AUTOMATING THE CORRECTION OF USGS DIGITAL ELEVATION MODELS USING FOURIER ANALYSIS AND THE MEAN PROFILE FILTER

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ABSTRACT

In the late 1990s, i-cubed, a value-added image processing company, produced a seamless mosaic of USGS 30-meter 7.5-minute digital elevation models (DEMs), known as eDEM. A few years later, USGS created a similar product, the National Elevation Dataset (NED). In assembling the NED, USGS used an innovative technique to remove regular striping and quilting artifacts found in some of the older DEM files. The filter eliminated many problems associated with these patterns while preserving almost all of the high-frequency topographic information. i-cubed advanced the use of this mean-profile filter by using Fourier analysis to identify the existence, interval and direction (horizontal and/or vertical) of striping in each DEM file. The interpretation of the Fourier analysis was completely automated and did not require human intervention. The identified artifact information was then used as inputs to the mean profile filter in the correction of each file. The end result was to be used in a new version of eDEM, known as eDEM-II. This paper presents the methodology and results of this method as used in eDEM-II. Although the inputs to the NED have largely been superseded by newer, higher-resolution, artifact-free DEMs, this research may have practical applications beyond the original purpose.

KEYWORDS: digital elevation model, DEM, Fourier analysis, mean profile filter, striping, quilting, automation

INTRODUCTION AND BACKGROUND

In 1998, i-cubed (information integration & imaging LLC, Fort Collins, Colorado) was contracted by Space Imaging LLC (now GeoEye, Inc.) to create a seamless mosaic of U.S. Geological Survey (USGS) 7.5 x 7.5-minute 30-meter digital elevation models (DEMs). The mosaic was to be filled in with 3-arc-second data wherever 30-meter data was unavailable. This contract presented a challenge, as the available USGS DEMs were not consistent in terms of horizontal datum, vertical datum, vertical units, or precision. Moreover, USGS produced each quad independently, so edgematching artifacts between quads needed to be addressed.

In addition to these inter-file inconsistencies, the intra-file quality of each DEM varied greatly from quad to quad, depending on the creation method, source data, vintage, and other factors. Many older DEM files contained systematic errors, such as “striping,” where a noticeable pattern of undulations occurred in one direction. Sometimes the striping occurred in two directions, in which case a “quilting” pattern could be observed. It was these problems that i-cubed spent the most time in trying to improve upon the original data. One of the main techniques used to smooth out artifacts was a “filter by slope” method, in which lower slopes were filtered – with average and/or median filters – with higher kernel sizes than higher slopes, resulting in the attenuation of bad artifacts over mild terrain and an acceptable preservation of detail over steep terrain. The end result was named “eDEM,” for “enhanced DEM,” a product that enabled Space Imaging to offer high-accuracy, fast response, orthorectified imagery products (Dial, 2011). Subsequently, i-cubed sold this product many times over—in both whole and part, including various derived products—to numerous customers throughout the United States.

A few years later, USGS came up with its own DEM mosaic, called the National Elevation Dataset (NED). The Federal Geographic Data Committee (FGDC) instigated the creation of NED when it identified elevation as a commonly needed geographic dataset for geospatial users in the United States as part of the National Spatial Data Infrastructure (NSDI). The goal of NED was to reduce the compilation time required to assemble digital elevation data over areas larger than a 7.5 x 7.5-minute quadrangle. Like eDEM, NED was produced with a consistent projection (geographic), horizontal datum (NAD83), vertical datum (NAVD88), and resolution (1 arc-second). In addition, NED was assembled from the best available data, with updates incorporated on a bi-monthly basis. Also like eDEM, edges were adjusted to match seamlessly across quad boundaries. Finally, NED incorporated an algorithm for striping artifact removal known as the “mean profile filter” (Gesch et al., 2002). Currently, there are several different levels of NED, including 1/3 arc-second for all of the conterminous United States and 1/9 arc-second data for several select areas (USGS, 2011).

