

A RIGOROUS TEST OF THE ACCURACY OF USGS DIGITAL ELEVATION MODELS IN FORESTED AREAS OF OREGON AND WASHINGTON

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ABSTRACT

A procedure for performing a rigorous test of elevational accuracy of DEMs using independent ground coordinate data digitized photogrammetrically from aerial photography is presented. The accuracy of a sample set of 23 DEMs covering National Forests in Oregon and Washington was evaluated. Accuracy varied considerably between eastern and western parts of Oregon and Washington, and to a lesser extent, by DEM production method.

The elevational root mean square errors (RMSE) computed from independent ground data for DEMs produced using the line-trace method were on average 4 times larger than RMSEs published by the USGS for both eastside and westside DEMs. Computed RMSEs for all westside line-trace DEMs exceeded 7m; whereas, 80% of eastside line-trace DEMs had computed RMSEs of 7m or less.

Published RMSEs of eastside DEMs produced using the photogrammetric technique agreed within 1m on average with RMSEs computed from independent ground data; and, all tested eastside photogrammetric DEMs had RMSEs of 7m or less. Published RMSEs for westside photogrammetric DEMs were on average 4m lower than the computed RMSEs; and, 75% of computed RMSEs exceeded 7m.

Although published RMSEs for line-trace DEMs were on average lower than published RMSEs for photogrammetric DEMs, the RMSEs computed from independent data sets did not follow this pattern: photogrammetric DEMs had lower RMSEs than line-trace DEMs. In addition, published RMSEs of photogrammetric DEMs had a much higher correlation ($r^2=0.64$) than did line-trace DEMs ($r^2=0.36$) with RMSEs computed from independent test data.

INTRODUCTION

A digital elevation model (DEM) is an array of numbers that contains the elevation of the ground surface at a series of sample points. The sample points can be regularly spaced horizontally, or they can be randomly spaced. The USDI Geological Survey (USGS) produces and distributes 4 types of regularly spaced DEMs that correspond to standard USGS map series: 7.5-minute; 15-minute; 30-minute; and 1-degree DEMs. In this study, we examined the 7.5-minute DEMs and all further references are to this series.

Planners use DEMs to compute a variety of terrain attributes that are used in the development and assessment of management alternatives (Twito et al. 1987; Moore et al. 1991). Most geographic information systems and remote sensing image analysis systems have utilities that use DEMs to produce slope, aspect, and elevation classifications for use in further analyses. Although the accuracy of such analyses is directly dependent on the accuracy of the DEM data, surprisingly few studies of DEM accuracy have been reported. Many studies have been conducted to investigate the effects of DEM characteristics and hypothetical error levels on derived terrain values (Vieux 1993; Vieux and Needham 1993), but most have not actually measured individual DEM accuracy against independent ground coordinate measurements. Bolstad and Stowe (1994) used 42 ground elevation measurements to compare the accuracy of a single USGS DEM of Blacksburg, West Virginia with a DEM produced from satellite images. Kenward et al. (1996) compared the accuracy of a high-resolution DEM with the corresponding USGS DEM for a small watershed in eastern Pennsylvania. Reutebuch and Carson (1996) reported the results of a low-intensity evaluation (10-20 checkpoints per DEM) of the accuracy of 39 DEMs. Their results indicated that a more intensive evaluation was warranted.

USGS DEMs studied

In the current study, the accuracy of 23 USGS DEMs from forested areas of Oregon and Washington were evaluated using 4,355 checkpoints. The DEMs used in this study were a subset of the 39 DEMs used in our earlier study. Ten of these DEMs were produced using the line-trace method in which contour lines from USGS 7.5-minute quadrangle topographic maps are digitized to produce the gridded elevation data that make up the DEM. The remaining 13 DEMs were produced via a photogrammetric profiling method (USDI 1990). Thirteen of the DEMs were of areas west of the crest of the Cascade Mountains. The remaining 10 DEMs were from east of the crest.

The accuracy of line-trace DEMs was compared to the accuracy of photogrammetric DEMs to see if the DEM production method might influence DEM accuracy. Additionally, accuracy of DEMs from areas east of the Cascades was compared to accuracy of DEMs from western areas of Oregon and Washington

to see if differences in vegetation and general topographic roughness might influence accuracy. Finally, the root mean square error (RMSE) of each DEM computed in this study from independent ground coordinates was compared to the RMSE reported by the USGS for each DEM to see if the reported USGS RMSEs compare favorably with RMSEs computed from independent data.

