NEON ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD): CAMERA MOSIAC

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1   DESCRIPTION

The AOP surveys each NEON site once per year. Each survey collects as many as 8000 individual RGB digital images. The raw images are orthorectified as described in RD[03]. This Algorithm Theoretical Basis Document (ATBD) describes the algorithm used to mosaic the individual orthorectified images to a single image and to a set of mosaic tiles.

1.1   Purpose

This ATBD describes the theoretical background algorithm used to create the image mosaic from the individual images.

1.2   Scope

The theoretical background and entire algorithmic process used to derive the Level 3 mosaic images from the Level 1 individual images is described in this document. This document does not provide computational implementation details.

2   RELATED DOCUMENTS, ACRONYMS AND VARIABLE NOMENCLATURE

2.1   Applicable Documents

AD[01]	NEON Scientific Data Products Catalog: http://data.neonscience.org/data-product-catalog

2.2   Reference Documents

RD[01]	NEON.DOC.000008	NEON Acronym List
RD[02]	NEON.DOC.000243	NEON Glossary of Terms
RD[03]	NEON.DOC.001211	NEON Digital Camera Image Orthorectification ATBD
RD[04]	NEON.DOC.003652	NEON AOP Digital Camera Orthorectification Level 1 Processing Procedure
RD[05]	NEON Tech Note	TN-2016-08-17-WG-README_for_NEON_Camera_Images
RD[06]	NEON Field Sites	NEON field sites as lists, maps, shape files and kmz's

Note: NEON documents can be found in https://data.neonscience.org/documents

2.3   External Documents

ED[01]	Google Earth: https://www.google.com/earth/
ED[02]	IDL: http://www.exelisvis.com/ProductsServices/IDL.aspx

2.4   Acronyms

Acronym	Explanation
AOP	Airborne Observation Platform
ATBD	Algorithm Theoretical Basis Document
CI	NEON Cyberinfrastructure
DEM	Digital Elevation Model (generic term for DSM or DTM)
DSM	Digital Surface Model (elevation of the surface including trees, buildings, etc. above sea level)
DTM	Digital Terrain Model (elevation of the bare earth above sea level)
DICAM	Digital Camera
DP	Data Product
L0	Level 0: raw data as recorded by the instrument. Here: raw images.
L1	Level 1: data that has been calibrated to engineering units. Here, color balanced, exposure corrected and orthorectified images.
L2	Level 2: Processed L1 data from a single data stream. There are no image L2 products
L3	Level 3: A data product derived from multiple data sources and/or over multiple time periods. Here, image mosaics.
LOS	line-of-sight
QA/QC	Quality assurance and quality control

Acronym	Explanation
RGB	RedGreenBlue: refers to a 3-band image approximating what the human eye sees

2.5   Variable Nomenclature

This section is not applicable for this algorithm: no variables are referenced.

3   DATA PRODUCT DESCRIPTION

3.1   Variables Reported

The data products reported here are mosaicked images tiles (NEON.DOM.SITE.DP3.30010).

3.2   Input Dependencies

Table 1 details the AOP digital camera (DICAM) related L1 DPs used to produce L3 DICAM DPs in this ATBD.

Table 1. List of the AOP L1 Products Used to Create the L3 Image Mosaic.

Description	Sample Frequency	Units	Data Product Number
Orthorectified images	Once per survey	NA	NEON.DOM.SITE.DP1.30010.001 http://data.neonscience.org/data-product-view?dpCode=DP1.30010.001

3.3   Product Instances

The digital camera is part of the AOP instrument package. Most core and gradient sites are surveyed once per year at 'peak greenness'. See the following like for the survey schedules:
https://www.neonscience.org/data-collection/flight-schedules-coverage.
There may be other surveys including the aquatic sites and assignable-assets surveys.

3.4   Temporal Resolution and Extent

Each site is surveyed nominally once per year. One camera image mosaic is produced each year for each site.