While the NED was being developed in the early 2000s, i-cubed was also endeavoring to improve upon the eDEM using techniques learned from the original process, in addition to some new ideas gleaned from the NED creators. This new product, known as “eDEM-II,” would include many enhancements, including lake leveling, directional filters along edge boundaries, floating-point 32-bit output, and coastline detail preservation. In particular, the mean profile filter was incorporated into this new product as a way to focus on the specific problems of striping and quilting without degrading useful elevation information in flatter areas, which was one the major shortcomings of the original “filter by slope” methodology.

i-cubed developed the methodology to create eDEM-II in early 2000, but due to the increasing popularity of the NED, the project was canceled. The research that went into the project, particularly regarding the mean profile filter, was nevertheless a worthwhile effort. The rest of this paper details the enhancements to the mean profile filter in pursuit of eDEM-II, in the hopes that it may be a useful contribution to the fields of digital elevation modeling and image processing.

STRIPING AND QUILTING ARTIFACTS IN LEVEL 1 USGS DEMS

Many of the older USGS 30-meter DEMs contain significant striping artifacts. These DEMs are primarily identified as “Level 1,” which indicates that they were created from image correlation or manual stereo profiling of National High Altitude Photography Program (NHAP) or similar photographs (USGS, 1998). The scale of Level 1 photography tended to be around 1:80,000, flown at an altitude of 40,000 feet. When it occurs, the striping is a regular, parallel, undulating up-and-down pattern that is more obvious in flat areas. See Fig. 1 for an example of bad striping in a USGS quad. The source of striping is generally attributed to manual stereo profiling from air photos. Striping artifacts from manual profiling are confined to the horizontal direction, since profiling was done primarily along lines with an east-west orientation. Because the profiling interval varied between 2 and 8 mm, the artifact interval varies from quad to quad (De Sawal, 1996). The RMSE of Level 1 quads is quoted as 7-15 meters (USGS, 1998).

Another category of artifact in Level 1 DEMs is quilting (a.k.a. “gridding”), a bi-directional striping pattern. This is generally caused by the patchwork collection pattern of the Gestalt Photo Mapper II (GPM2), an automated system used primarily in the late 1970s and early 80s (De Sawal, 1996). See Fig. 2 for an example of a quad with bad quilting artifacts. DEMs created this way tend to have artifacts on the order of 500 m x 500 m, which corresponds to the patch size of the GPM2 system (Hunter & Goodchild, 1995). For these quads, we have observed that the horizontal stripes tend to be more prominent than the vertical ones.

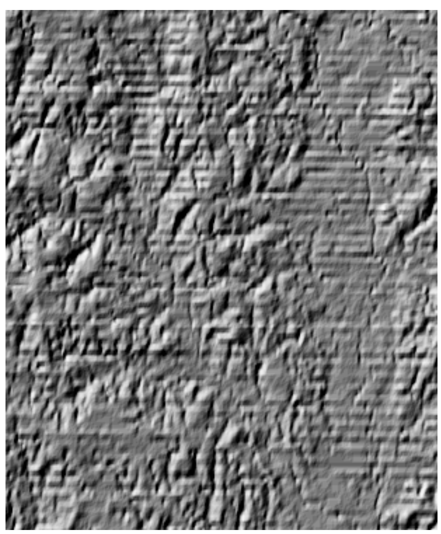

Figure 1. Original quad with bad horizontal striping. Visually observed striping distance = approx. 8 pixels. Quad name: Earlville, AL-MS. Vertical exaggeration: 5X

Figure 2. Bad quilting artifacts in quad created with GPM. Visually observed artifact distance = approx. 16 pixels between both horizontal and vertical stripes. Quad name: Bloomsburg, PA. Vertical exaggeration: 5X.

While a hillshade is an obvious example of the problems associated with striping and quilting, these artifacts are much more than a visual nuisance. Striping and quilting errors tend to be amplified when derivative products such as slope, aspect, contours, or drainage patterns are calculated, in some cases rendering them completely unusable. For example, in flat areas, an average slope derived from a DEM with striping artifacts can erroneously make the area appear to have steep terrain. Such a DEM will also exhibit many more drainage channels—mostly oriented in a horizontal direction—than it actually has (Oimoen, 2000).

