# QUALITY EVALUATION OF THE NATIONAL DIGITAL ELEVATION MODELS


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## ABSTRACT

Digital elevation models (DEM) are available and widely used in several different data formats and resolutions. The National Imagery and Mapping Agency (NIMA) and the United States Geological Survey (USGS) are the primary producers and distributors of this data. Some of the most commonly used and analyzed DEM are produced at spatial resolutions of 30 meters and 3 arc seconds. Through a comprehensive study on a large number of datasets, this article analyzes different characteristics and different types of processing errors in each type of these DEM sources. ArcView GIS v3.2 software is used in this study to perform the comparative analysis and evaluation on the consistency and quality of these national DEM. The study area included various locations in the state of Indiana. In resampling the 30 meter DEM to the spatial resolution of the 3 arc second DEM several differences between the two data sources become apparent. These differences may include a relationship between the slope of the terrain and the consistency of the data from the two different spatial resolutions. Other differences include processing effects such as data 'striping', 'ghost' contours, boundary merge effects, and random errors.


## INTRODUCTION

A digital elevation model (DEM) is a digital file consisting of terrain elevations for ground positions at regularly spaced horizontal intervals. Different techniques have been used for the production of DEM (http://edc.usgs.gov/glis/hyper/guide/1_dgr_dem). The DEM data has been generated by a variety of automated and manual photogrammetric compilation systems. The current method is interpolation from digital line graph (DLG) data. When the data is obtained from cartographic sources, the topographic features are digitized and processed into the proper interval spacing. When data is collected from photographic sources, elevations along a profile are weighted with such information as drainage and spot elevations to interpolate the final elevations at the proper interval spacing.

Several DEM products are available for public use. One such product is described as a 1-degree DEM. The 1-degree DEM consists of a one square degree of elevation data at a grid or post spacing of 3 arc seconds. Most 1-degree DEM are produced by the National Imagery and Mapping Agency (NIMA) from cartographic and photographic sources. NIMA identifies these 1-degree elevation models as digital terrain elevation data (DTED®) Level 1. The US Geological Survey (USGS) reformats and distributes this data as a 1-degree DEM. Sometimes the DEM is called '1:250,000 scale' data. This is because a one square degree area of data is based on half of a 1:250,000 scale cartographic map (http://edcwww.cr.usgs.gov/glis/hyper/guide/1_dgr_dem). The data is referenced to a geographic coordinate system (WGS 84) in horizontal spacing of arc seconds and elevation data in meters. The accuracy of the 1-degree DEM as assessed by NIMA is a horizontal accuracy (feature to datum) of 130m circular error at 90%, and a vertical accuracy (feature to sea level) of +/- 30 meters (http://edcwww.cr.usgs.gov/glis/hyper/guide/1_dgr_dem). The 1-degree DEM used in this study is obtained from the USGS web site http://edcwww.cr.usgs.gov/glis/hyper/guide/1_dgr_demfig/index1m.html.

Another widely used DEM product is described as the 30-meter DEM. This DEM is produced by the USGS as part of the National Mapping Program. Each 30-meter DEM is based on a 7.5-minute USGS topographic quad sheet. The data is referenced to the Universal Transverse Mercator (UTM) coordinate system. The elevation data for lower relief areas is usually referenced in feet (http://edc.usgs.gov/glis/hyper/guide/7_min_dem). The USGS refers to the accuracy of data in terms of levels. Level 1 DEM have a vertical accuracy of 7 meters to a maximum of 15 meters. Level 1 accuracy usually is applied to data that originated from scanned photography. Level 2 DEM has an accuracy of one-half contour interval of the cartographic data they were digitized from. Level 3 DEM are generated from DLG data. Most 30-meter DEM fall into Level 1 (http://edc.usgs.gov/glis/hyper/guide/7_min_dem).

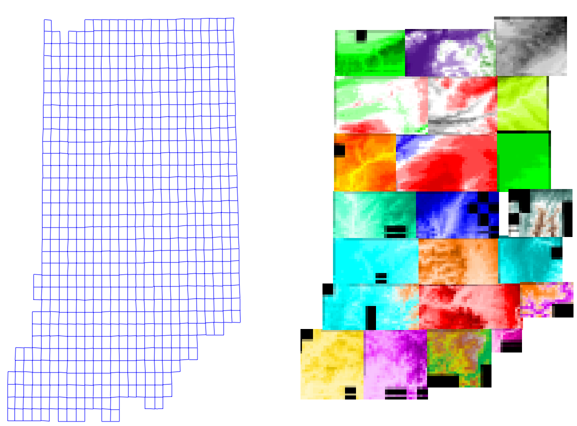
In contrast, the level of NIMA elevation products (DTED®) refers to the grid or post spacing of the data. Level 2 data corresponds to a spacing of one arc second (approximately 30 meters). Level 1 data corresponds to a three arc second spacing and Level 0 to a thirty arc second spacing. Level 0 data is available to the public at http://164.214.2.59/nima-bin/dted/dted_ovr.cgi?90w60n:60:-90:30:-60. The data formats for 30-meter and 3 arc second DEM can be found on the Eros Data Center website listed under Other Useful Web Sites.

Systematic errors in DEM have been investigated on numerous occasions. Garbrecht and Starks (1995) reported on the effects of data striping in an analysis of DEM in Nebraska. Rees (1998) investigated the accuracy of DEM interpolated to higher resolutions. In that study, the accuracy of various data interpolation techniques was calculated, including bilinear interpolation, bicubic interpolation, and kriging. Brown and Bara (1994) investigated systematic errors in DEM by identifying patterns of variation in north-south and east-west directions. They found that although systematic errors may be difficult to detect in the original data set, they may become apparent in 'derivative' products such as slope. Guth (1999) studied the 'ghost' contour lines that are visible in the slope derived from DEM.

In contrast, this study will compare a dataset resampled by the nearest neighbor technique to a lower resolution dataset. It will describe the results of resampling data with a sampling interval of 30 meters to a wider spacing (3 arc seconds). This study will show that there are sometimes significant differences between DEM even though they may have the same spatial resolution. Also, several examples of processing errors will be identified and described. For this study, ArcInfo and ArcView GIS are used to perform the data manipulation and analysis.

