ADVANCED TERRAIN PROCESSING: ANALYTICAL RESULTS OF FILLING VOIDS IN REMOTELY SENSED DATA

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ABSTRACT

Void areas are a common and inherent characteristic of remotely sensed data. Voids occur for various reasons in remotely sensed or computationally derived terrain data whether produced, for example, from stereo photogrammetry, LIDAR, or IFSAR. The authors have previously developed and described a comprehensive terrain processing technology, LiteSite® applicable to terrain data produced from diverse sources. In this paper we focus on one key element of LiteSite®, our Terrain Inpainting technology. We provide a brief review of Terrain Inpainting, and discuss typical applications to various types of void fill from diverse sources. In particular, we highlight application to space-based and airborne IFSAR terrain data, and provide recent analytical results. Quantitative analyses are provided which illustrate Terrain Inpainting's unique ability to provide metrics regarding error contribution of data voids to overall data set accuracy. Qualitative results illustrate other benefits such as Terrain Inpainting's unique ability to minimize or eliminate undesirable terrain data artifacts.

Keywords: Terrain, Inpainting, Void, IFSAR, LIDAR

TERRAIN INPAINTING

The LiteSite® software package automates the creation of geospatial products including bare earth Digital Terrain Models (DTM) and image-textured 3D site models. This paper focuses on a core component of LiteSite®, Terrain Inpainting. This technology has been previously described (Kelley, P., et. al., May 2008). Terrain Inpainting provides void fill processing for geospatial data production in areas where information is incomplete. Geospatial products created through digital processing can introduce visible artifacts from void fill and other associated processing. This is most evident for automated product generation, but is also often easily discernable even for products created using highly accurate manual editing techniques. Terrain Inpainting produces minimal artifacts, and at the same time provides a representation designed to be as accurate as possible with quantifiable accuracy. Quantitative assessment and built-in error estimation are vital for the robustness and applicability of Terrain Inpainting

We provide a brief description of the application of Terrain Inpainting to bare earth processing in the next section, followed by a more detailed discussion of its applicability to IFSAR. We will highlight elements of our approach to filling certain eligible source voids in Shuttle Radar Topography Mission (SRTM) data as another example application of Terrain Inpainting. Examples and results shown use the 3 arc-second SRTM data set available for distribution from the USGS. We have also performed Terrain Inpainting post-processing for a large set of 1 arc-second SRTM data using the same approaches described here.

APPLICATION TO BARE EARTH

One of the more common applications of LiteSite's Terrain Inpainting is in the creation of a DTM of an input scene as either a final product or as an intermediate input for further processing (e.g., 3D site model creation or orthomosaic production). During this process, LiteSite® automatically classifies and removes culture and vegetation from the input Digital Surface Model (DSM). LiteSite® is designed to process DSMs created from multiple sources. Primary examples are surface models created from photogrammetry, LIDAR, or IFSAR.

After the completion of the automated bare earth process, LiteSite® outputs a model containing only those points that fall on the terrain surface (see Figure 1). All other points in the input belonging to cultural or vegetation features have been removed. These void areas introduced during bare earth processing must be filled to create a complete DTM.