In contrast to Level 1 DEMs, Level 2 DEMs lack any of the abovementioned striping and quilting artifacts. These DEMs were derived from hypsographic and hydrographic data using a "contour-to-grid" method, and were edited and smoothed to remove systematic errors. An RMSE of one-half of the contour interval is the maximum allowed for this type of data. Even better results were obtained by including ridge lines and major transportation features, resulting in a Level 3 classification, with a maximum RMSE of one-third of the contour interval (USGS, 1998). It is worthwhile to note, roughly one decade later, that USGS source data for the current version of NED consists primarily of 1/3 arc-second DEMs derived from contour-to-grid techniques with supplementation from higher-resolution LIDAR and digital Photogrammetry (USGS, 2011).

THE MEAN PROFILE FILTER

The mean profile filter was developed by USGS as a way to eliminate the effects of striping and quilting in the Level 1 sources of the NED. The filter consists of three basic steps:

1. Low-pass filter along direction of striping. The kernel size should be large in the direction of striping and small in the direction perpendicular to the striping. For example, if the striping is horizontal, the kernel size may be 25x1. On the other hand, for vertical striping, the kernel size might be 1x25.
2. High-pass of the above, perpendicular to striping. The kernel size should be tied to the striping interval. For example, if the striping is horizontal with a 9-pixel interval between stripes, the ideal kernel size will be 1x9.
3. Subtraction of above from the original elevation data.

When quiting is present, the mean profile filter is applied once to each direction (Oimoen, 2000).

At i-cubed, the initial application of the mean profile filter involved fixed, unweighted kernels. The low-pass filter width was fixed at 31 pixels, based on (Oimoen, 2000). The high-pass filter size was manually determined by an inspection of the pixel interval between artifacts; the nearest odd number would be used as the filter height (since filter kernels must use odd numbers). See Figure 3 for a flowchart showing how i-cubed applied the mean profile filter to a DEM with a horizontal striping interval close to 7 pixels.

The main intervals chosen for the filter were based on observations of many USGS Level 1 DEM files. The most commonly identified intervals were as follows:

- Horizontal striping, 5-pixel interval
- Horizontal striping, 7-pixel interval
- Horizontal striping, 9-pixel interval
- Horizontal striping, 13-pixel interval
- Quilting, 15½ -pixel interval

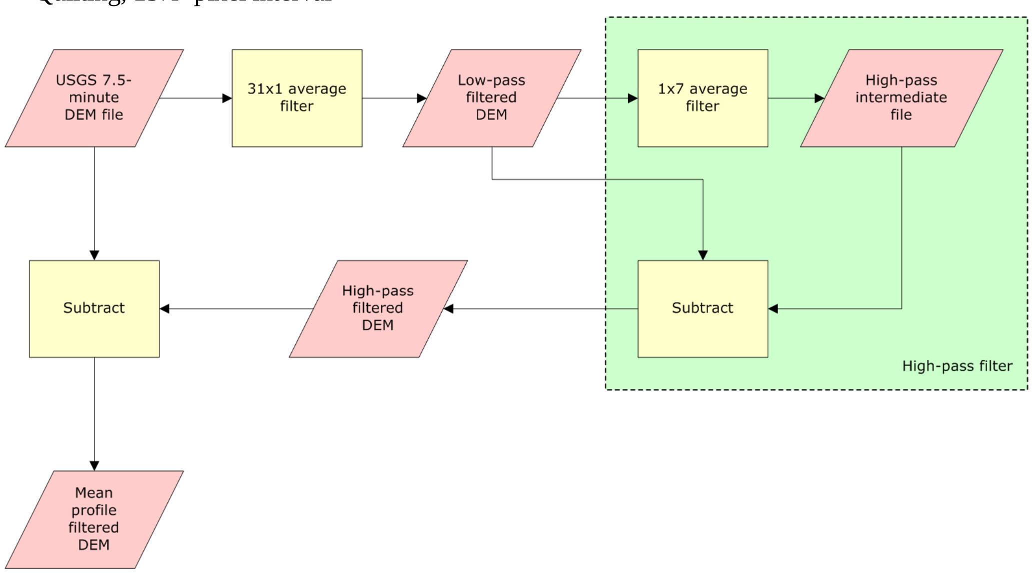

Figure 3. i-cubed's application of the mean profile filter for a 7-pixel horizontal striping interval.

