot sufficiently describe the accuracy of terrain shape representation. It thereby seems necessary to introduce other, possibly local, statistics (such as local standard deviation of elevation errors as used in Table 1) to evaluate DEM accuracies. In addition, the accuracy of first- and second-order DEM

derivatives, such as slope, aspect, upslope contributing area and topographic wetness index, can only be reported reliably with some knowledge of error distributions in DEMs (Hutchinson 1989). The above concerns about DEM errors are further complicated by the rapid emergence and development of new DEM data sources (e.g. IFSAR,

**Table 1. DEM errors, shape representation, and appropriate/inappropriate statistics**

Distribution of point elevation errors	<table border="1"><tr><td>2</td><td>2</td><td>2</td></tr><tr><td>2</td><td>2</td><td>2</td></tr><tr><td>2</td><td>2</td><td>2</td></tr></table>	2	2	2	2	2	2	2	2	2	<table border="1"><tr><td>8</td><td>8</td><td>8</td></tr><tr><td>8</td><td>8</td><td>8</td></tr><tr><td>8</td><td>8</td><td>8</td></tr></table>	8	8	8	8	8	8	8	8	8	<table border="1"><tr><td>0</td><td>2</td><td>4</td></tr><tr><td>2</td><td>0</td><td>4</td></tr><tr><td>4</td><td>0</td><td>2</td></tr></table>	0	2	4	2	0	4	4	0	2	<table border="1"><tr><td>0</td><td>8</td><td>16</td></tr><tr><td>8</td><td>0</td><td>16</td></tr><tr><td>16</td><td>0</td><td>8</td></tr></table>	0	8	16	8	0	16	16	0	8
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Mean local error	2	8	2	8																																				
Local RMSE	2	8	$\sqrt{(20/3)}$	$\sqrt{(320/3)}$																																				
Currently adopted error description	low	high	low	high																																				
Distortion of terrain shape	none	none	low	high																																				
Local standard deviation of errors	0	0	$2/\sqrt{3}$	$8/\sqrt{3}$																																				

LIDAR), which, like recent USGS DEMs, offer higher resolution elevation data but little new information about uncertainty and errors across landscapes. Therefore, it is desirable to obtain some knowledge of the systematic errors that may exist in DEM data and to be able to use this information to generate spatial error information for DEMs.

The next section of the paper describes the materials and methods adopted for two groups of experiments that were designed to test, describe, and compare DEM data errors in a spatially explicit fashion. The first group of experiments provides a description of relative errors as represented by the residual surface between different DEMs. Knowledge of these relative errors may be indicative of the patterns and characteristics of absolute errors that are difficult to measure. The second group of experiments examined the absolute errors of the DEMs at three sets of sampled points. The third section of the paper reports the results of the above

experiments and discusses the implications of the results. Conclusions are given in the last section.

## **2. Materials and Methods**

The study area is located in the Santa Monica Mountains National Recreation Area that covers parts of Los Angeles and Ventura Counties in southern California. Within the study area, the Santa Monica Mountains extend east-west along the Pacific coast with medium to steep slopes and an elevation range of 0 – 950 m. The dominant vegetation is dense, medium-height to tall chaparral shrub. In most of the study area, the natural terrain surface is well preserved, but human disturbance is substantial in some locations.

### **2.1 Group 1 Experiments**

#### *2.1.1 Data acquisition and pre-processing*

Two 10 m USGS DEMs, corresponding to the Point Dume and Triunfo Pass map quadrangles, were downloaded as SDTS (Standard Data Transfer Format) files from the GIS Data Depot (<http://data.geocomm.com/>). These data were first converted into the USGS DEM format with the “SDTS2DEM” tool offered by USGS, then imported into the ArcInfo grid format with ArcToolbox, and lastly merged with the ArcInfo MERGE command. The original projection – UTM (zone 11), datum – NAD27, vertical reference – MSL (mean sea level), and geoid model – NGVD29, were preserved.

Two 5 m Global Terrain Synthetic Aperture Radar (SAR) DEMs (or Digital Terrain Models – DTMs – as called by Intermap Co.) for the same map quadrangles were obtained from Intermap Co. and imported into the ArcInfo grid format with the FLOATGRID command as recommended by Global Terrain ([http://www.globalterrain.com/pdf%20files/GT\\_product\\_handbook\\_v2\\_3.pdf](http://www.globalterrain.com/pdf%20files/GT_product_handbook_v2_3.pdf)). This task was

accomplished after writing a new header file for the DTM. The projection of the DTM – UTM (zone 11), and the vertical reference – MSL, were preserved. The horizontal datum of the DTM – WGS84, was converted into NAD27 with the procedure recommended by ArcInfo. No direct tools were found to convert the geoid model of SAR DTMs from EGM96 to NGVD29. However, it is possible to transfer GPS measurements of elevations to both the EGM96 and NAVD88 geoid models with the Trimble Pathfinder software, and the VERTCON (North American Vertical Datum Conversion Utility) tool offered by the U. S. National Geodetic Survey (<http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html>) converts between NAVD88 and NGVD29. The mean difference between the NGVD29 and EGM96 geoid models was calculated for a sample watershed (as described in the next section) and this value,  $1.92 \text{ m} = 1.13 \text{ m (EGM96 - NAVD88)} + 0.79 \text{ m (NAVD88 - NGVD29)}$ , was used to adjust the elevations of both SAR DEMs. The SAR DEMs were then merged and resampled to a 10 m spacing and the resampled SAR DEM lattice was shifted to match the USGS DEM lattice. This last task was accomplished using the LATTICERESAMPLE command in ArcInfo with the bilinear interpolation option. The small lattice shift (0.7 m) meant that DEM values barely changed.