3.5   Spatial Resolution and Extent

The mosaic is created at 0.10-meter resolution. The mosaic extends over the entire flight box, typically at least 10 km by 10 km.

4   SCIENTIFIC CONTEXT

The NEON Airborne Observation Platform (AOP) contains three sensors: a hyperspectral imager (**N**EON **I**maging **S**pectrometer (**NIS**), a waveform lidar and a digital RGB camera. The principal instruments are NIS, which is used to determine state of vegetation, and the lidar, which is used to determine canopy height and elevation changes. Both the NIS and the lidar data are processed to 1-meter spatial resolution. The camera images, which are processed to 0.1-meter resolution, are used to provide context to the NIS and lidar data: there are no other scientific products derived from the images. **Figure 1** shows a sample orthorectified image, taken from the site Blandy Experimental Farm, Virginia (BLAN) in NEON Domain 2 in 2016. (For a complete list of NEON sites and abbreviations, see RD[06].)

Figure 1. An orthorectified image from BLAN in 2016. The black border around the image represents no-data.

Figure 2 shows a typical flight pattern: here the plane flies a series of N-S passes (called flight lines) designed to cover the Blandy Experimental Farm site. The flight lines are designed to provide 30% overlap in the camera images between adjacent lines (sidelap). The camera frame rate is set to provide 50% overlap between sequential images. There may be other diagonal and E-W flight lines used for calibration purposes. The images from these later flight lines are typically not included in the mosaic.
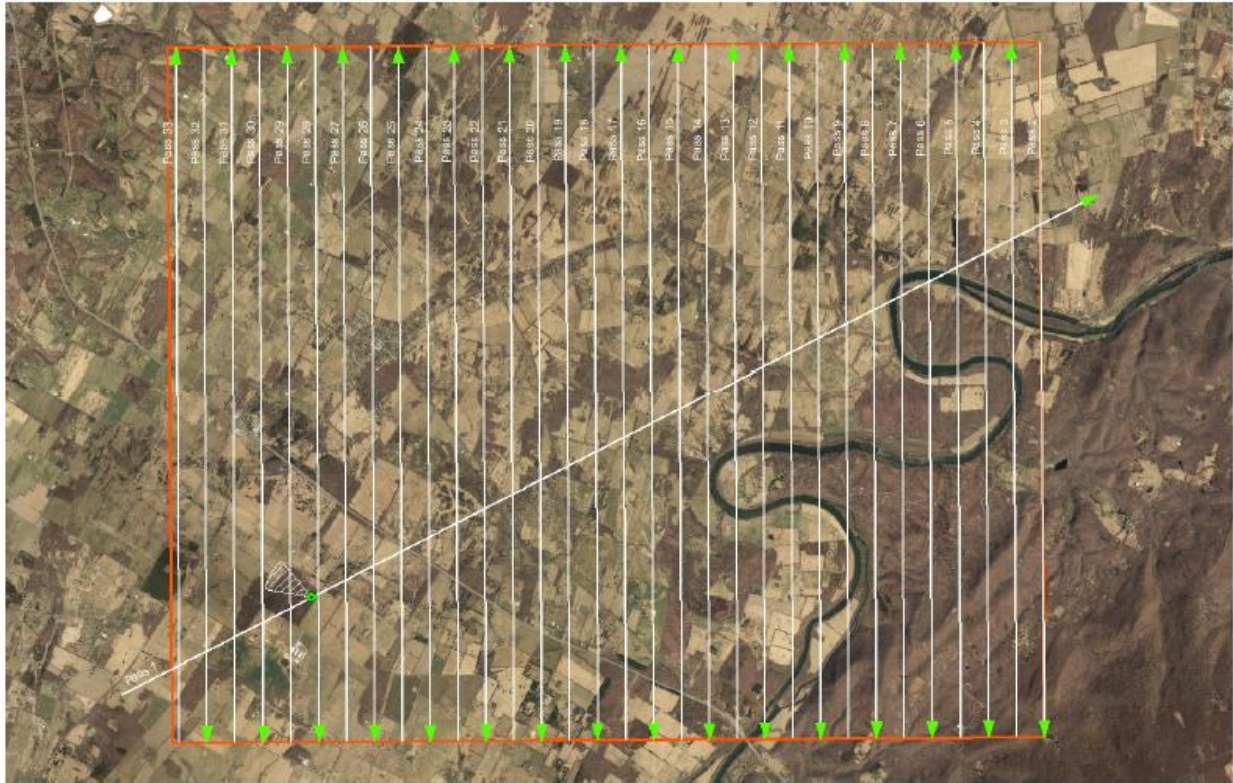
Figure 2. Flight lines for the site Blandy Experimental Farm in Domain 2.