USGS DEM accuracy assessment technique

It is important to understand how the USGS computes the RMSE of a DEM and the source of checkpoint coordinates used in the accuracy calculations. RMSE is defined as:

$$(Eq. 1) \quad RMSE = [\Sigma(e_c - e_d)^2/n]^{0.5}$$

where: RMSE is the elevational or vertical root mean square error;
 e_c is the elevation of the checkpoint;
 e_d is the DEM elevation for the checkpoint; and,
 n is the number of checkpoints.

In computing RMSEs, the USGS uses checkpoints whose coordinates are measured from 7.5-minute topographic maps at well defined points such as bench marks, spot elevations, and points located directly on contour lines. In other words, the RMSE computed and published by the USGS is an indication of how accurately a DEM matches its associated topographic map--it is not a direct estimate of how well the DEM represents the actual ground surface.

Aerotriangulation ground coordinates and error assessment

In the late 1980s and early 1990s, the National Forests of Oregon and Washington undertook a project to generate new 1:24,000 orthophotos for each 7.5-minute quadrangle that included National Forest lands. A set of 1:40,000 aerial photos were flown and aerotriangulated for each forest. A global positioning system (GPS) survey was used to establish ground control. The typical horizontal and vertical RMSE for each photo block was less than 1m. During the aerotriangulation (AT) process, six to ten points per stereomodel were produced and marked on the aerial photos. Since ground-coordinates were produced for each of these AT points, they can be used to reorient stereopairs in an analytical stereoplotter.

METHODOLOGY AND RESULTS

Each USGS DEM covers a 7.5-minute quadrangle in the 1:24,000 map series. The 1:40,000 photography was captured such that 10 photos cover the map area. Each set of 10 aerial photos compose 8, 60% endlap stereopairs lying within the map sheet area. One of these pairs was randomly chosen for use in

the analytical stereoplotter as a representative sample area from each DEM area. Each stereopair provides stereo-coverage of an approximately 50 sq. km.

Once a stereomodel was mounted in the stereoplotter, ground coordinate data (X, Y, Z) were collected, in a generally uniform pattern across the model. The data were categorized as coming from 7 feature types, namely: i.) streams or rivers; ii.) lakes; iii.) small patches of ground seen on the forest floor down through the tree canopy; iv.) forest roads; v.) bare ground in recent clearcuts; vi.) bare ground in open fields; and, vii.) AT points used in the stereomodel orientation.

Between 250 and 300 points were collected per stereomodel. The following guidelines were followed: i.) digitize streams and rivers only at points where they could be seen through the canopy; ii.) digitize lakes at their edges; iii.) digitize in forests only where the ground could be seen through the canopy; and, iv.) digitize forest roads only where the roadway was in clear view.

The AT points were redigitized so that any bias from operator differences could be estimated and removed. A total of 143 AT points were used to compute the operator bias for each stereomodel. The operator biases ranged from -1.3m to 2.1m. The redigitized AT points were also used to compute an elevational RMSE of 1.5m for the photo measurement process.

The elevation error of the DEM at each photo checkpoint was computed by subtracting the interpolated DEM elevation at the photo checkpoint and the computed stereomodel bias from the photo checkpoint elevation (Eq. 2).

$$(Eq. 2) \quad \text{Error}_{dem} = e_p - e_d - b$$

where: Error_{dem} is elevational error of the DEM at the checkpoint;
 e_p is the elevation of the photo checkpoint;
 e_d is the DEM elevation at the photo checkpoint; and,
 b is the operator bias for the stereomodel.

The RMSE was then computed for each DEM using Eq. 1. Results of these error calculations are given in Table 1, along with the RMSE published by the USGS for each DEM used in the study and the number of checkpoints used to compute the test RMSE. Published RMSEs and DEM elevations are rounded to the nearest meter by the USGS; therefore, all study results have been rounded to the nearest meter. Some of the photo checkpoints fell outside the DEM area and were discarded, resulting in an average of 189 checkpoints per DEM.

In Figure 1, the RMSE computed using the photo checkpoints is displayed beside the RMSE published by the USGS for each individual DEM in the study.