The two sets of DEMs were then trimmed because the USGS and SAR quadrangles did not match exactly (90% overlap) and some parts of the two quadrangles are covered by the ocean. The common land part was cut out and used as the study area for this research – this area covers  $225 \text{ km}^2$  or 2,254,262  $10 \times 10 \text{ m}$  cells.

### *2.1.2 Experimental design*

A simple raster calculation in ArcMap Spatial Analyst was performed to obtain the difference surface between the two DEMs. Several statistics were calculated for the USGS DEM, the transformed SAR DEM and the difference surface, and they were used along with the difference

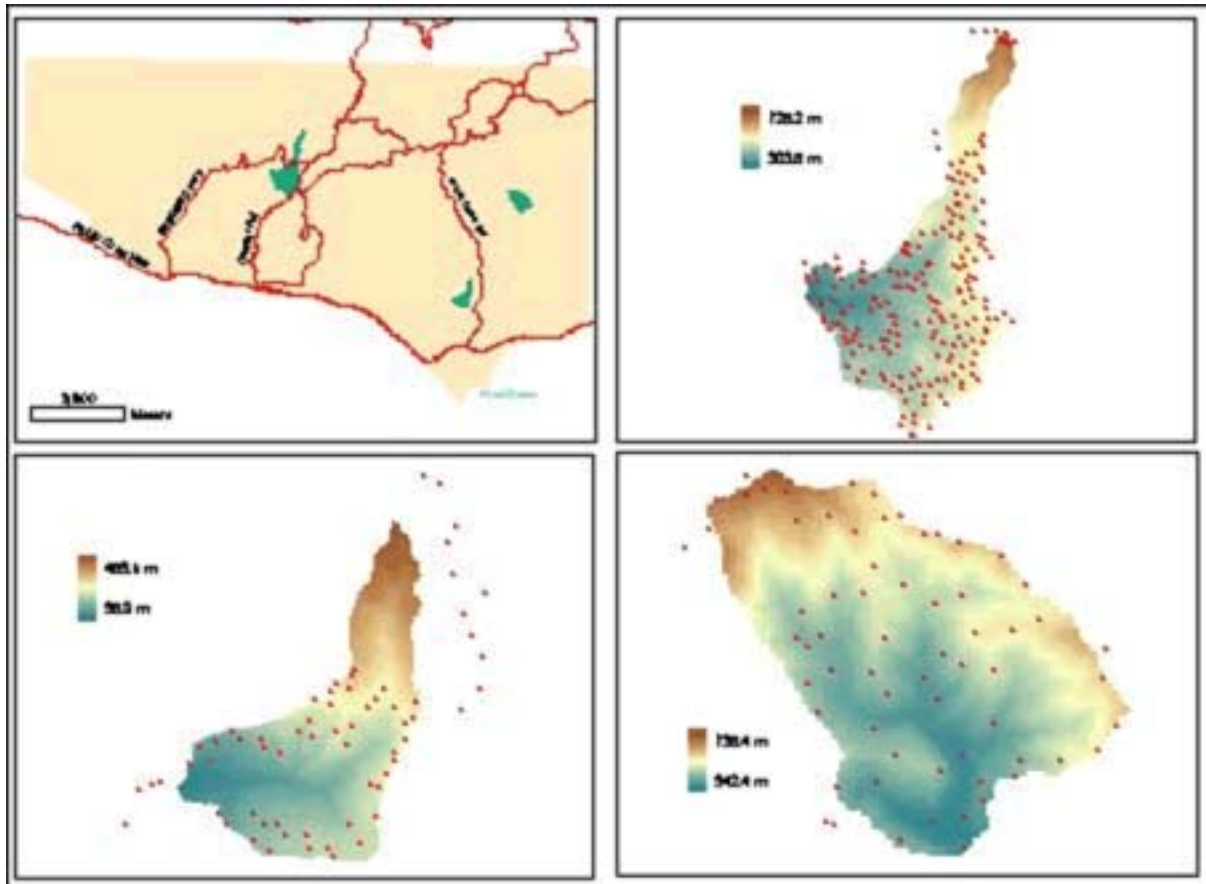
map to evaluate the differences between the two sets of DEMs. A sample area, roughly 9.4% of the entire DEM, where the differences of the two DEMs show certain structures, was selected from the difference map. The counts and percentages of cells falling within each of a series of difference ranges were calculated for both the sample area and the entire DEM. Mean SAR and USGS elevations within each of the difference ranges were calculated for the sample area so as to detect possible correlations between altitudes and elevation differences. Next, according to the difference map of the sample area, a small ridgeline area (see Figure 4) and a small streamline area (see Figure 5) within the sample area were selected to examine the structure of the elevation differences (or the apparent correspondence between elevation differences and landform patterns) in this small area in more detail. Local means, local standard deviations, and local coefficients of variation of the differences were then calculated for the sample area using a 5×5 moving window. Because local standard deviations of elevation errors may be used to evaluate how severely terrain shape is distorted by distributed errors in DEMs (see Table 1), a comparison of four grids – elevations, local mean elevation differences, local standard deviations of elevation differences, and local coefficient of variation of elevation differences – may be performed to assess (1) the relative and absolute severity of local distortion of terrain shape under certain elevation differences, (2) the topographic locations of these distortions, and (3) the possible correlation between the magnitudes of local elevation differences and severity of terrain shape distortions. Last, the Moran's coefficient and Geary's coefficient of the difference surface were calculated to evaluate the possible spatial autocorrelation of the differences.