The camera images give context to the hyperspectral images: they show individual trees, surface features and backgrounds at ten times the spatial resolution of the hyperspectral images. However, using the individual images is difficult because of their large number: the survey for a single site may contain 8000 individual images taken over as many as five different days. Individual camera images taken over BLAN are shown in **Figure 3**.
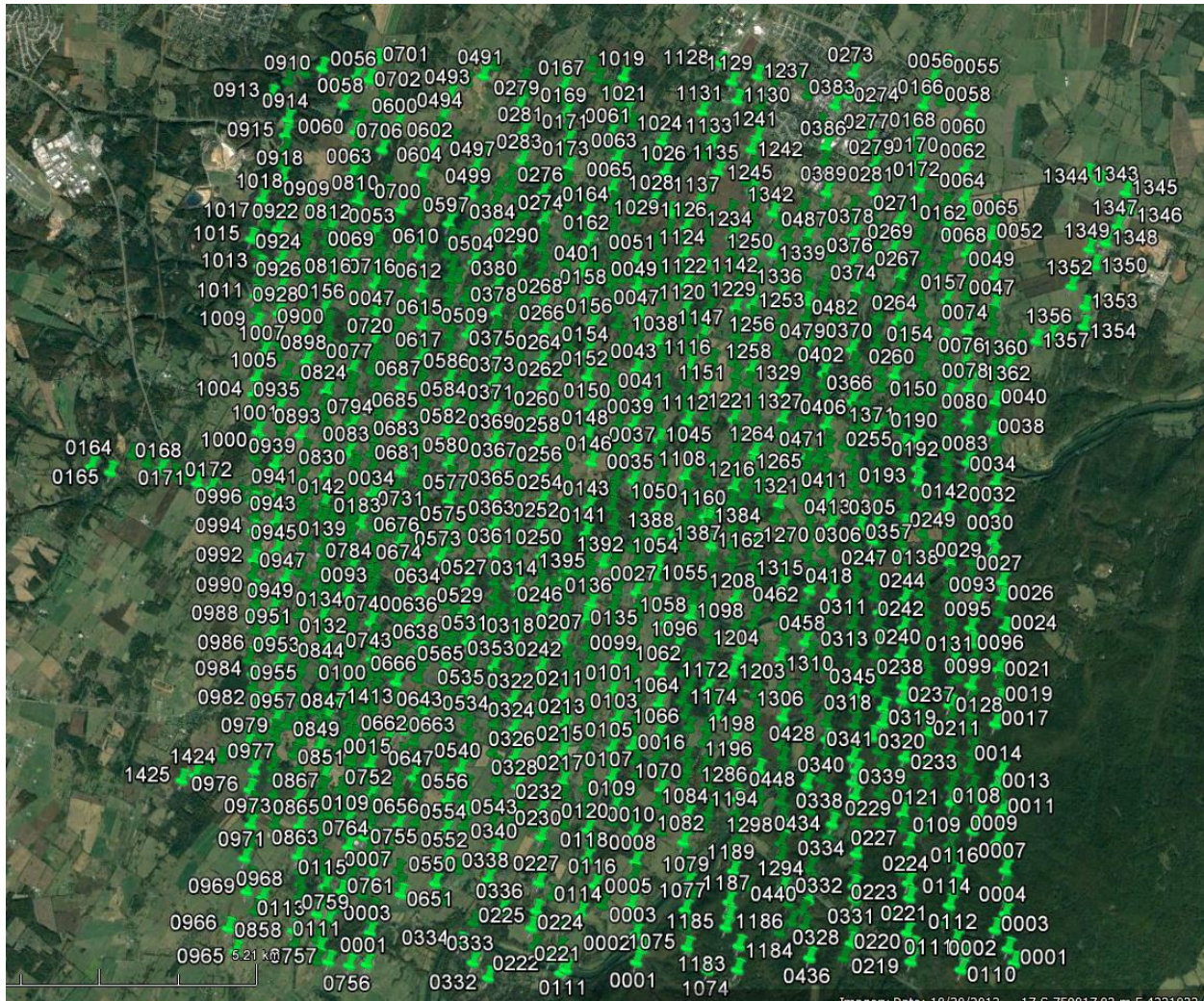
Figure 3. A screen shot from Google Earth showing the locations of all the images (green pushpins) taken over Blandy Experimental Farm in 2016.