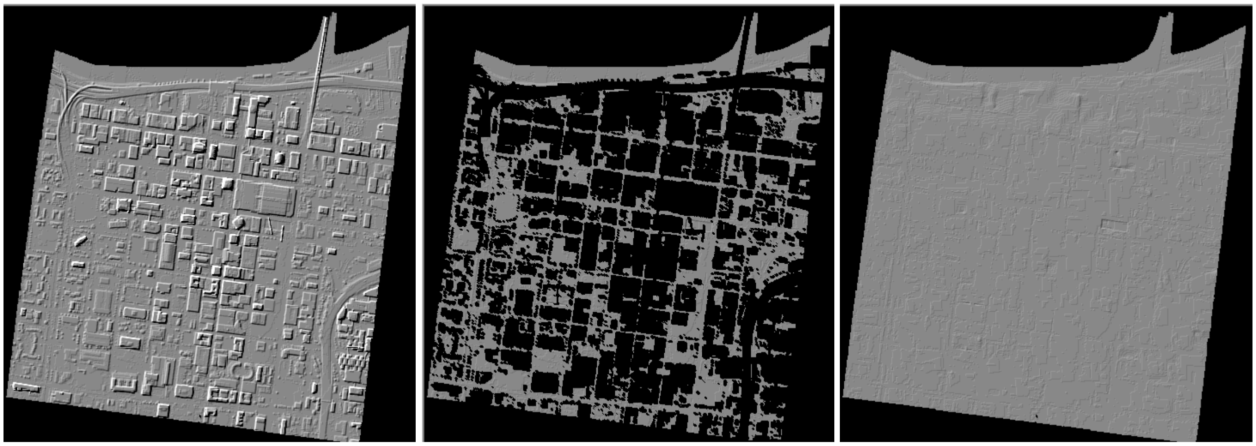

Original Input	LiteSite BareEarth Extraction	LiteSite Terrain Fill Results

Figure 1. LiteSite® Bare Earth Application

Terrain Inpainting provides the void fill processing to complete the DTM product. The example depicted is somewhat straightforward, with fairly flat underlying terrain. There are many more complex and challenging terrain conditions which may include a variety of combinations and densities of cultural and vegetation features with hilly or mountainous terrain. High quality Terrain Inpainting is of greatest value in these more complex terrain conditions.

APPLICATION TO IFSAR

A second category of application of LiteSite's Terrain Inpainting is the reconstruction of voids in the source data itself. This may occur, for example, in DSMs automatically created from imagery due to limited visibility in certain areas or in terrain data sets created from radar. This section presents key elements of the processing flow used by LiteSite® to fill voids in IFSAR terrain data. While the examples used here are SRTM (space-based) IFSAR, we have also successfully applied Terrain Inpainting to airborne IFSAR terrain data with excellent results. We subdivide the presentation of IFSAR processing into four parts describing Preprocessing, Cell Interior Fill, Cell Edge Fill, and Land/Water Void Fill.

Preprocessing

The area immediately surrounding the void region is extremely important for Terrain Inpainting. Radar derived terrain data sets can contain unreliable data near the boundary of void regions. The best results for Terrain Inpainting are achieved when the boundary information is as accurate as possible. The goal of preprocessing is to improve the quality of information in the boundary area by identifying any questionable data bordering the void region. Also, any disjoint "islands" of data that exist inside of radar void regions are also generally questionable.

Before Terrain Inpainting is applied, all questionable points on the void boundaries and interiors are automatically detected by LiteSite®.

Cell Interior Fill

Terrain Inpainting in LiteSite® combines statistical sampling and fill techniques with a partial differential equations based seamless region merge. The result, while compute intensive, is able to adapt to the terrain characteristics of the region currently being filled. This is one of the major benefits to the Terrain Inpainting approach. Terrain Inpainting takes advantage of information from larger portions of the input data set instead of focusing entirely on the small region directly adjacent to the void itself. In doing this, the results more accurately fit into the surrounding scene. Figure 2 shows an example of how this can provide a significant improvement even for relatively flat elevation inputs.

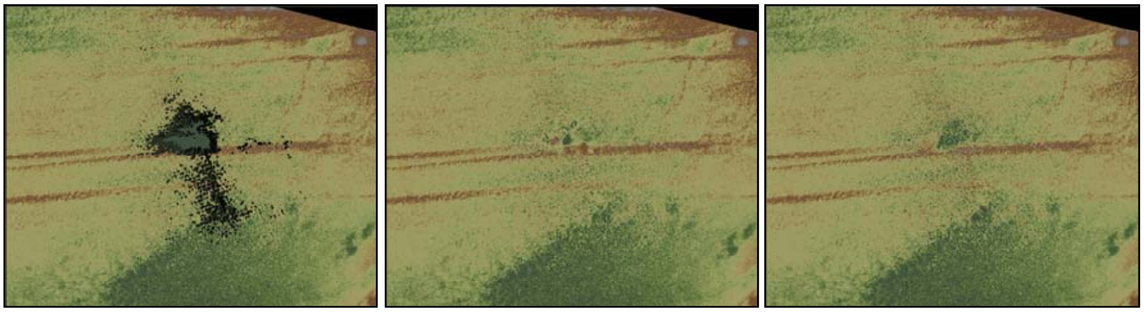


Figure 2. LiteSite® IFSAR Terrain Inpainting Example (Cell Interior Fill)