## DATA SOURCES

The 30-meter DEM for this study was obtained from the Purdue Center for Advanced Applications in GIS (CAAGIS, http://danpatch.ecn.purdue.edu/~caagis). It is based on the 7.5-minute USGS quad sheets and is available in twenty-two areas of combined 7.5 minute DEM data. It was desired to obtain as much statewide coverage as possible for Indiana. This DEM data contains a nearly complete statewide coverage in a NAD 27 horizontally referenced format. Figure 1 shows the individual 7.5-minute quads and the twenty-two areas made up from the quads. Using ArcView GIS, the twenty-two areas are merged into one 30-meter DEM covering most of Indiana. The rectangular gaps in the coverage correspond to missing topo quads of DEM data when the areas are created. The resultant grid of merged 30-meter DEM data for Indiana was over 598Mb in size. The 3 arc second data is obtained from the USGS web site http://edcwww.cr.usgs.gov/glis/hyper/guide/1_dgr_demfig/index1m.html. Nineteen separate 1-degree squares are downloaded. The area encompassed by the 1-degree DEM is larger than the 30-meter because the 1-degree areas are available only in complete one square degree cells. Using ArcView GIS, the nineteen cells were merged into one large 3 arc second DEM. Figure 2 shows the merged 1-degree cells of 3 arc second data. No attempt is made to smooth the boundaries between downloaded cells. As a matter of fact, part of this study is to identify problem areas within the data and no smoothing or mosaicing is performed.



**a.** Topo Quads **b.** DEM files

**Figure 1.** 30 meter (7.5minute) DEM

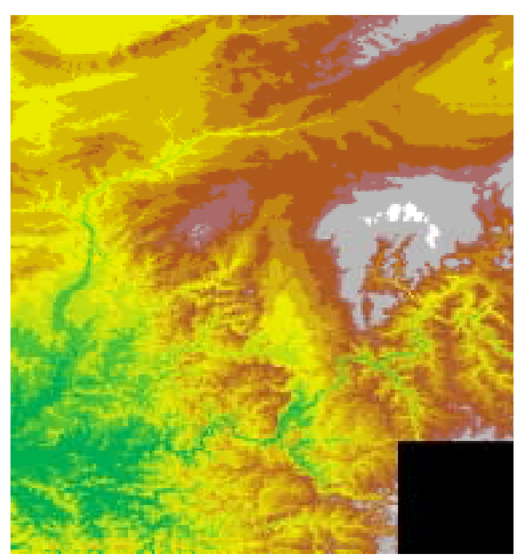


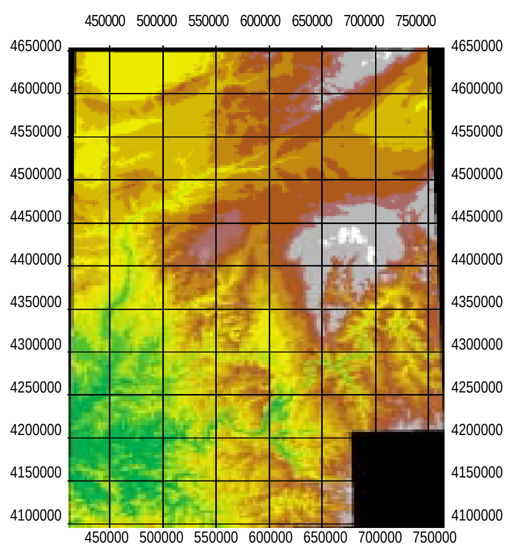
**Figure 2.** Merged 1-degree DEM

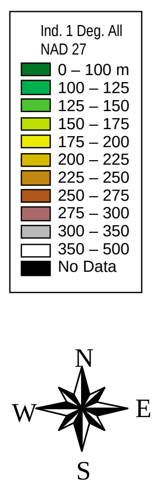
# METHODOLOGY

In order to begin analysis of the two DEM, the 30-meter (7.5-minute) and the 3 arc second (1-degree), they must first be georeferenced to the same coordinate system. The original 30-meter DEM is referenced to the NAD 27 datum and the UTM coordinate system. Since the 30-meter DEM is such a large file, it was decided to re-reference the 3 arc second file from a geographic coordinate system to match the UTM. Indiana is located in UTM grid zone 16. Grid zone information can be found in the ArcView GIS and ArcInfo projection files. (See also http://www.dmap.co.uk/utmworld.htm). The first step is to change arc seconds to meters and seconds of latitude and longitude to meters. The next step is to change elevation in feet from the 30-meter DEM to meters in order to match the units of the 3 arc second DEM.

ArcInfo is used to convert the geographic coordinate system in seconds of latitude and longitude of the 1-degree DEM to a UTM projection. The UTM grid zone 16 was defined for both DEM, as was the NAD 27 horizontal datum. In ArcInfo, the 3 arc second DEM needs to be initialized in units of DS (degrees and seconds) before converting to UTM. The data file itself is actually in units of seconds in western coordinates (i.e. –308000 seconds longitude). After conversion, a grid spacing of 3 arc seconds amounts to 82 meters in UTM ground coordinates for the latitude range of Indiana. Figure 3 shows the converted 3 arc second DEM to the UTM coordinate system. Next, the 30-meter DEM was converted from elevation units in feet to meters (1 meter = 3.28084 feet). The resampling distance for the 30-meter DEM is 82 meters. This distance will match the spacing of the converted 3 arc second DEM. Figure 4 shows the resampled 30-meter to 82-meter DEM.

Before a comparison of the resampled and converted DEM can begin, the horizontal and vertical transformations must be verified. The 1-degree DEM is originally referenced to the NAD 83 datum. Over eastern North America the transformation from the NAD 83 datum to the WGS 84 datum is 0 meters in x, y, and z (NIMA, 1997). The transformation from NAD 27 to WGS 84 and thus NAD 83 is x = -9 m, y = 161m, and z = 179 m (NIMA, 1997). Using thematic overlays of elevation horizontally referenced to the NAD 27 datum and also to the NAD 83 datum, the x and y transformations are verified. The elevation data remain consistent with the CAAGIS database. No bias due to a z transformation error on the order of 179 m is observed. Figure 5 is a flowchart of the steps taken to prepare the DEM.



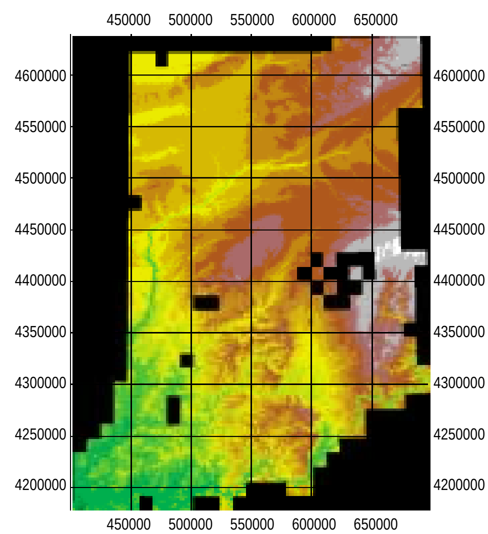




**Figure 3.** Merged 1-Degree DEM

This data is merged from nineteen separate USGS 1-degree DEM. Then, using ArcInfo, the merged data is georeferenced to a UTM system from a geographic coordinate system.

**Figure 4.** Resampled 30m DEM (UTM zone 16, NAD 27) to 82m (3“)

This data is merged from twenty-two separate 30-meter DEM. The data is then resampled to match the spacing of 1-degree DEM.