Mosaicking is the process of combining the individual overlapping images to form a single seamless image. **Figure 4** overlays eight sequential images from BLAN that will be combined to make part of the mosaic.

Figure 4. An overlay of eight of the individual images contributing to the tile shown in **Figure 6**.

However, the full mosaic image may be as large as 40 GB and is typically too large to view conveniently. Tiling is the process of dividing a mosaicked image into smaller adjacent images, typically 1 km by 1 km tiles. **Figure 5** shows a low-resolution (5-meter) version of the full mosaic for BLAN plus the boundaries of the tiles making up the mosaic displayed in Google Earth.

Figure 5. A low-resolution mosaic of the site BLAN showing the boundaries of the tiles (in red). The image is displayed in Google Earth that provides the background. The pushpins identify the individual tiles.

Figure 6 shows one mosaic tile from BLAN. The boundaries between the regions filled in by the different contributing images are seen as differences in contrast. The red arrows point to some of these boundaries. The contributing images may come from different flight lines (N-S vs S-N), at different times (different solar zenith angles) and different days (different cloud/haze conditions.) The different lighting and viewing conditions lead to contrast differences at the image boundaries.
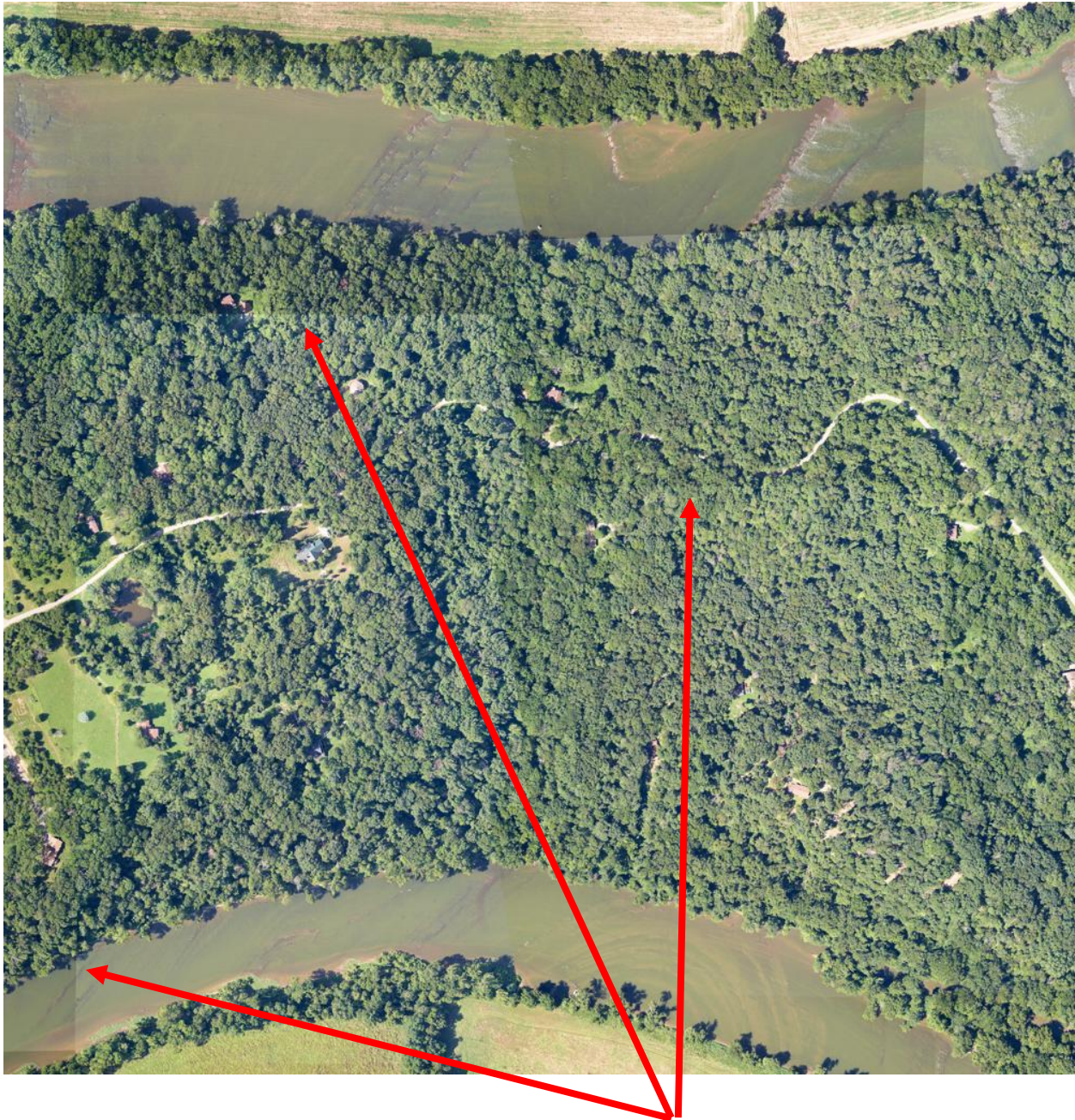
Figure 6. A 1-km-by-1-km mosaic tile from the site BLAN. The boundaries between the images contributing to the tile can be seen as faint lines of contrast.