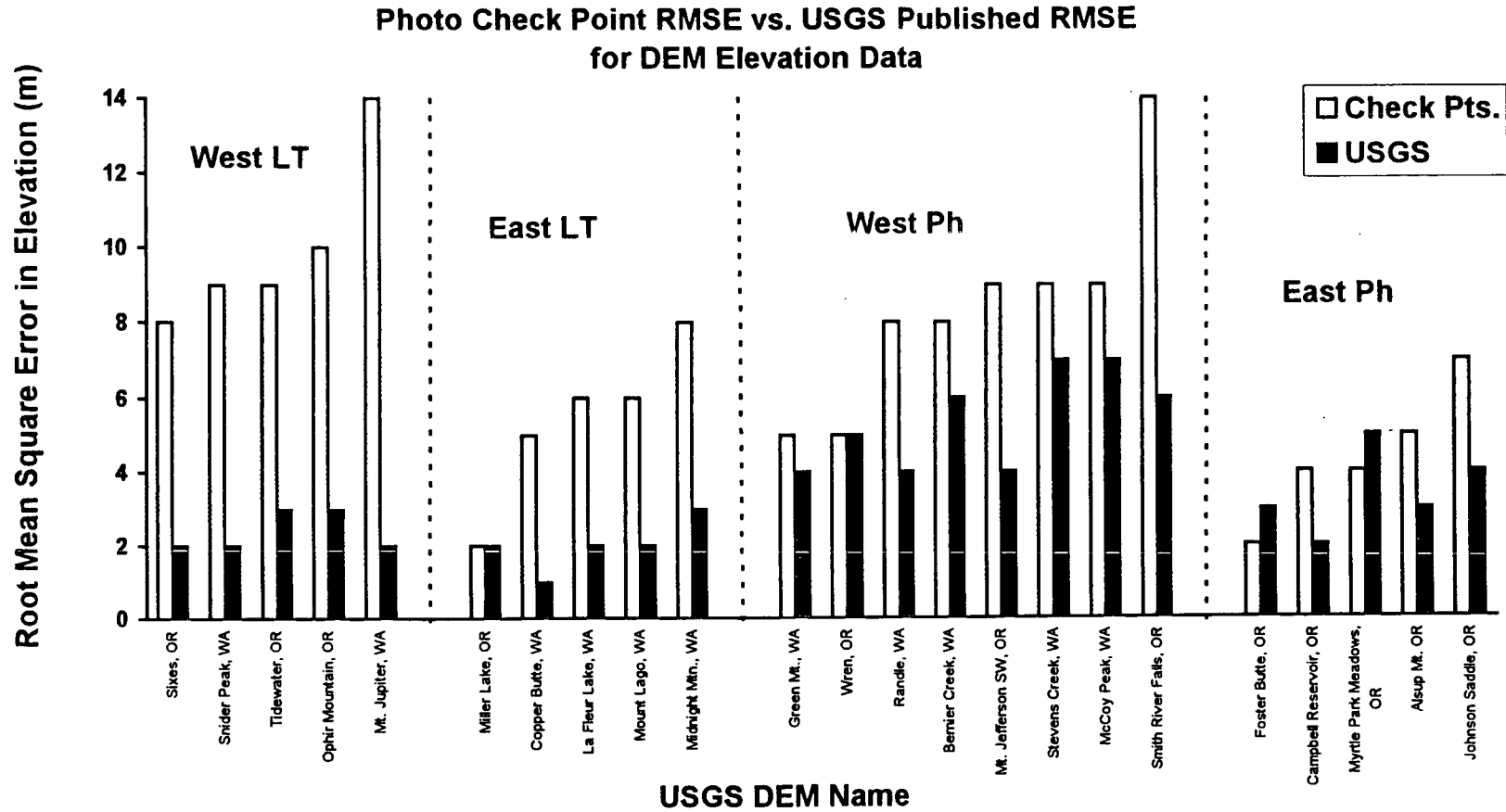


Figure 1. RMSEs computed from photo checkpoints are displayed beside RMSEs published by the USGS.

The RMSE was also computed for each category of DEM, along with the arithmetic mean and range of elevation errors (Table 2). Figure 2 displays average photo checkpoint RMSEs and USGS RMSEs for each DEM category.

Table 1. List of studied USGS DEMs: number of photo checkpoints in each DEM, the computed RMSE, and the published USGS RMSE.