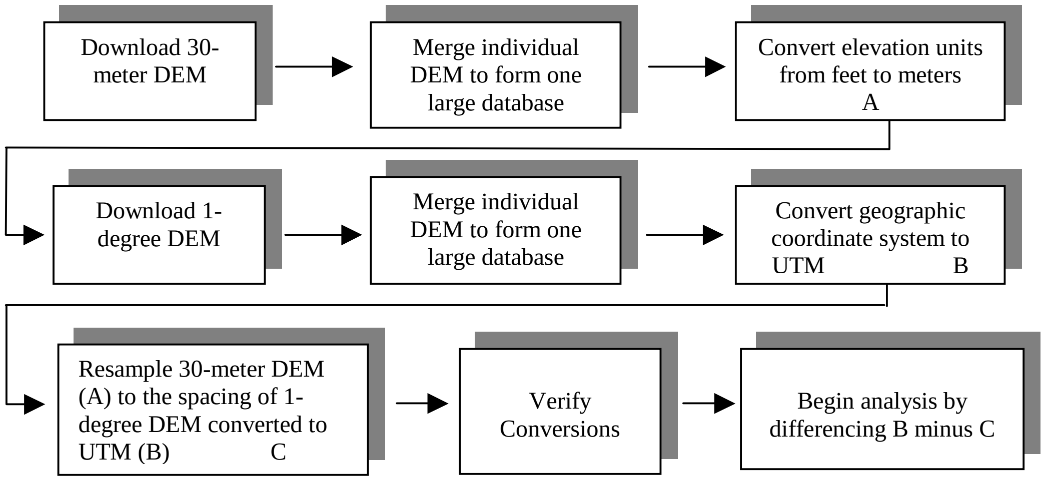
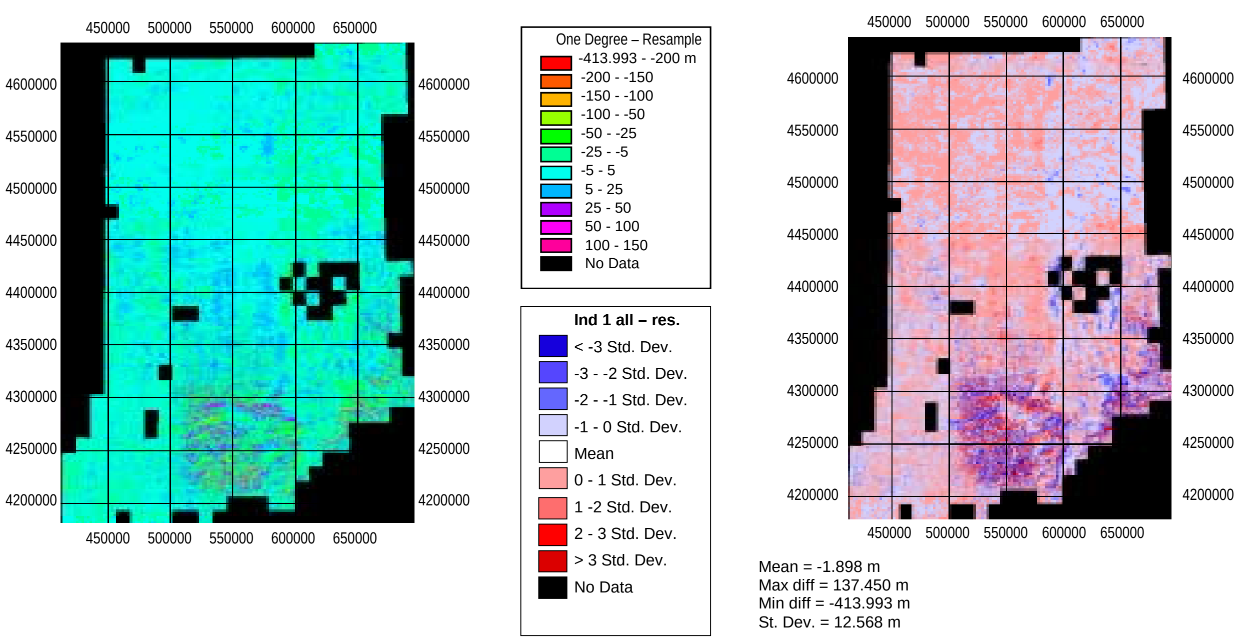



**Figure 5.** Flowchart of the data preparation process

# ANALYSIS

The purpose of this analysis is not to ascertain which DEM is ‘better’. This study will identify differences between the two DEM and will make some observations regarding the quality of processing by highlighting sample defects in each DEM. In order to observe regional trends, the resampled level 2 DEM (30 meter to 82 meter) was subtracted from the level 1 (3 arc second) DEM. Figure 6 shows the differences and standard deviations of the entire data set. The mean difference (level 1 minus resampled level 2) is –1.898 meters and the standard deviation is 12.568 meters. One can see immediately from both figures that the regions of the largest differences between the DEM are found in the hilly areas in southern Indiana nearer to the Ohio River. Notice the variations in the ‘character’ or the ‘texture’ of the differences throughout the plots. The large difference of -413.993 meters is due to a bad elevation value in the original 30 meter DEM data. It is not an artifact of the resampling process.




**a.** Differences **b.** Standard Deviations

**Figure 6.** Statewide results of Level 1 DEM minus resampled Level 2 DEM

Figure 7 is a close up of part of the hilly area. The boundaries of the original 7.5-minute topo quads from the level 2 DEM are also shown. Note the change in character or 'texture' of the standard deviations along a vertical line the third full grid from the left (see arrow). This could indicate a possible problem along one of the merged 1-degree DEM cells. The magnitude of the standard deviations may also suggest a correlation between the slope of the terrain and the consistency of the data. Note how the topography is reflected in the differences.