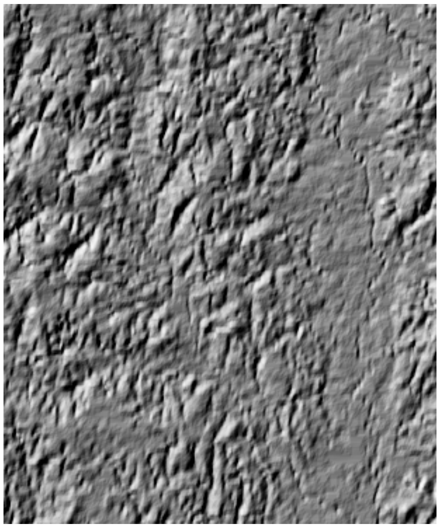

Figure 4. Earlville, AL-MS quad after application of a 9-pixel horizontal mean profile filter. 5X vertical exaggeration.

The variable nature of horizontal striping is understandable, given that the manual profiling interval varied between 2 and 8 mm on the original photographs. At a scale of 1:80,000, with 30-meter pixels, the expected range from these numbers would be anywhere from 5 to 21 pixels, which corresponds well to the range of observed values. Also, the 15½ -pixel (465-meter) quilting interval is roughly equivalent to the 500-meter patch size of the GPM2 system.

Results of the mean profile filter are shown in Figs. 4 and 5. In Fig. 4, a 9-pixel horizontal mean profile filter was applied to the quad pictured in Fig. 1. In Fig. 5, both 15-pixel horizontal and vertical mean profile filters were applied to the quad shown in Fig. 2. Note how the original striping and quilting have been completely eliminated. In Fig. 5, the diagonal orientation of the terrain is now much more obvious than before.

While producing a far better product than the original DEM, there are nevertheless some drawbacks to the mean profile filter. For example, the result in Fig. 4 tends to have a somewhat blocky appearance, leaving it not quite as nice as an artifact-free Level 2 DEM. In order to eliminate this, a minimal low-pass filter (such as a 3x3 average) is sometimes needed. Another problem may be the attenuation of naturally occurring features (especially ridges or valleys) that happen to lie along the direction of the filter. Sometimes the filter removes so much in the direction of application that it almost tends to accentuate features lying at a significant angle to this direction. Yet another problem is that, because it requires an odd filter size, the actual pixel interval may only be approximated in the case of an even number.

A final category of problem arises when the mean profile filter is applied to a DEM that contains flattened lake or coastal data. In these cases, the filter will actually introduce perturbations to the water near the coastline, as well as reduce the effectiveness of the filter on the land side of a coastline. i-cubed solved this problem in eDEM-II by gradually decreasing the low-pass long dimension as the filter gets close to a known water edge, as well as masking out known water bodies from the filter.

FOURIER ANALYSIS AS AN IDENTIFICATION TOOL

Because it changes data values and attenuates natural features in the filter direction, it is preferable *not* to apply the mean profile filter to artifact-free DEMs. With this in mind, i-cubed wanted to develop a methodology to determine whether or not artifacts were present in a Level 1 DEM (since some Level 1 files were fine). A similar question applies to quads produced using GPM2 for the removal of quilting artifacts. Quads without artifacts would be left alone, while those with artifacts would need to be fixed using the mean profile filter.

Another problem was the variable nature of the striping interval. The mean profile filter works best when the long dimension of the high-pass filter roughly corresponds to the striping interval. If the mean profile filter size is too short, some striping will remain. Conversely, if the filter size is too long, excessive data modification may occur. Identification of the striping level present in a file—to the nearest odd number—would help in choosing the most correct filter size for artifact removal. It is still worth noting that the application of the mean profile filter, even with the wrong size, will still result in an improvement over an original artifact-laden DEM file. This is probably what USGS had in mind when it applied the same mean profile filter to all Level 1 quads (Oimoen, 2011).

Acknowledging the limitations of the mean profile filter, i-cubed decided to develop a mechanism to identify the presence, type, and interval of artifact. Moreover, since there were approximately 17,000 Level 1 quads at the time, the identification method needed to be automatable, fast, and reliable.