Western DEMs

DEM Name	No. of Check Points	Computed RMSE (m)	USGS RMSE (m)
Line-Trace DEMs (total=5)			
Sixes, OR	167	8	2
Snider Peak, WA	163	9	2
Tidewater, OR	176	9	3
Ophir Mountain, OR	148	10	3
Mt. Jupiter, WA	157	14	2
Photogrammetric DEMs (total=8)			
Green Mt., WA	179	5	4
Wren, OR	239	5	5
Randle, WA	218	8	4
Bernier Creek, WA	193	8	6
Mt. Jefferson SW, OR	184	9	4
Stevens Creek, WA	217	9	7
McCoy Peak, WA	217	9	7
Smith River Falls, OR	169	14	6

Eastern DEMs

Eastside Line-Trace DEM Name	No. of Check Points	Computed RMSE (m)	USGS RMSE (m)
Line-Trace DEMs (total=5)			
Miller Lake, OR	198	2	2
Copper Butte, WA	183	5	1
La Fleur Lake, WA	171	6	2
Mount Lago, WA	133	6	2
Midnight Mtn., WA	174	8	3
Photogrammetric DEMs (total=5)			
Foster Butte, OR	180	2	3
Campbell Reservoir, OR	223	4	2
Myrtle Park Meadows, OR	222	4	5
Alsup Mt. OR	253	5	3
Johnson Saddle, OR	191	7	4

Table 2. Results of the elevation error comparisons by DEM class. All values have been rounded to the nearest meter.

DEM Class	No. of Check Points	Max. Elv. Error (m)		Mean Elv. Error (m)	RSME (m)	
		(-)	(+)		Check Pts.	USGS
West Photog.	1616	-32	36	0	9	5
West LT	811	-59	45	-1	10	2
East Photog.	1069	-25	19	-2	4	3
East LT	859	-24	22	2	6	2
All Photog.	2685	-32	36	-1	7	5
All LT	1670	-59	45	2	8	2
All West	2427	-59	45	0	9	4
All East	1928	-25	22	0	5	3

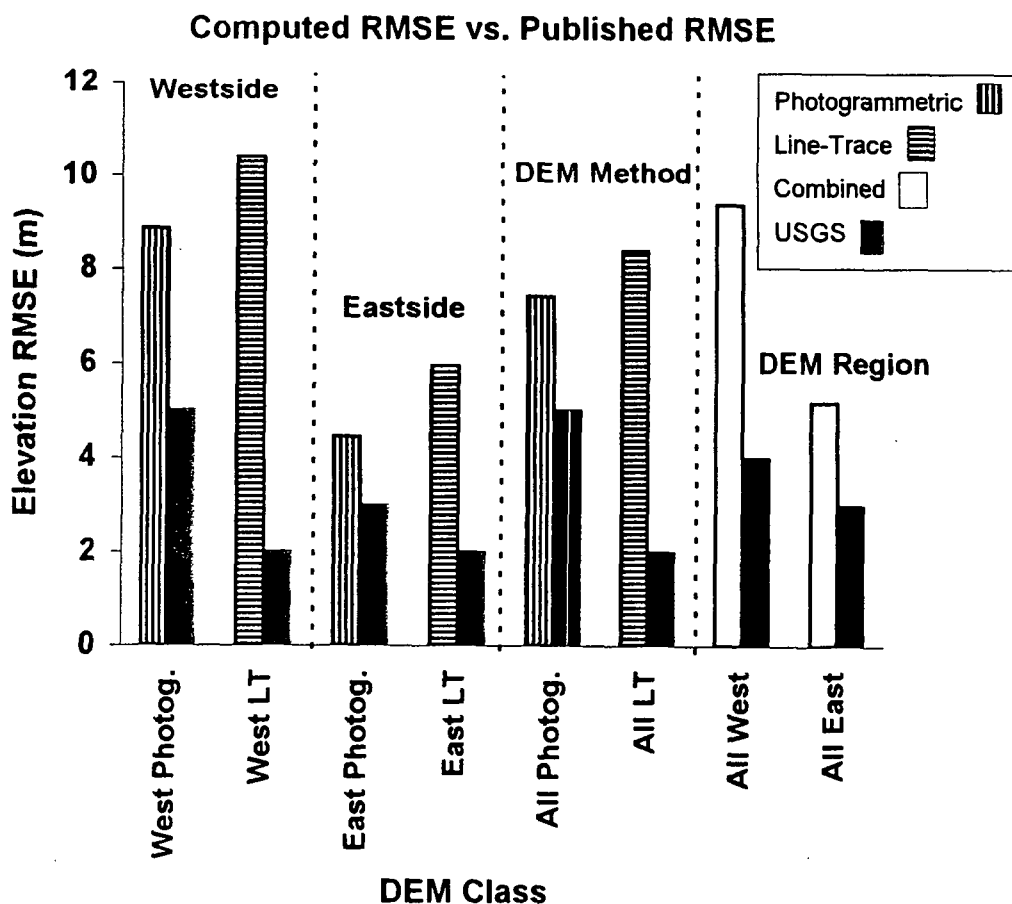


Figure 2. Average RMSE of each DEM class: computed from photo checkpoints compared to published USGS values.