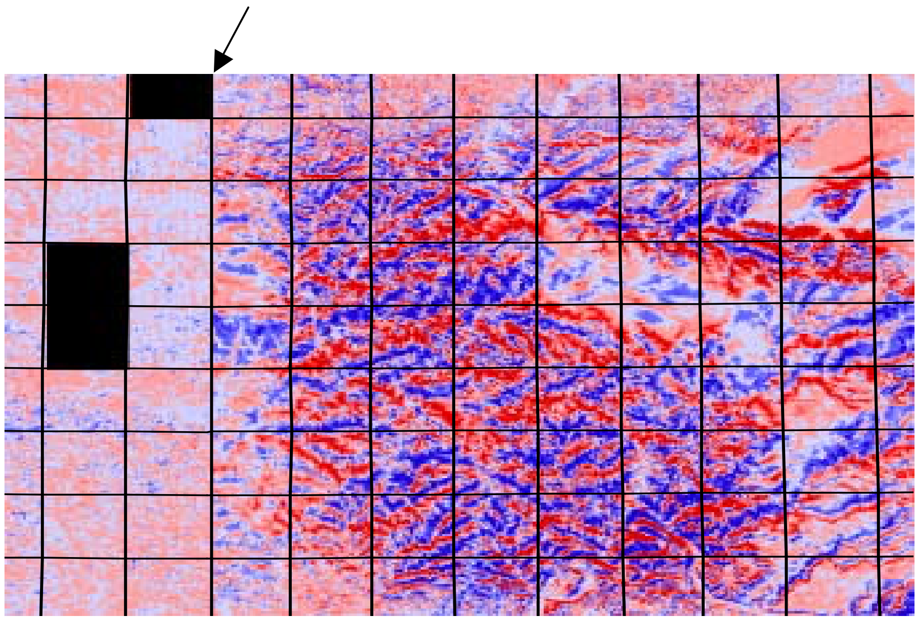
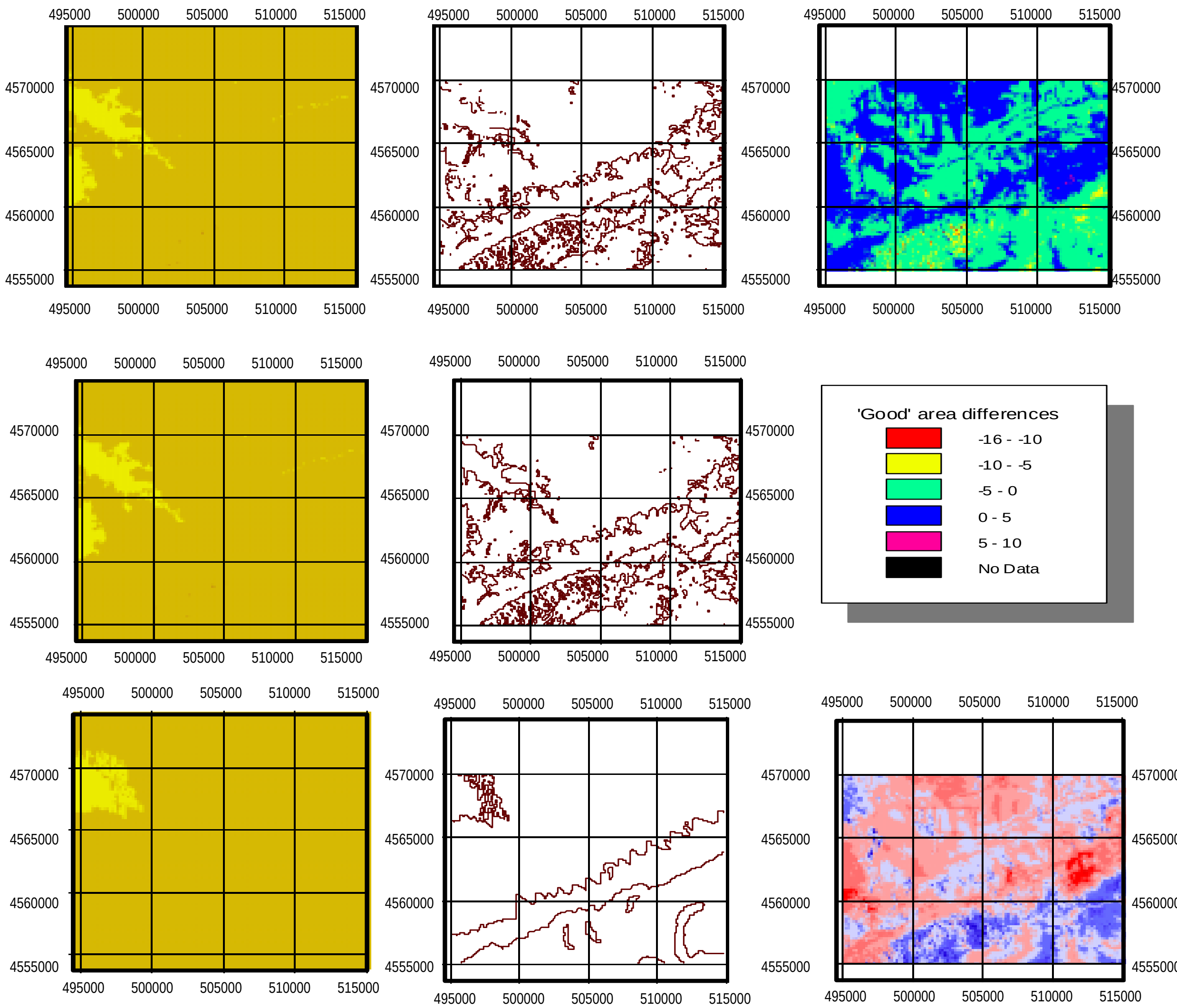
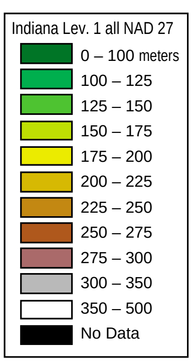


**Figure 7.** Topo Quad boundaries and DEM standard deviations

A statistical analysis of these DEM shows a wide range of results. Figure 8 shows a plot of the elevation data, contours, and differences between the 30-meter resampled and the original 3 arc second data. This is a fairly 'well behaved' area. Note how the difference and standard deviation plots show a river that is not portrayed at the color scale used for the elevation data itself. Note also that there is not much detail lost in the nearest neighbor resampling process between the original 30-meter DEM and its resampled version. The contours of the respective areas are nearly identical. The contours of the original 3 arc second data show much less detail except for some blockiness in part of the data around 497000 meters east. The blockiness may be due in part to data striping described later.