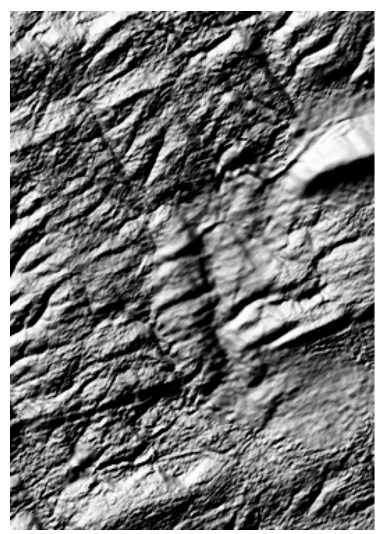

Figure 5. Bloomsburg, PA quad after application of a 15-pixel mean profile filter in both the horizontal and vertical directions. 5X vertical exaggeration.

Fourier analysis seemed to be a promising technique for the identification of striping presence, type, and interval. DEM files with significant artifacts tend to present a set of bright spots on the Fourier diagram that correlate well to the striping interval. For example, Fig. 6 shows the Fourier magnitude transformation of the center portion of the quad from Fig. 1 as a 256x256-pixel image, created using PCI Geomatica (Richmond Hill, Ontario, Canada) software. The bright areas closest to the center along the vertical line are located approximately 31.5 pixels from the center, corresponding to a striping interval of 8.13 pixels (256 ÷ 31.5). This matches the visually observed striping interval of 8 pixels.

On the other hand, a Fourier magnitude transform of the quad with quilting artifacts, such as the one shown in Fig. 2, results in a very regular pattern of bright spots along the primary axes of the quad. See Fig. 7 for an example of this. The distance between the bright spots is approximately 16.5 pixels, which corresponds to a quilting interval of 15.5 pixels (256 ÷ 16.5). Note that the pattern along the vertical axis—which corresponds to horizontal artifacts—is eaily appraent, but a similar pattern is not seen in the horizontal direction. In fact, a similar pattern *does* exist in the horizontal direction, but it requires some manipulation in order to be apparent. This difference in signal strength gives credence to the idea that artifacts from the GPM2 are stronger in the horiztontal direction than the vertical one.

In order to consistently identify artifacts, the Fourier images needed to be refined so as to better highlight bright spots. Accordingly, a process was developed:

1. A generalized high-pass filter (15x15-pixel unweighted kernel) was applied to the source data.
2. Fourier analysis was applied to the above result over a 256x256 window.
3. The ratio of a localized average filter (3x3 kernel) of the Fourier magnitude to a more generalized average filter (15x15 kernel) was generated.

The result of this methodology was an image that highlighted deviations from an artifact-free Fourier pattern. Fig. 8 shows how the analysis of Fig. 6 was refined to the degree that only a few bright spots are visible. Similarly, Fig. 9 shows the corresponding analysis applied to Fig. 7. Here, the regular horizontal pattern is somewhat visible, but still much fainter than the vertical one.

Another interesting thing to note in Fig. 9 is that the axis of orientation of the bright spots is slightly off from vertical. This is due to the fact that quilting and/or striping artifacts were introduced when the quad was aligned with geographic (true) north. Since the digital product is projected in UTM, true north differs from grid north except along the central meridian of the UTM zone. While this slight angular difference is not significant enough to adjust the mean profile filter for, it *is* significant for locating the identifying marker in the Fourier pattern.

i-cubed used the enhanced Fourier methodology to develop an automated system for identifying striping and quilting artifacts. Given the rotation angle of grid north to true north, the predicted location of a bright spot corresponding to a regular interval could be determined. If the spot had an average DN value higher than a certain threshold, it would predict that particular artifact pattern. If not, the spot for the next possible artifact pattern would be checked. For GPM2-created quads, the standard quilting pattern would first be tested, followed by striping patterns. For non-GPM2 quads, only striping patterns would be tested. If none of the known

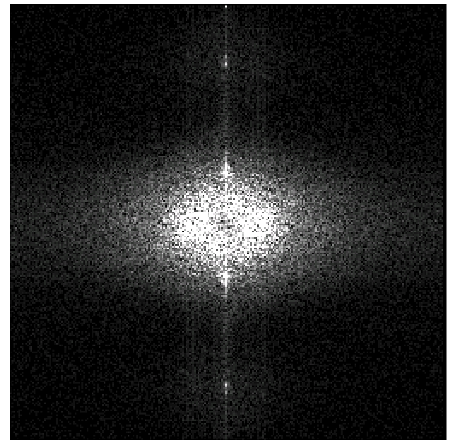

Figure 6. Earlville, AL-MS quad after a Fourier transformation into a 256x256-pixel image. Magnitude displayed.