DISCUSSION

Before discussing results of this study, it is important to note that the RMSE published by the USGS for each DEM is computed with checkpoints measured from its corresponding 7.5-minute topographic map, not checkpoints generated from independently measured terrain elevations. In other words, the published RMSEs indicate how well DEMs match associated map sheets, not the actual terrain surface that the map sheets depict. Map generated checkpoints are used by the USGS to check both photogrammetric and line-trace DEMs.

The photo checkpoints used in this study were measured independently of the 7.5-minute topographic maps. These independent points were used to compute an RMSE that indicates how well a DEM actually models the terrain surface, not simply the surface depicted on the map.

DEM RMSEs published by the USGS

The published RMSEs for all DEMs in the study were 7m or less (Table 1). Both eastside and westside line-trace DEMs had the lowest average USGS RMSE (2m), followed by the eastside photogrammetric DEMs (3m), and then the westside photogrammetric DEMs (5m).

Because the line-trace DEM production technique uses map contours as its source of elevation data, one would expect that line-trace DEMs would fit their corresponding maps better than the photogrammetric DEMs which utilize a three-dimensional stereomodel as their source of elevation data. As shown in Figure 2, this was the case for the DEMs used in this study. The average RMSE published by the USGS for the line-trace DEMs was 2m; whereas, the average for the photogrammetric DEMs was 5m.

Additionally, due to heavy vegetative cover and highly dissected terrain on the westside of the Cascades, one would expect that the published RMSEs for westside DEMs would generally be higher than those published for eastside DEMs. Again, this was the case (Fig. 2). The average published RMSE for westside DEMs was 4m; whereas, the average for eastside DEMs was 3m.

DEM RMSEs computed using photo checkpoints

The checkpoint-derived RMSEs for all DEMs in the study were 14m or less, with most values being 10m or less (Fig. 1). The eastside photogrammetric DEMs had the lowest average RMSE (4m), followed by the eastside line-trace DEMs (6m), then the westside photogrammetric DEMs (9m), and finally the westside line-trace DEMs (10m).

Because the photogrammetric DEM production technique uses a three-dimensional stereomodel of the terrain (stereo aerial photos) as its source of

elevation data, one would expect that these photogrammetric DEMs would fit the ground better than the line-trace DEMs which use map contour lines as their data source. As shown in Figure 2, this was the case. The average RMSE (computed from the photo checkpoints) for the photogrammetric DEMs was 7m; whereas the average for the line-trace DEMs was 8m.

As was found for the published USGS RMSEs, the checkpoint-derived RMSEs also differed due to geographic region. The average RMSE for westside DEMs was 9m; whereas, the average for eastside DEMs was 5m (Fig. 2).

It should be noted that the photo checkpoints used in this study do not provide an accurate assessment of DEM accuracy in areas covered by heavy timber because the ground surface is not visible; therefore, no checkpoints were measured in such areas. One would expect the computed RMSEs to be greater if points were measured on the ground in such heavily timbered areas and included in the RMSE computations.

Comparison of published RMSEs to checkpoint RMSEs

Using either the published RMSEs or the checkpoint-derived values, all of the DEMs in the study meet the first part of the USGS DEM Level 1 accuracy standard which states that an RMSE of 7m or less is desired, but that up to 15m is acceptable. (Two DEMs had a computed RMSE of 14m). One DEM, Mt. Jupiter, Washington, failed the second part of the accuracy standard which states that no single point shall be in error over 50m (Fig. 1 and Table 2). However, it is obvious from Figures 1 and 2 that the published RMSEs differ considerably from the RMSEs computed using independent photo checkpoints.

On average, the USGS reported a higher RMSE for photogrammetric DEMs (5m) when compared to line-trace DEMs (2m). When independent coordinates were used, the average RMSE of photogrammetric DEMs (7m) was slightly lower than the RMSE of line-trace DEMs (8m).