## **2.2 Group 2 Experiments**

### *2.2.1 Data collection and pre-processing*

Three small watersheds within the two quadrangles were selected for sampling purposes. These watersheds covered 162 ha (16,218 10×10 m cells), 46 ha (4,556 cells) and 55 ha (5,524 cells) respectively. Watershed 1 contained both well preserved natural areas and heavily disturbed sites. The natural landscape in watershed 2 is well preserved. The natural terrain surface and vegetation in watershed 3 are severely disturbed around most of the sampled points. Stratified random sampling (Taylor 1977, Wilson et al. 1998) was performed in all three watersheds by dividing them into 200×200 m cells and measuring elevations at 3 or 4 random locations within each cell. The number of samples was reduced in about 20% of the cells due to physical and/or private land ownership accessibility problems. Figure 1 shows the entire study area, the locations of sampled watersheds, and the distribution of field GPS measurements. A Trimble Pro XR GPS unit was used to collect and average  $\geq 12$  elevation values at each point with a 3-second reading interval and a 6.0 PDOP (Position Dilution of Precision) threshold. The dominant land cover type was also recorded within a 5 m circle from the sampling point. Five land cover classes – trees, high dense shrub, low sparse shrub, grass/meadows, and bare ground – were used. The Pathfinder software was then used to differentially correct the original GPS readings to the Sequoia USFS base station with code processing. Similar to the conversion of SAR DTMs, GPS point measurements were projected to the UTM projection, MSL vertical reference (from Height Above Ellipsoid – or HAE – using the Geoid96 model offered by the National Geodetic Survey) and the NGVD29 geoid model. These procedures ensured that the elevations from the three data sources were comparable.

To diminish the influence of the coarse resolutions of the USGS and SAR DEMs in the steep study area (relative to point measurements), the 10m USGS DEM and 5m SAR DTM were interpolated to a 2 m resolution using spline interpolation offered by the ArcInfo TOPOGRID



**Figure 1. The study area(s): upper-left – the entire area and locations of three sample watersheds; upper-right – watershed 1 and sample locations; lower-left – watershed 2 and sample locations; lower-right – watershed 3 and sample locations.**

command. The GPS point measurements were also converted into a 2 m grid with the ArcInfo POINTGRID command.

### 2.2.2 Experimental design

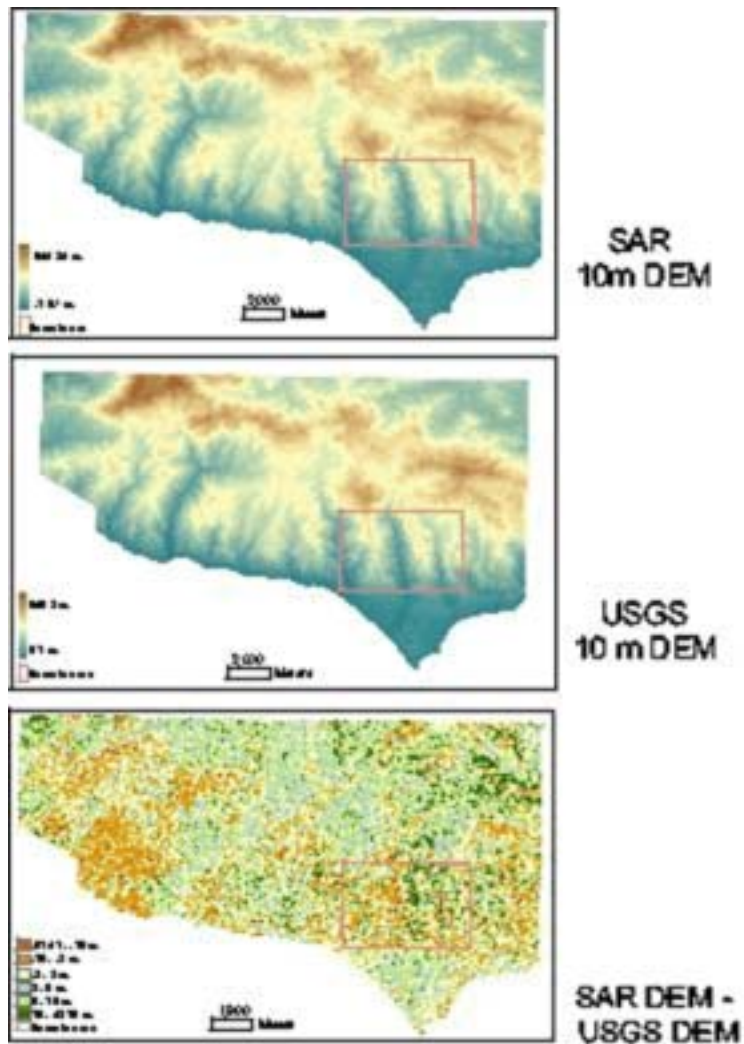
USGS and SAR DEM errors were calculated at the sampling points as elevation differences between two 2 m DEM grids and the 2 m GPS grid. The following analyses were then performed to identify, characterize and compare the systematic errors occurring in the USGS and SAR DEMs. First, several statistics of SAR and USGS errors were calculated and compared to assess which DEM offers more accurate point elevation data. Because the sampling points are not distributed densely enough, it is difficult to detect and evaluate systematic patterns of DEM