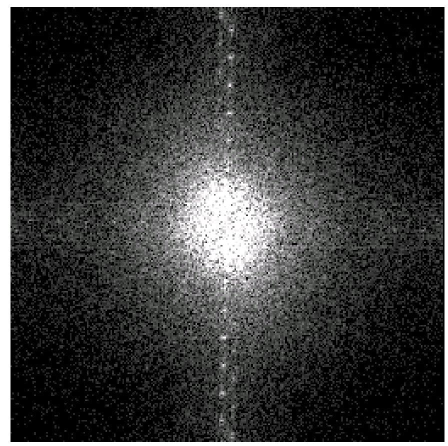

Figure 7. Bloomsburg, PA quad after a Fourier transformation into a 256x256-pixel image. Magnitude displayed. The regular pattern is easily visible in the vertical direction but not in the horizontal direction.

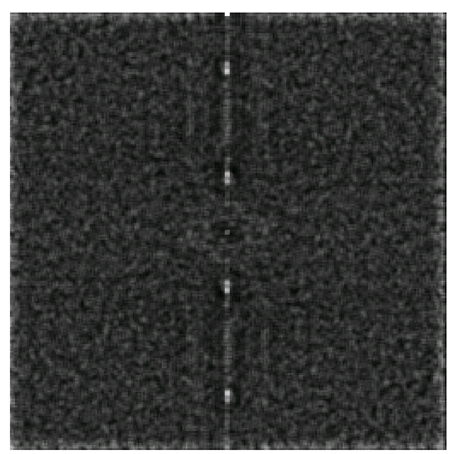

Figure 8. Earlville, AL-MS quad after refined Fourier analysis.

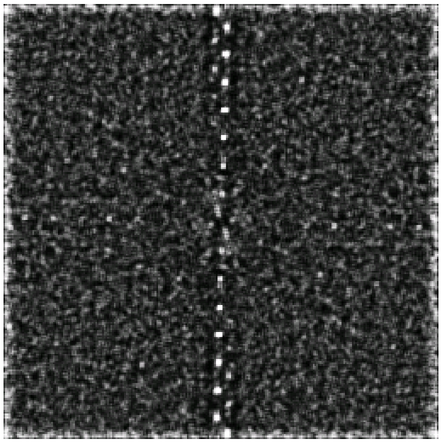

Figure 9. Bloomsburg, PA quad after refined Fourier analysis.

patterns matched, the algorithm would assume that no artifact pattern was present in the quad.

Although editing in the Fourier domain could potentially have been used to de-stripe data, the mean profile filter had already proven itself to be effective for this purpose. The Fourier domain was thus used for pattern identification purposes only. The combination of identification with Fourier analysis, with mitigation via the mean profile filter, proved to be quite successful. It was used to optimize the creation of a high-quality product in the form of eDEM-II.

CONCLUSION

The mean profile filter is a useful, and relatively simple, method for removing regular striping or quilting artifacts in elevation data. The filter is also fairly tolerant of incorrect inputs. However, as shown by this research, identifying the correct interval will produce the most optimal results. We have also shown that interval identification need not be a manual process, as Fourier analysis can be applied to each individual input in an automated fashion. The automation can be straightforward if the raster gridding direction is precisely known, the striping/quilting intervals are regular, and the intervals can be chosen from a limited set of values (as in the case of the USGS DEMs).

Although DEMs are generated using much more advanced methods than they were 30 years ago, the mean profile filter may still be relevant for legacy data. In addition, the filter may be a potentially useful option to de-stripe satellite or other imagery when the striping interval is known and is severe enough to warrant mitigation.

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