**STATISTICS**

Min Diff = -15.381 m
Max Diff = 6.260 m
Mean = -0.578 m
Stand. Dev. = 1.979 m

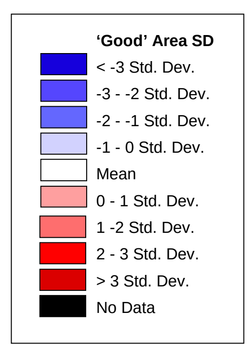
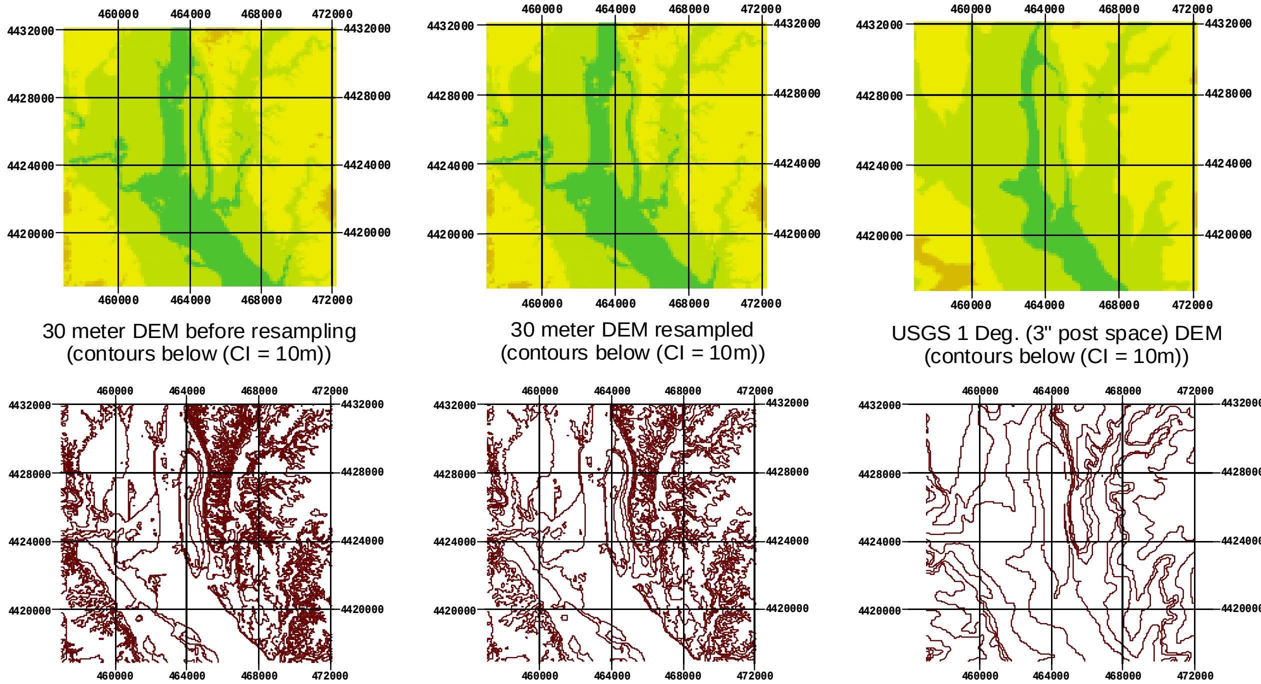



**Figure 8.** 'Good' area results

Figures 9 and 10 show an area with a bit higher range of differences. The contours of the original 30-meter DEM are again nearly identical to the resampled DEM. The 3 arc second (1-degree) DEM shows less detail than the 30-meter as would be expected. It also shows less detail than the resampled DEM at the same spatial resolution. As before, the drainage features are reflected in the difference and standard deviation plots (see Figure 10).




Note the similarities between the 30-meter DEM and the resampled DEM. Although the resampled DEM has less resolution, the contours generated from each database are nearly identical. The resampled DEM and the one degree DEM are sampled at the same interval. However, the resampled DEM retains more detail than the original one degree DEM portrays.

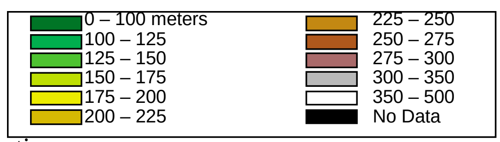



**Figure 9.** 'Good' Area 2 Elevations

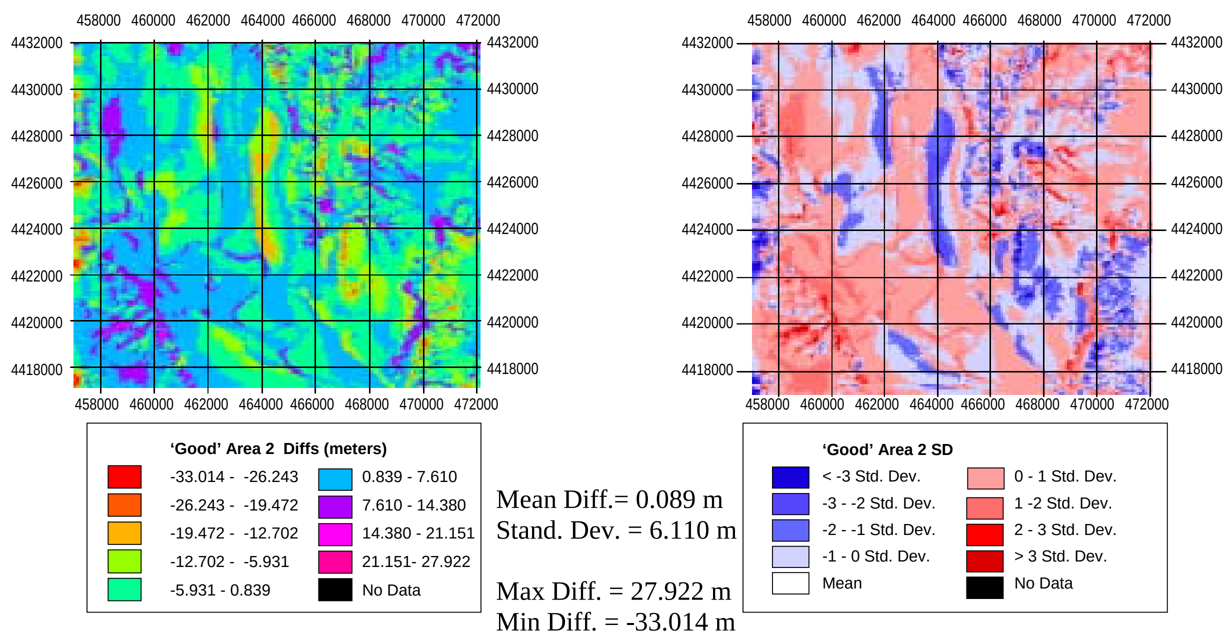



**Figure 10.** 'Good' Area 2 Results

The next test area returned some particularly interesting results. This test covers a hilly area in southern Indiana. Figure 11 portrays a color plot and contours of the area. The contour interval is 40 meters.