errors. To overcome this shortcoming, the three watersheds were divided into a series of elevation ranges in which the error statistics were compared and numbers of cells within 3 error ranges ( $\leq -2.0$  m,  $-2.0$  to  $2.0$  m, and  $\geq 2.0$  m) were counted. This part of the analysis explored how the errors in these two DEMs are distributed at different heights and whether one DEM performs systematically better than the other over different elevation ranges. Finally, chi square correlation analyses were performed between these elevation errors and their corresponding altitudes, aspects, slope gradients, and vegetation types to identify whether any of the DEMs tends to incorporate errors that are systematically correlated to topographic and land cover factors.

### **3. Results and Discussion**

#### **3.1 Group 1 Results**

Figure 2 displays the two DEMs and the difference surface map obtained from them. Viewed at the scale adopted by these maps, the two DEMs show very similar landform patterns: a series of small, parallel watersheds along the southern coast with a line of hills and mountains extending west-east across the middle of the maps and serving as the boundary dividing north- and south-facing watersheds. However, the difference surface obtained by subtracting the USGS DEM from the SAR DEM reveals some important differences. For example, some SAR elevations are 42 m higher than the corresponding USGS elevations, and some USGS elevations are 81 m higher than the corresponding SAR elevations. Table 2 lists several statistics for these three surfaces. The relatively low standard deviations of both the regular and absolute difference surfaces indicate that large differences are small in number and contribute very little to the overall (i.e. mean) differences between the two DEMs. The SAR elevations are 1.96 m higher than USGS elevations over the two quadrangles on average, and there is a 4.23 m absolute



**Figure 2. Comparisons of SAR and USGS DEMs**

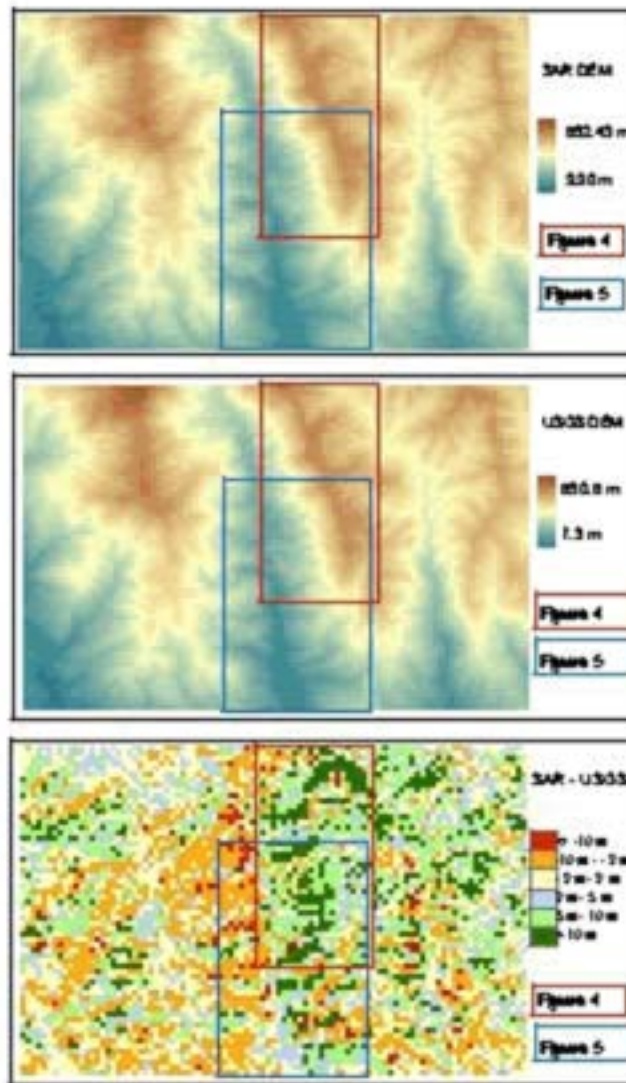
difference between the SAR and USGS point elevations. The difference surface in Figure 2 also shows that the differences between the two DEMs are not random – certain spatial structures seem to exist. First, the differences seem to be autocorrelated in space and negative/positive values tend to cluster. This outcome was verified by the Moran (0.935) and Geary's coefficients (0.063), since positive spatial autocorrelation is represented by high values of the Moran coefficient (close to 1) and low values of Geary's coefficient (larger than 0 but much smaller than 1; see Griffith and Layne 1999).

**Table 2. Basic statistics describing the two DEMs and their difference surface**

	Mean (m)	Minimum (m)	Maximum (m)	Standard deviation (m)
SAR 10m DEM	370.41	-1.66	944.24	184.23
USGS 10m DEM	368.45	0.1	948.2	183.83
Difference grid (SAR - USGS)	1.96	-81.42	42.15	5.18
Absolute difference grid  SAR - USGS	4.23	0	81.42	3.57

Figure 3 shows the SAR and USGS DEMs along with the difference grid for a small sample area (see Figure 2). The slightly larger elevations recorded by SAR DEM are not apparent on the first two maps of Figure 3. However, the difference grid in Figure 3 illustrates how high positive and negative values of elevation differences tended to appear on neighboring slopes with contrasting aspects in this sample area. This structure is visually obvious on the third map of Figure 3 and it helps with the identification of some ridgelines and creeks in this area (Figure 3). The explanation for these patterns could be given by studying these ridgelines and streamlines.