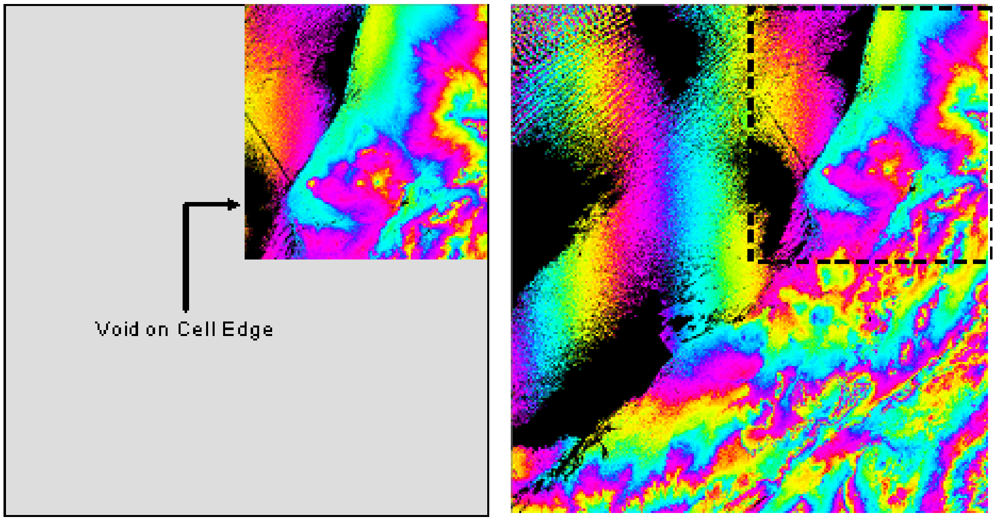
In the process of Terrain Inpainting, we want to balance providing this larger regional context for each void to be filled with a tiling of the data that permits distributed processing. With SRTM, for example, the data are already naturally segmented into one degree cells. We find that the size of a single cell of SRTM is sufficient context to accurately fill most voids. We define *interior voids* as those voids completely inside a given cell or tile of data having no intersection with the cell's boundary. Filling interior voids, which are the majority case, independently on a cell by cell basis provides adequate parallelism for SRTM processing. We have also implemented additional fine-grained parallelism approaches for further subdividing the processing of interior voids within a cell that may be applied if required. The next step is to apply appropriate processing to accurately fill voids that intersect cell boundaries. Voids on cell edges are filled after all cell interiors are filled as discussed in the following section.

Cell Edge Fill

To fill the remaining edge voids, we must combine adjacent cells that have already had interior voids filled. This creates new interior voids in the combined regions from what were previously edge voids. The new voids now also have a larger and more complete informational context from additional neighbor cells and can be filled by the same process described above for cell interior fill. The following summarizes the cell edge fill process:

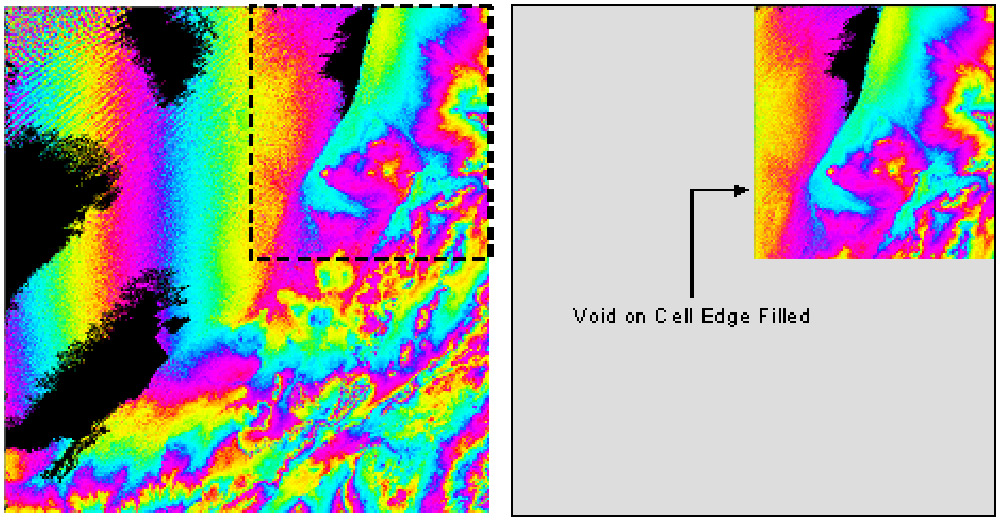
1. For each given cell whose cell interior has been filled, automatically identify and locate adjacent neighbor cells.
2. For each corner of the current SRTM cell being edge filled, merge the 2x2 set of cells surrounding that corner; i.e., the current cell plus three adjacent neighbors, which places the current corner point at the center.
3. For each of the four 2x2 sets of cells created in the previous step, fill every void that is interior to the cell (i.e. has no point touching the boundary of the 2x2 cell) using the same method used previously on the interior regions (see previous sub-section).
4. Make updated results available for subsequent fills.

Figure 3 is an illustration of the cell edge fill process.



Original Input Cell

SW Corner 2x2 Combined Fill Area



SW Corner 2x2 Interior Filled (Across Edges)

Original Input Cell Updated by SW Corner Fill

Figure 3. LiteSite® IFSAR Terrain Inpainting Example (Cell Edge Fill)

The southwest corner of the input is used as the center point of a 2x2 cell set created from the current cell's west, south, and southwest neighbor cells which were automatically determined and located. At this point, the voids that fall interior to this 2x2 cell are filled. This allows for the full set of boundary context to be available to the fill of cell edge voids and allows for the entire edge void region to be filled at one time. Precise edge matching is necessary for SRTM data; each cell must contain redundant border rows and columns populated with the common cell boundary elevation values for its neighbors. LiteSite® Terrain Inpainting provides consistency across cell boundaries, better quality edge void fill due to larger context across cells, and automatically ensures correct edge matching.

By only filling voids that are completely in the interior of the larger 2x2 cell, we purposely defer the filling of voids that fall only partially in this combined area to a subsequent fill step. An example of this is shown in the Figure 3 by the large void region left in the updated results. Leaving this void region unfilled allows for this void to be filled by a later cell created using the 2x2 set of cells around the northwest corner (vs. southwest shown in Figure 3). The only scenario where this approach does not converge is when a void is too large to be encompassed by the largest specified combined area (e.g., an extremely large void that stretches across multiple cells). While these cases would not be likely candidates for an autonomous fill method anyway, they are detected and can be handled as special cases at the end of processing.

Land/Water Void Fill

For IFSAR terrain data sets in general, water bodies are processed separately due to the nature of the data that can be returned from radar where water is present. Water bodies are commonly set to constant heights using additional source information and/or manual processing. In the SRTM data set, for example, major water bodies have been flattened as part of the finishing process. Even with manual processing of the water body areas, it is common to have remaining suspect areas or voids in the terrain on or near the water body features.

We apply Terrain Inpainting to these cases as well. However, voids that share boundaries with water bodies may require additional source for the best fill. For this reason, we automatically detect voids with these characteristics so that they can be analyzed separately or flagged as candidates for additional source fill. By treating them separately, we can also provide an improved default void fill using different fill parameters controlling the Terrain Inpainting.

SAMPLE QUANTITATIVE ANALYSES

LiteSite® builds and applies a statistical prediction model for each given data set type (e.g., SRTM) to allow prediction of error in the cases where voids occur in the source and no truth data is present. The statistical prediction model is able to predict the error characteristic of a specific fill method and provide a measure of confidence in the prediction. Using the constructed model, LiteSite® can provide improved fill results through Terrain Inpainting along with an error prediction on a per void basis in a way that is specific to the fill algorithm itself.