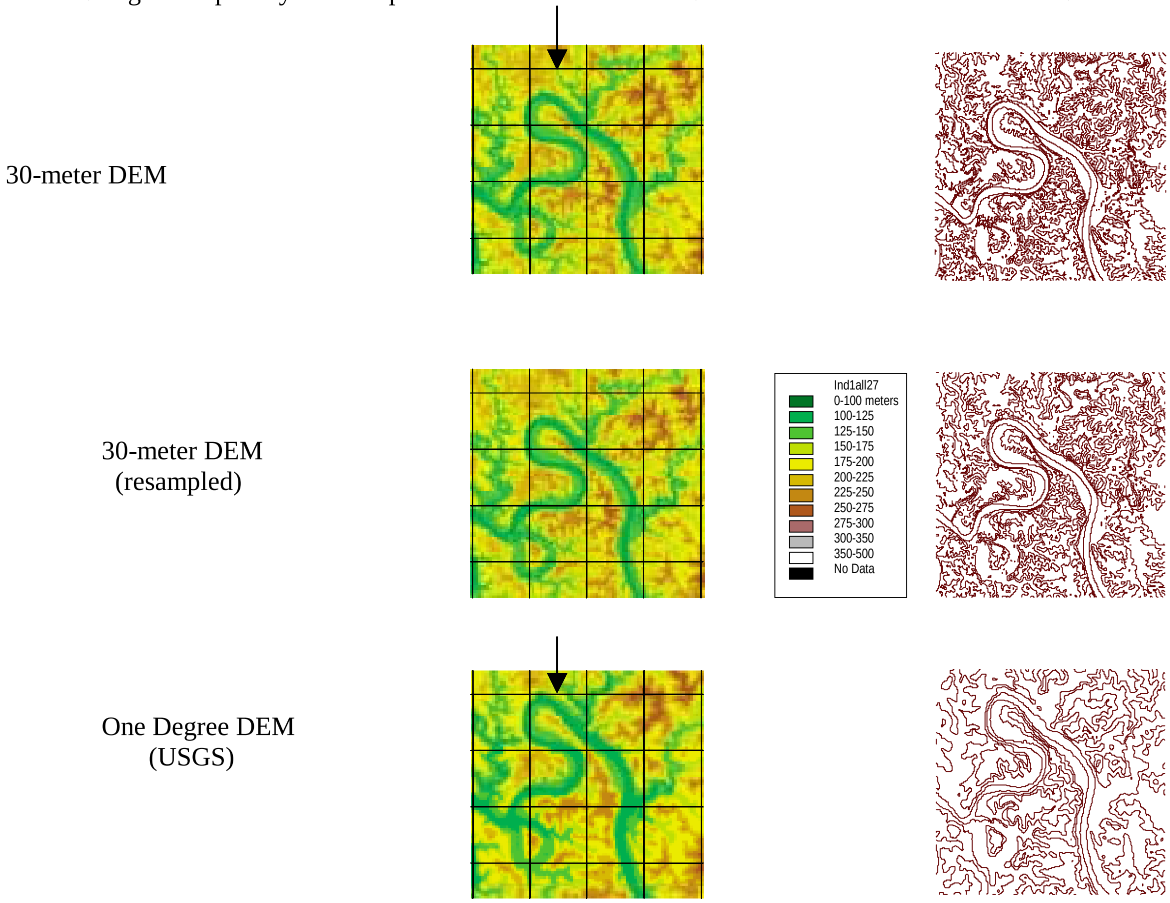



**Figure 11.** Shifted Area Elevations

All areas shown above are shifted approximately *2000 meters* with respect to the 30-meter and the resampled DEM (see arrow). Figure 12 is a plot of the differences and standard deviation of the shifted area.

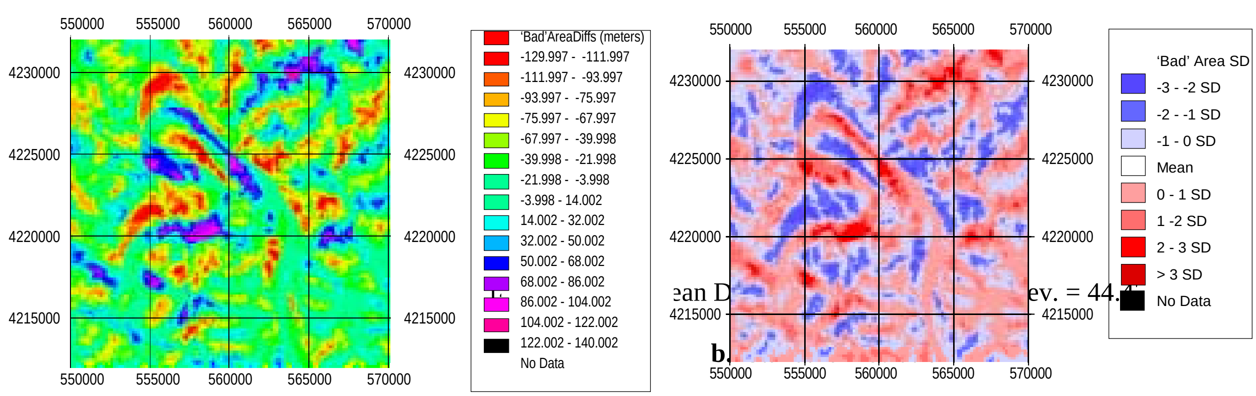



**Figure 12.** Shifted Area Results

Figure 13 shows portions of the previous test area having a difference greater than +/- 44.4 meters or one standard deviation.

The next test areas were chosen based on smoothness or roughness of terrain. The ‘smooth’ area has an overall slope value of < 1%. The slope along the banks of some drainage features may be greater than 1% but are usually less than 10% on the average for short distances. The rougher areas have slopes exceeding 20%.

Statistics for the ‘smooth’ areas are:

Max diff = 13.966 m   Min diff = -17.997 m
Mean diff = -0.101 m   Stand. Dev. = 2.515 m

Statistics for the ‘rough’ areas are:

Max diff = 77.003 m   Min diff = -88.097 m
Mean diff = -1.590 m   Stand. Dev. = 15.560 m

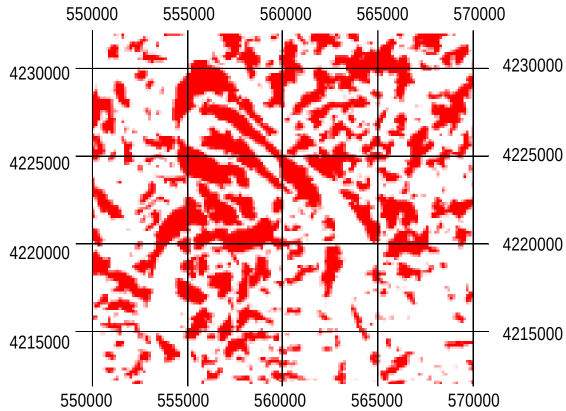



**Figure 13.** Areas > One Standard Deviation

Caution should be exercised when interpreting these results. The areas of the roughest terrain may only appear rough because of a possible shift in the way the data referenced to in Figure 7 was calculated.

The largest (most negative) difference is not found in the area shown in Figure 7. The difference of –413.993 meters is due to a bad elevation in the original level 2 (30 meter) DEM. In the Terre Haute and the Muncie subfiles there were a total of six points found in this study that were grossly in error. Three points in the Terre Haute subfile of the level 2 (30 meter) DEM were found to be over one thousand feet above the surrounding terrain. Each of these points were found to be exactly 2004.568848 feet. This elevation is not possible in Indiana. Likewise, in the Muncie subfile, two points were found to be exactly 3113.479248 feet and one was found to be 2916.631104 feet. Again, these are elevations that are not possible in Indiana and all six points are over one thousand feet higher than the surrounding terrain. Realistically, gross errors at six points out of millions of points in the database is a negligibly small percentage. However, the magnitude of the errors made the points quite easy to detect. Figure 14 shows the location of these six points.