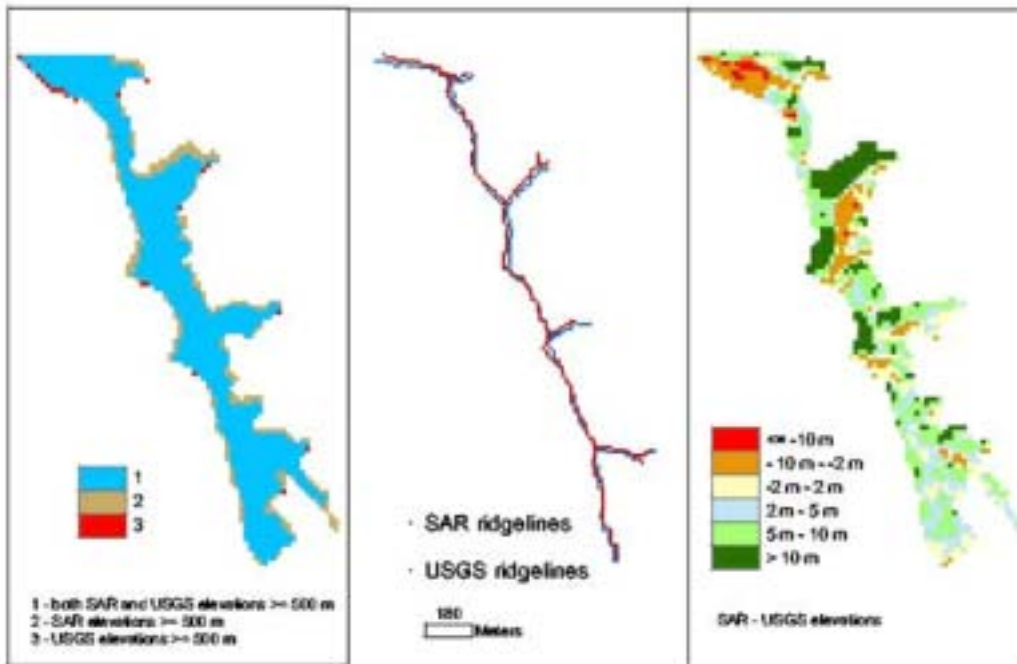
Figure 4 shows the distribution of cells with elevations exceeding 500 m on the two DEMs (left map), two sets of ridgelines (middle map, drawn from SAR and USGS DEMs separately), and the elevation differences (right map) in the narrow area covering the inset box in Figure 3 that encloses the middle ridgeline in the sample area. The small (mostly 1 to 3 cell) variations in the locations of the 500 m contours (left map) and ridgelines (middle map) between the two DEMs – visible in the northern part of the area – corresponds very well with the occurrence of strong contrasts between large contiguous areas of large magnitude of positive and negative elevation differences in the northern area. The same patterns were identified when a similar set of maps was prepared for a canyon area (elevations  $\leq 121$  m) in Figure 3 (Figure 5).



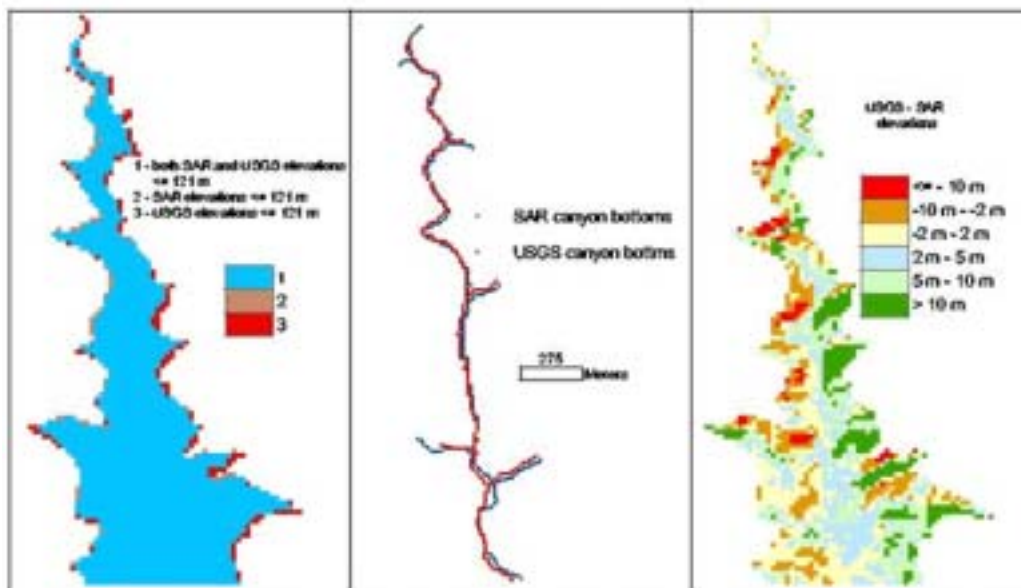
**Figure 3. Comparisons of SAR and USGS DEMs for the sample area shown in Figure 2**

These patterns suggest that the spatial structure visible in the difference maps in Figures 2 and 3 (which also show the existence of the same shifts in landforms between SAR and USGS DEMs) is related to small, but systematic (or continuous) shifts of landforms between different DEMs.