The orthorectification process uses a digital terrain model (DTM) with a 1.0 meter resolution to locate image pixels on an 0.1 meter grid. This mismatch in resolution can lead to distortions in the orthorectified image by locating an object either above or below where it should be. The effect depends strongly upon the zenith angle of the LOS at the ground: it is negligible for a vertical LOS and can be severe at the edge of an image where the zenith angle can be 30 degrees or more. Typical distortion effects can render straight lines (street edges, roof tops) as curved, tall object (trees, poles) appear to

lean away from the center, and tree canopies appear swirled. **Figure 7** shows an example of these effects.

Figure 7. Distortions at the edge of an image caused by the mismatch between resolution of the DTM (1 meter) and that of the images (0.1 meter).

The mosaicking process minimizes these effects by selecting for inclusion in the mosaic image the pixel from the overlapping images with the smallest zenith angle.

4.1   Theory of Measurement

The measurements here are the individual orthorectified images. The process of orthorectification is described in the camera orthorectification ATBD RD[03]

4.2   Theory of Algorithm

4.2.1   Overview

The process of creating the mosaic is broken down into the following steps:

1.   Select the images to be included in the mosaic
2.   Create zenith files which include the zenith angle of each pixel in each image
3.   Create a set of tiles boundaries
4.   Fill in the tiles with the pixels from the overlapping images with the smallest zenith angle.
5.   Create a kmz for the display of the mosaic properties in Google Earth