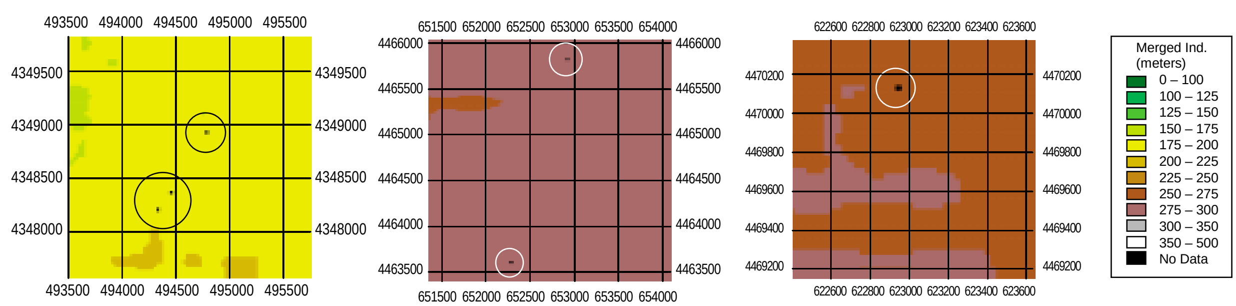
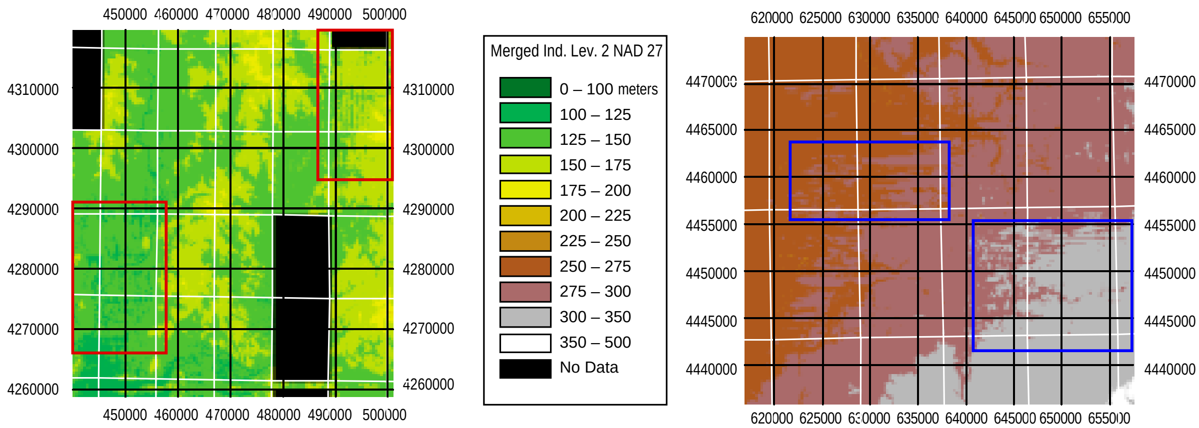



**Figure 14.** Bad Points

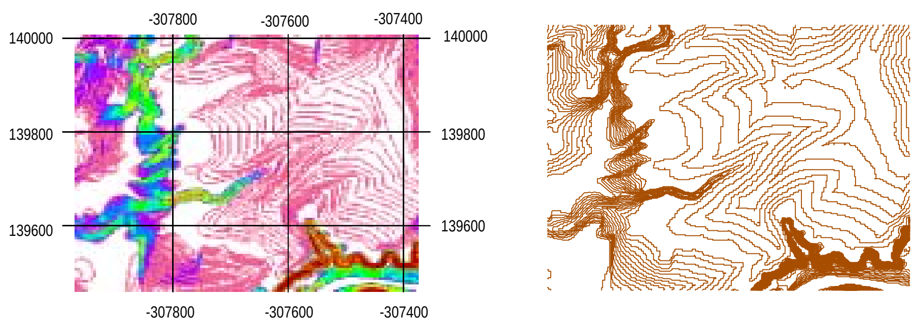
Garbrecht and Starks (1995) report that data striping is related to the DEM production process. Profiles are scanned at a 90 meter separation, and elevations are recorded at intervals depending on the characteristics of the terrain. Sources of error in this profiling are human error and errors in the interpolation algorithm. Human errors can be in the form of different technicians having different perceptions of the ground level. Interpolation errors result from incorrect data values between scanned profiles being generated. This effect is seen in several areas in the resampled DEM. The data along the stripes is recorded in many places as if a constant elevation value was somehow ‘stuck’ along a track. Statistically, the values may or may not have any effect on the data quality. However, data striping does account for easily recognizable errors in the DEM and it causes an unrealistic portrayal of the terrain. Figure 15 shows two highlighted areas where data striping is visible.




Data 'striping' is a processing error characterized by a constant elevation value being digitized into regions of the database that do not make topographical 'sense'. Striping may not cause any statistical problems with the database. However, the physical terrain may not be accurately portrayed. (see red and blue outlined areas). The white lines are the boundaries of the merged topo quads.

**Figure 15.** Data Striping

Guth (1999) reports that contour 'ghosting' is an imprint of the source map contour lines that remain in a DEM after processing. This ghosting phenomenon creates unwanted effects in the distribution of the elevation data. These effects are enhanced in 'derivative' products of elevation data such as slope. Figure 16 shows an example of this effect. The ghost lines from slope are shown as well as a contour plot of the same area. The ghost lines in many portions of the sample slope area have a value of exactly 9.462322 while the slope of the 'white space' is zero.




'Ghost' lines from slope
of USGS 0ne Degree DEM

Contour lines of same area (CI = 2 meters)
(contours thinned and grid removed for clarity)

**Figure 16.** Contour Ghosts

This effect would imply that if the terrain really had a character similar to that shown in Figure 17, contour ghosting would portray the same terrain as shown in Figure 18.