Table 3 shows that, if differences from -2 to 2 m are viewed as insignificant (e.g. because small errors may possibly be introduced by the pre-processing, such as importing and/or format conversion, of the original data for this research), the SAR DEM is significantly higher on 48%



**Figure 4. Spatial patterns of elevation differences along ridgelines**



**Figure 5. Spatial patterns of elevation differences along streamlines**

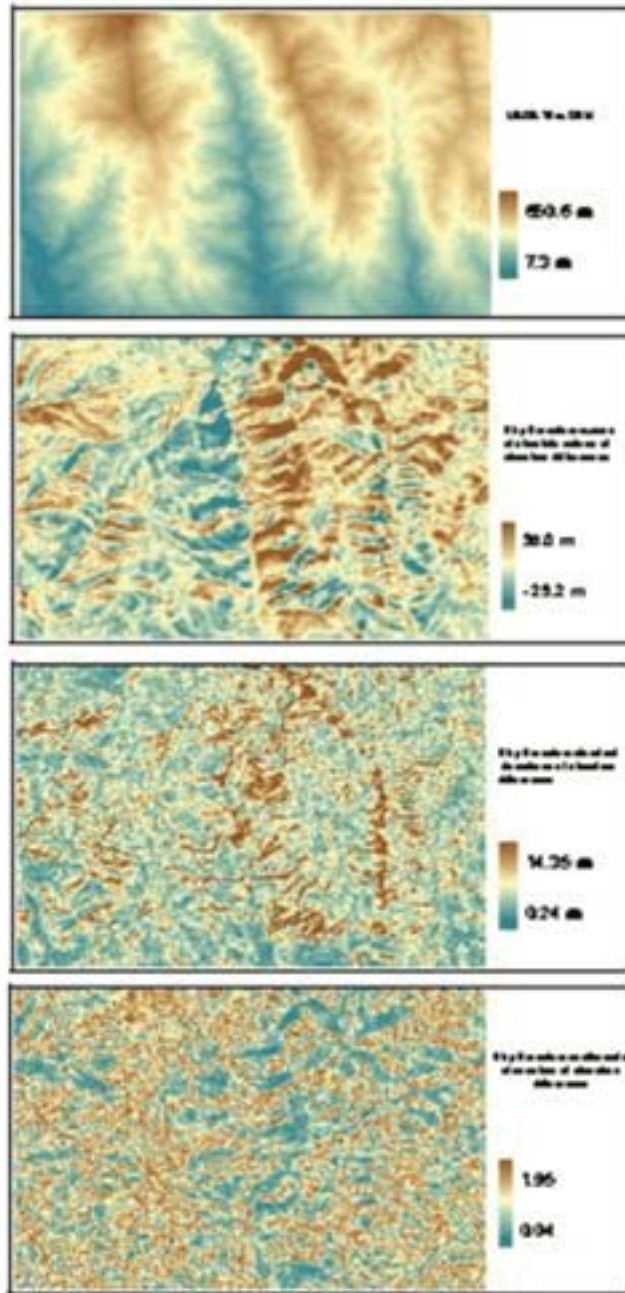
of the cells in the entire study area and the USGS DEM is significantly higher on 21% of the study area. The two DEMs give similar elevation values on only 31% of the area. This, again,

indicates that (1) the mean difference between the SAR and USGS DEMs (1.96 m) was not caused by aberrant high values, but by systematic differences between these two DEMs, and (2) mean error statistics may not adequately represent the extent of DEM errors over space. In addition, the mean elevations increase steadily in the sample area (as reproduced in Figure 2) as the differences increase in magnitude (i.e. the differences between the SAR elevations and USGS elevations grow larger on a cell-by-cell basis). Therefore, both the difference map and the cell distribution analysis show that DEM differences are correlated with altitudes.

**Table 3. Distribution of DEM differences**

SAR-USGS differences	Explanation	Percentage of cells (%)		Mean elevations (m) in the sample area	
		Entire study area	Sample area	USGS	SAR
> 10 m	SAR DEM is substantially higher	6	11	314.5	328.3
5 to 10 m		19	19	314.7	322
2 to 5 m		23	18	311.3	314.8
2 to -2 m	Two DEMs are similar	31	26	301.7	301.8
-2 to -5 m	USGS DEM is substantially higher	13	14	288.6	285.2
-5 to -10 m		7	10	271.3	264.4
< -10 m		1	2	254.2	241.4

As shown in Table 1, local standard deviations of elevation errors or differences may be used to represent how much terrain shape is distorted by the differences between two DEMs. The bottom two maps in Figure 6 show that the largest distortions of terrain shape between SAR and USGS DEMs usually occur as linear features along the sides of narrow, deep canyons where SAR elevations are substantially different than the corresponding USGS elevations. The middle two maps reproduced in Figure 6 show the partial overlap of areas with large local mean elevation differences and large local standard deviations of the differences. This partial overlap suggests that the largest distortion of terrain shape occurs in between areas with minimum and maximum elevation differences (instead of areas with largest elevation differences). The final



**Figure 6. Local statistics of elevation errors in sample area delineated in Figure 3**

map reproduced in Figure 6 shows the local coefficients of variation of elevation differences – calculated by dividing local standard deviations by the local mean elevation differences – and shows how the distortion of terrain shape across this sample area can be best represented as a series of linear features. Further work is needed to interpret these patterns to clarify whether or

not, and if so, how they correspond to the landform pattern (the first map). The four maps reproduced in Figure 6 do indicate that relative distortions of terrain surface caused by the differences between SAR and USGS DEMs are structured, or systematic, rather than random.