For line-trace DEMs there was very poor correlation between the computed RMSEs and the published RMSEs ($r^2=0.36$). The RMSE value computed using independent ground coordinates (8m) was 4 times greater than the average published USGS RMSE value (2m). The published RMSE of an individual line-trace DEM was off by up to 12m (Fig. 1).

The average published RMSE for photogrammetric DEMs (5m) was reasonably close to the average RMSE computed using independent ground coordinates (7m). The published RMSE of an individual photogrammetric DEM was off by up to 8m (Fig. 1). The computed RMSEs for photogrammetric DEMs corresponded much better with the published USGS RMSEs ($r^2=0.64$).

Range of elevation errors by DEM class

The range of elevation errors computed at the checkpoints is given in Table 2. The line-trace DEMs had a wider range of errors (-59m to +45m) than the photogrammetric DEMs (-32m to +36m). A wider range of elevation errors was also encountered in the westside DEMs (-59m to +45m) than in the eastside DEMs (-25m to +22m).

CONCLUSIONS

The authors have developed a technique for assessing the accuracy of USGS DEMs using independent coordinates digitized from well-controlled aerial photos. The technique can be used to check the elevational accuracy of DEMs whenever well-controlled aerial photos are available and an analytical stereoplotter is available for making independent measurements. In the study reported here, checkpoint coordinates were digitized from aerial photos that had precise control data generated in a prior orthophoto project. Approximately 200 checkpoints were digitized in each of 23 DEM areas.

In this study, the RMSE values published by the USGS indicate that line-trace DEMs matched the USGS 7.5-minute topographic maps better than the photogrammetric DEMs. However, the checkpoint-derived RMSEs indicated that the photogrammetric DEMs matched the actual ground surface slightly better than the line-trace DEMs.

In addition, the RMSEs published by the USGS for photogrammetric DEMs were generally close to the RMSEs computed from the independent checkpoints. However, the RMSEs published for line-trace DEMs were generally much lower than the RMSEs computed from independent checkpoints.

The eastside DEMs had considerably lower RMSEs than westside DEMs, regardless of DEM production method. The computed RMSEs of westside DEMs were often several times greater than the published USGS RMSEs.

Point errors of +/-30m were found in many westside DEMs and +/-20m in eastside DEMs. In many software systems that use DEMs, such errors may cause significant problems.

ACKNOWLEDGMENTS

The authors wish to thank the geometronics staff of the Forest Service Regional Office in Portland, Oregon. Particular thanks goes to Rod Dawson for many helpful suggestions, Bob Race for providing AT data and DEMs, and Roger Crystal for his enthusiastic support of the study.

REFERENCES

- Bolstad, P. V.; T. Stowe. 1994. An evaluation of DEM accuracy: elevation, slope, and aspect. *Photogrammetric Engineering and Remote Sensing*, 60(11): 1327-1332.
- Kenward, T.; D. Lettenmaier; E. Wood; M. Zion. 1996. Vertical accuracy of digital elevation models. Amer. Geol. Union. 1996 Spring Meeting. Poster T31A-10.
- Lemkow, D. Z. 1977. Development of a digital terrain simulator for short-term forest resource planning. M.S. Thesis. Vancouver, B.C.: University of British Columbia: 207p.
- Moore, I. D.; R. B. Grayson; A. R. Ladson. 1991. Digital terrain modeling: a review of hydrological, geomorphological and biological applications. *Hydrological Processes*, 5(1): 3-30.
- Reutebuch, S. E.; W. W. Carson. 1996. Accuracy of USGS digital elevation models in forested areas of Oregon and Washington. In: Greer, J. D., ed. Proceedings of the Sixth Forest Service Remote Sensing Applications Conference. 1996 April 29-May 3, Denver, CO. Bethesda, MD: ASPRS.
- Twito, R. H.; S. E. Reutebuch; R. J. McGaughey; C. N. Mann. 1987. Preliminary logging analysis systems (PLANS): overview. Gen. Tech. Rep. PNW-GTR-199. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 24p.
- USDI, U.S. Geological Survey. 1990. Digital elevation models: Data users guide 5. USDI Geological Survey, Reston, VA: 51p.
- Wolf, P. R. 1983. *Elements of Photogrammetry*, 2nd Ed., New York, McGraw-Hill: 628p.

1997

ACSM/ASPRS

Annual Convention & Exposition
Technical Papers

ACSM 57th Annual Convention
ASPRS 63rd Annual Convention

Seattle, Washington
April 7-10, 1997



Resource Technology

Volume 1
Surveying & Cartography