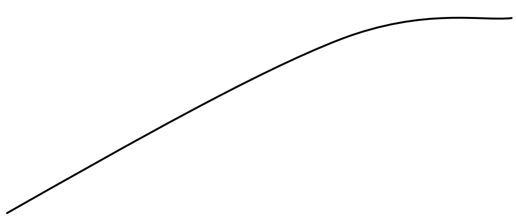


**Figure 17.** 'Normal' Slope

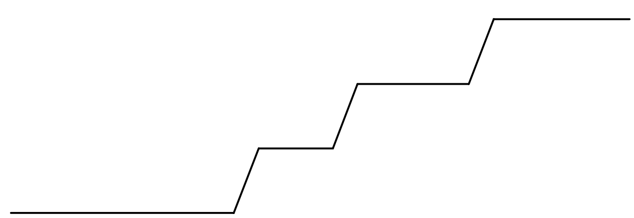


**Figure 18.** Slope Portrayed by Contour Ghosting

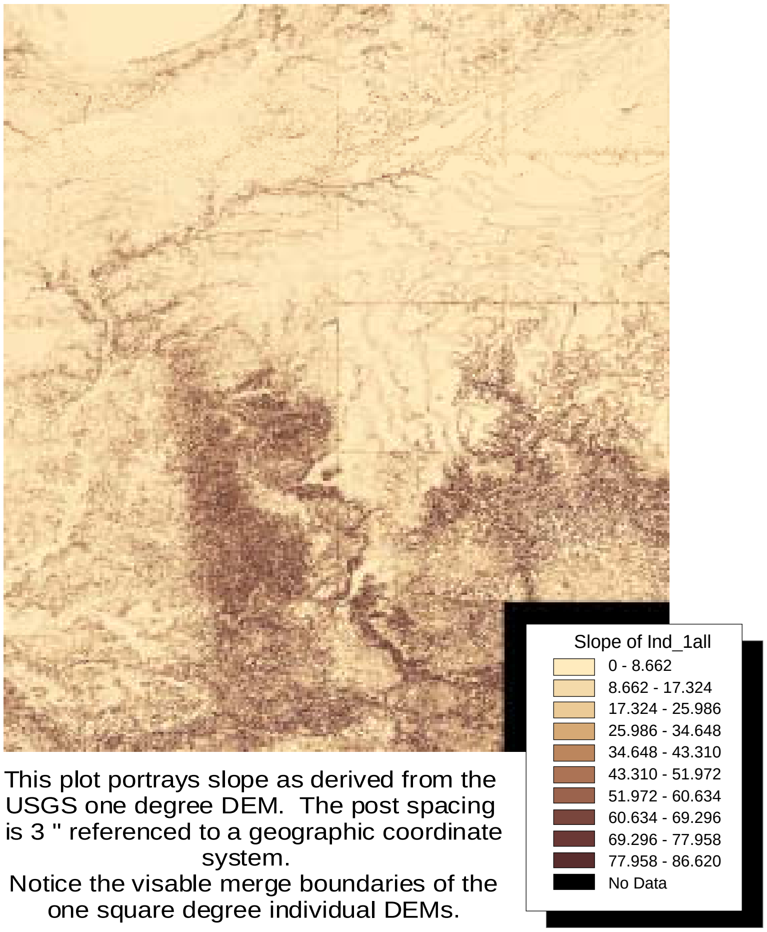



**Figure 19.** One Degree DEM Mismatches

The boundaries of merged 1 degree DEM areas in many places do not seem to display a smooth transition from one cell to another. If the transition or mismatch between cells is severe enough, the effect will show up in a computation of the slope. Figure 19 portrays many mismatches between one degree cells for Indiana.

## SUMMARY

Resampling (by the nearest neighbor method) 30-meter DEM to the spatial resolution of 3 arc second (one degree) DEM retains much of the quality of the original 30-meter DEM before resampling. Contour lines of 30 meter DEM are nearly identical to the contour lines of resampled data. 3 arc second data is smoother or more general in appearance than 30-meter data resampled to the same spatial resolution. Resampled data seems to retain the spatial resolution of the 30 meter DEM while at the same time the DEM file itself is nine times smaller than that of the 30-meter DEM. For the datasets in the study, 85% of the 3 arc second minus resampled 30 meter DEM fall into a standard deviation of 12.6 meters. Sample 'smooth' areas (slope < 10%) reflect a standard deviation of approximately 2 meters, while hilly areas near the Ohio River display standard deviations of 44 meters. These extreme differences should be looked at with caution, however. The pattern or 'texture' of the differences and standard deviations in these statistically extreme regions seem to mimic the terrain that the data portrays.

In portions of the DEM, long horizontal or vertical 'breaks' in texture identify data merging problems between one degree DEM cells. These breaks often correspond to boundaries of combined 7.5-minute topo quad cells.

Common processing errors such as data striping and erroneous data can be found in this 30-meter DEM. Nearest neighbor resampling corrects some of the problems with erroneous data. Contour ghost lines are apparent in the 3 arc second DEM. Computations of slope seem to reflect an unrealistic distribution of elevation data.

Boundary merge mismatches are apparent in the 3 arc second DEM. Production and quality certification processes should be able to easily identify boundary merge errors and allow a smooth transition of elevation data from one cell to the next.

Large errors in the 30-meter DEM data, although very few in number compared to the volume of the entire merged DEM, are easily detectable. Production and quality control processes could be modified so that these 'outliers' are detected and modified by interpolation to conform to the surrounding data.

It would make sense that the precision and accuracy of DEM data could be at least partially dependent on slope or slope variation. Smooth (not necessarily flat) terrain obviously has a small variance in slope. It follows that in order to more accurately portray rougher terrain, the data must have greater accuracy or be of a closer grid or post spacing. This DEM portrays inconsistencies between cells of data that are not related to vertical datum shifts. An investigation of a correlation between terrain slope or slope variation and the precision and accuracy of DEM data will continue with this data set.

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Garbrecht, J., and J. Starks, 1995. Note on the Use of USGS Level 1 7.5 Minute DEM Coverages for Landscape Drainage Analysis, *Photogrammetric Engineering and Remote Sensing*, 61(5):519-522.

Guth, P., 1999. Contour Line "Ghosts" in USGS Level 2 DEMs, *Photogrammetric Engineering and Remote Sensing*, 65(3):289-296.

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Rees, W.G., 1998. The Accuracy of Digital Elevation Models Interpolated to Higher Resolutions, *International Journal of Remote Sensing*, 21(1):7-20.


## OTHER USEFUL WEB SITES

http://abe.www.ecn.purdue.edu/~caagis/tgis/course/gistrc.html
http://danpatch.ecn.purdue.edu/~caagis/ftp/gisdata/data.html
http://164.214.2.59/nima-bin/dted/dted_ovr.cgi?90w60n:60:-90:30:-60
http://edcwww.cr.usgs.gov/glis/hyper/guide/1_dgr_demfig/index1m.html
http://www.usd.edu/esci/geodepts.html
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http://www.pasda.psu.edu/access/dem24klist.cgi?letter=a
http://www.pasda.psu.edu/flash.shtml
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http://www.esri.com/software/arcview/extensions/index.html
http://webhost8.sdvc.uwyo.edu/node/frmSource.html
http://edc.usgs.gov/glis/hyper/guide/7m_dem.supplement (description of 7.5 minute DEM record format)
http://edc.usgs.gov/glis/hyper/guide/1_dgr_dem.supplement (description of 1 degree DEM record format)