### 3.2 Group 2 Results

Table 4 shows USGS and SAR errors obtained by comparing two DEMs to ground GPS measurements in the three watersheds delineated in Figure 1. The following conclusions can be drawn from the various statistics reported in Table 4.

**Table 4. Comparisons of USGS and SAR DEM errors.**

	Elevation class	USGS errors (m)					SAR errors (m)				
		MEAN	MEAN	STD	MAX	MIN	MEAN	MEAN	STD	MAX	MIN
Watershed 1	≤ 350m	-1.77	2.29	2.11	1.77	-5.44	2.89	3.25	2.91	9.6	-1.36
	350 - 400 m	0.08	2.03	2.59	5.77	-5.77	-3.36	2.47	2.06	6.63	-3.35
	400 - 450 m	0.08	2.15	2.71	5.22	-8.51	1.58	2.12	2.23	8.35	-3.77
	450 - 500 m	-0.83	2.12	2.68	5.6	-8.86	0.76	1.82	2.17	6.8	-4.54
	> 500 m	-0.12	2.39	2.92	6.42	-5.72	1.34	2.11	2.19	5.5	-4.5
	<b>Total</b>	<b>-0.37</b>	<b>2.17</b>	<b>2.74</b>	<b>6.42</b>	<b>-8.86</b>	<b>1.44</b>	<b>2.15</b>	<b>2.29</b>	<b>9.61</b>	<b>-4.54</b>
Watershed 2	≤ 100 m	1.68	1.83	1.75	4.27	-0.47	4.49	4.49	1.52	6.47	2.51
	100 - 200 m	1.7	2.6	3.45	10.5	-2.77	3.5	3.83	1.33	5.05	0.47
	200 - 300 m	1.03	3.07	3.92	11.2	-5.22	2.21	2.75	2.54	8.89	-3.15
	> 300 m	-0.53	2.75	3.74	6.63	-8.58	6.9	6.9	1.72	9.67	3.36
		<b>Total</b>	<b>1.02</b>	<b>2.76</b>	<b>3.68</b>	<b>11.2</b>	<b>-8.58</b>	<b>3.6</b>	<b>3.83</b>	<b>2.63</b>	<b>9.67</b>
Watershed 3	≤ 580 m	0.28	3.34	4.23	8.71	-7.07	4.81	5.04	3.56	13.13	0.15
	580 - 640 m	0.86	2.92	3.68	9.36	-5.53	3.56	3.53	2.49	9.21	0.2
	640 - 690 m	-1.37	2.19	2.08	2.85	-4.26	2.49	2.79	2.68	8.61	-2.01
	> 690 m	-1.4	2.54	2.7	2.88	-4.79	0.77	1.41	1.37	2.07	-1.93
		<b>Total</b>	<b>-0.17</b>	<b>2.78</b>	<b>3.51</b>	<b>9.36</b>	<b>-7.07</b>	<b>3.3</b>	<b>3.49</b>	<b>3.03</b>	<b>13.13</b>

- In general, the USGS DEM seems to offer elevation values of higher accuracy than the transformed SAR DEM in all three watersheds. This is shown by (1) higher mean error values of the SAR DEM – the average SAR DEM errors have absolute values that are 1.1 m to 3.1 m larger than the corresponding USGS DEM errors over the three watersheds consistently, and (2)

generally higher (though not significant) means of the absolute values of SAR errors. In the three watersheds, the SAR DEM elevations were 1.4 m to 3.6 m higher than the corresponding GPS elevation measurements and 1.8 m to 3.5 m higher than the corresponding USGS DEM elevations. These values correspond well with the mean elevation difference between the SAR and USGS DEMs (1.96 m) obtained in the group 1 experiments. In contrast, the USGS DEM elevations do not reveal systematic differences from the corresponding GPS measurements – the average errors in the three watersheds are very low and take both positive and negative values.

- The biggest observed error for point elevations is 11.2 m for the USGS DEMs and 13.1 m for the SAR DEMs.
- The average error patterns described above can be observed for most of the elevation ranges in the three watersheds. When the absolute values of mean errors are compared between USGS and SAR DEMs for all 13 elevation ranges in the three watersheds, no USGS errors can be interpreted as significantly higher than SAR errors, if  $>1$  m is considered significant. In contrast, the absolute values of SAR errors can be seen to be significantly higher in 11 of the 13 elevation ranges.
- No systematic trend of USGS errors (or their absolute values) over increasing or decreasing altitudes is evident in Table 4. The variations of SAR errors over elevation ranges did not show any obvious trend in watershed 1 and 2 either. However, there is a trend of SAR error decrease when elevations increase in watershed 3. This may be important because the land cover on the sampling points of watershed 3 is uniform – mostly bare ground, while watershed 1 and 2 have much more diverse land cover types and the controlling factors of DEM errors may be more complicated.

Table 5 verifies some of the above conclusions. For the SAR DEM, many more sampling points fall in the upper class of errors than in the lower class over each of the three watersheds, meaning that the SAR elevations are significantly higher than the corresponding GPS measurements for many more sampling points. This general conclusion was repeated over each of the elevation classes. In contrast, no such significant and consistent pattern was observed for the USGS DEM errors – sampling points are split more or less equally between the upper and lower error classes across most elevation classes in all three watersheds.