The table below shows the results of two randomly selected cells of SRTM from a group with known truth data. These results illustrate an example of the improvement that can be realized over standard fill methods.

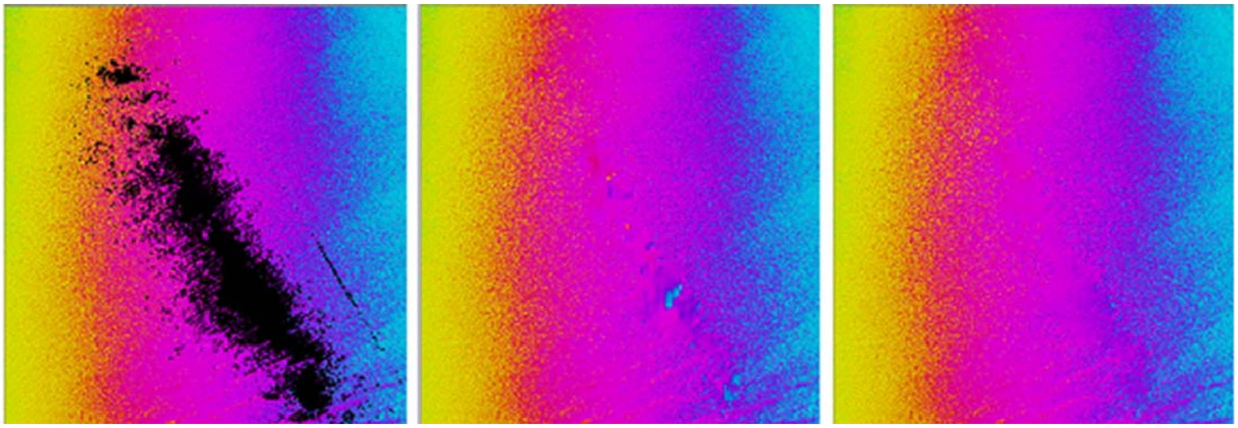
Sample Cell #1		
	Void Region Count	**65**
	Cell-wide RMSE Improvement over Standard Interpolation (meters)	30.1
	Single Void Maximum RMSE Improvement over Standard Interpolation (meters)	132.3

Sample Cell #2		
	Void Region Count	**181**
	Cell-wide RMSE Improvement over Standard Interpolation (meters)	26.1
	Single Void Maximum RMSE Improvement over Standard Interpolation (meters)	31.0

SAMPLE QUALITATIVE RESULTS

LiteSite’s Terrain Inpainting has the capability to adapt to the full input data set provided to it. This also allows for an integrated methodology to be used across multiple data set types. The combination of multiple techniques into a single void fill process allows for superior qualitative output results.

Below in Figures 4, 5, and 6 are sample SRTM cells with void fill from LiteSite’s Terrain Inpainting as well as an interpolated output for comparison. Through the built-in error estimation described in the previous section, we are able to automatically segregate those cells/voids that are processed using Terrain Inpainting at any specified threshold for error tolerance. The cells below are extreme examples where very large portions of a cell contain void areas. Typical production applications would contain much simpler voids selected for automated void processing. The good qualitative performance even in these extreme cases illustrates the power of this approach for void processing for a wide range of applications.