**Table 5. Counts of sample points that fall in different error and elevation classes**

	Elevation class	USGS - error ranges			SAR - error ranges			Total
		≤ -2.0 m	-2.0 - 2.0	≥2.0 m	≤ -2.0 m	-2.0 - 2.0	≥2.0 m	
<b>Watershed 1</b>	≤ 350m	5	6	0	0	4	7	11
	350 - 400 m	8	21	7	1	18	17	36
	400 - 450 m	11	27	11	2	25	22	49
	450 - 500 m	19	34	8	5	40	16	61
	> 500 m	10	21	9	2	21	17	40
	<b>Total</b>	<b>53</b>	<b>108</b>	<b>36</b>	<b>10</b>	<b>108</b>	<b>79</b>	<b>197</b>
<b>Watershed 2</b>	≤ 100 m	0	4	2	0	0	6	6
	100 - 200 m	2	11	6	0	3	16	19
	200 - 300 m	6	13	10	2	12	15	29
	> 300 m	2	7	2	0	0	11	11
	<b>Total</b>	<b>10</b>	<b>35</b>	<b>20</b>	<b>2</b>	<b>15</b>	<b>48</b>	<b>65</b>
<b>Watershed 3</b>	≤ 580 m	5	7	5	0	3	14	17
	580 - 640 m	5	10	8	0	7	16	23
	640 - 690 m	9	9	2	1	8	11	20
	> 690 m	2	3	1	0	5	1	6
	<b>Total</b>	<b>21</b>	<b>29</b>	<b>16</b>	<b>1</b>	<b>23</b>	<b>32</b>	<b>66</b>

Table 6 displays the results of 24 chi-square analyses for the purpose of detecting possible correlations between USGS/SAR DEM errors and various landscape (land cover) factors. The primary conclusion is that SAR errors show stronger correlations to topographic factors than the USGS errors do. The chi-square analyses show that SAR errors were correlated to aspect, elevation, or vegetation in five of 12 instances whereas the USGS errors were

**Table 6. Chi Square test results for relationships between USGS/SAR DEM errors and various landscape factors**

		Elevation	Aspect	Slope	Vegetation
Watershed 1	USGS errors	5.55	19.21	2.41	11.86
	SAR errors	<b>10.54</b>	<b>50.01</b>	8.65	8.26
Watershed 2	USGS errors	2.58	<b>32.54</b>	7.12	10.01
	SAR errors	<b>12.34</b>	<b>24.41</b>	5.69	<b>17.96</b>
Watershed 3	USGS errors	8.23	9.56	4.36	14.04
	SAR errors	9.14	17.96	2.18	9.96
Degrees of freedom		4	14	4	8
Test statistics of 0.05 level of significance		9.49	23.68	9.49	15.51

correlated to aspect in only one instance (i.e. watershed). None of the results of the chi-square analyses was significant in watershed 3. The largest number of significant correlations between SAR USGS errors and landscape factors occurred in watershed 2, in which the GPS sample locations show few signs of human disturbance. The watershed 2 results suggest that SAR errors are correlated to aspect, elevation, and vegetation types under natural conditions.

### **3.2 Discussion**

Although the sampling density adopted for this research is much higher than the one used by the USGS to calculate RMSEs (> 28 points per quadrangle), it is still too sparse to generate a continuous terrain surface and facilitate the evaluation of the two DEMs or some other terrain attributes. This may expose the fundamental difficulty in evaluating DEM accuracy – we can never expect to have accurate DEMs to evaluate inaccurate DEMs (and the evaluation would be unnecessary if we did have good data). However, this research shows that certain error patterns and characteristics which can be discovered in a small area may be meaningful to larger areas. Because each type of DEMs tends to adopt relatively uniform or consistent technology and

procedures to collect and process data, certain error characteristics may even be universally applicable. In addition, lessons can be learned about the spatial characteristics of DEM errors – such as how terrain shape may be distorted by one or both DEMs, where errors tend to be larger than other places (i.e. landscape positions) – by comparing existing DEMs in a spatial framework like the one adopted for this study.

The above-mentioned knowledge may potentially be used to generate spatial information of DEM errors and improve the process of reporting DEM errors. The local mean and/or standard deviation statistics calculated in this study tell us something about the variability in terrain shape as well as elevation, for example. However, much still needs to be learnt about how these statistics can be generated from limited field measurements and topographic characteristics, how/where the generated statistics can be used, and how the extent of terrain shape distortions can be measured and reported by DEMs.

#### **4. Conclusions**

Although the results may need to be further verified in larger areas and over more diverse landscapes, this study provides several important insights into the magnitudes and spatial patterns of SAR and USGS DEM errors. First, the results confirm (like many other studies) that many differences and potential errors are glossed over with the currently adopted error statistics for DEMs. Second, terrain shape may be distorted in different ways by DEMs derived from different sources. Third, the relative differences between different DEMs may be linked to real, absolute errors in DEMs. Fourth, the two USGS DEMs examined in this study offer more accurate point elevations than corresponding SAR DEMs. The USGS DEMs did not show significant, systematic differences from the GPS measurements, although tremendous differences

were encountered at some sampling points. Finally, the SAR DEM errors were correlated with altitude, aspect, and land cover.

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