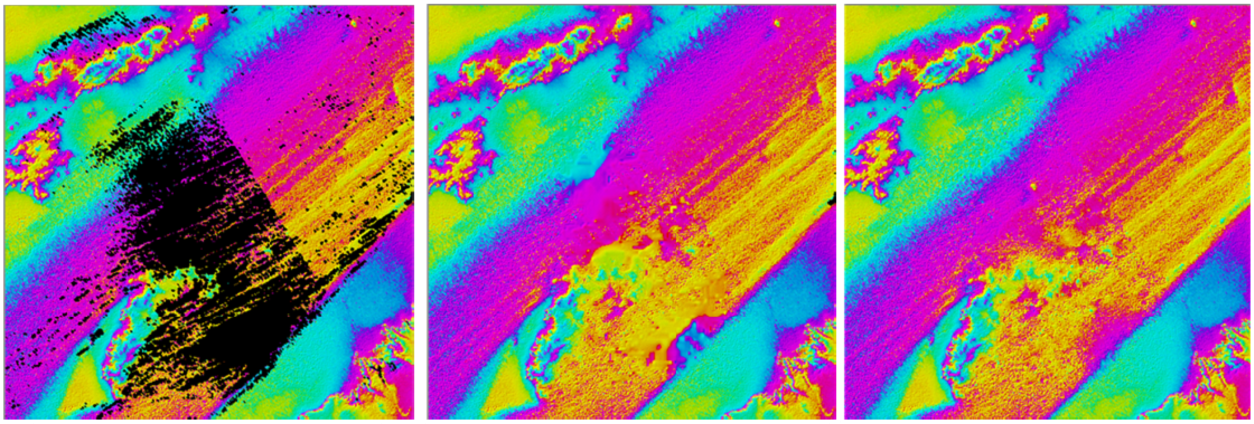


Original Input

Standard Interpolation (Texture Disruption)

LiteSite Terrain Inpainting Results

Figure 4. Sample STRM Terrain Inpainting

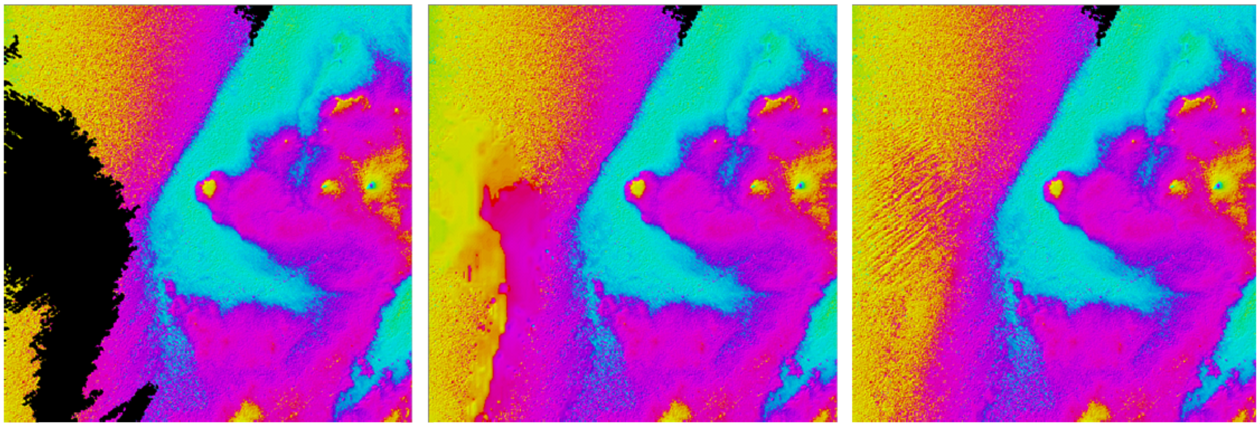


Original Input

Standard Interpolation

LiteSite Terrain Inpainting Results

Figure 5. Sample STRM Terrain Inpainting



Original Input

Standard Interpolation

LiteSite Terrain Inpainting Results

Figure 6. Sample STRM Terrain Inpainting

SUMMARY

In this paper we discussed Terrain Inpainting for voids introduced during processing, such as for bare earth DTM generation, and for voids existing inherently in source data such as IFSAR. The latter case was discussed in some detail using SRTM data as an example case where this type of processing has been performed. The production processing flow presented displays Terrain Inpainting's ability to automatically fill voids using only the original source data at hand and in a way that both mitigates and quantifies error, and creates minimal processing artifacts.

ACKNOWLEDGEMENTS

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REFERENCES

Kelley, P., Yates, J. H., Rahmes, M. D., Allen, J., "Seamless Exemplar Inpainting Method Using Poisson Merging and Normalization for Terrain Void Filling", *ASPRS*, May 2008