4.2.2 Detailed Steps

4.2.2.1 Select the Images

For the mosaic, it is preferable to use only images that fall along the N-S flight lines and avoid images on diagonal or E-W flight lines. **Figure 8** shows the location of all the images for BLAN that are within the DTM. In this figure, images corresponding to aircraft headings outside of ±20 degrees of N-S are colored red and are not used in the mosaic.
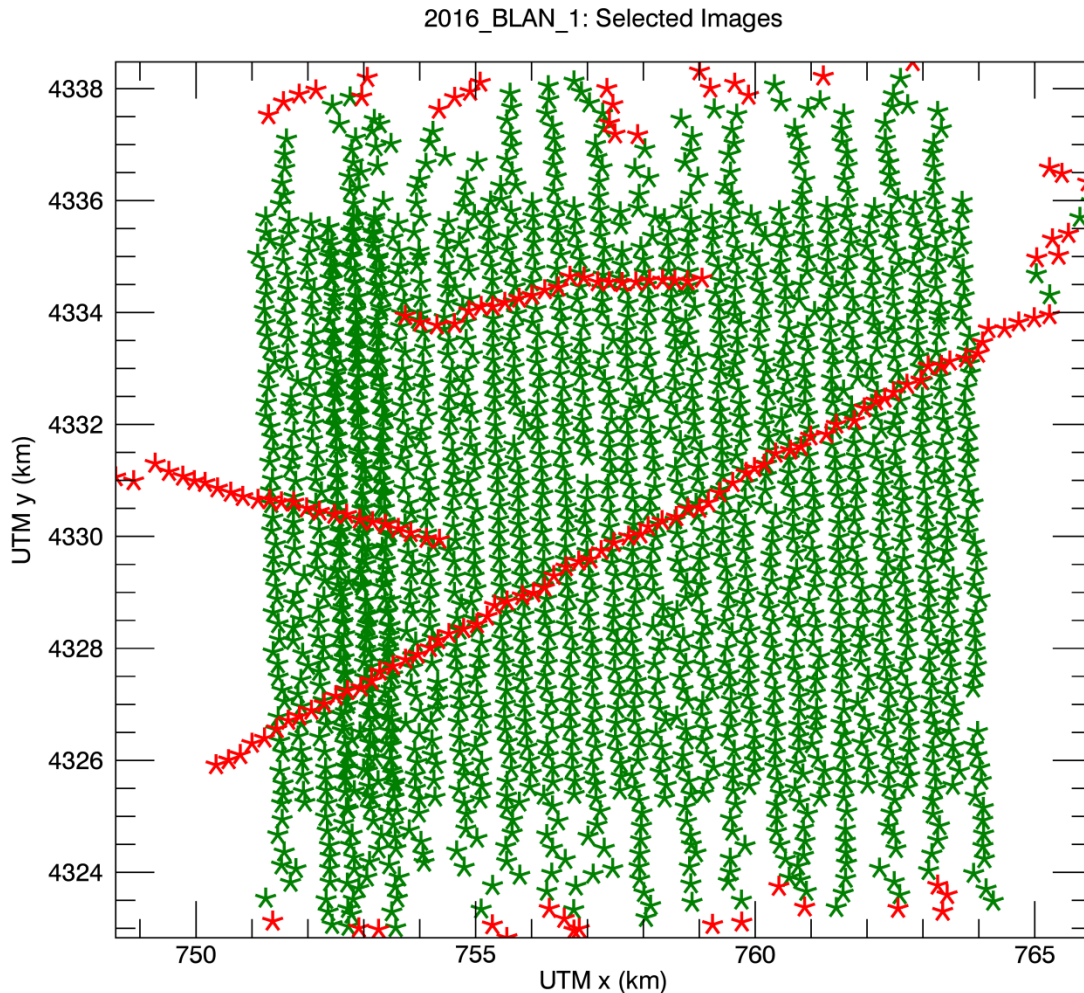

Figure 8. Plot of the center locations of the images for the site BLAN in 2016 with selected images in green and rejected images in red.

4.2.2.2 Create the Zenith Files

For each image file, create a file that contains the off-zenith angle of the line-of-sight of each pixel at the ground. Note: for the geometry considered here (AGL less than 1.5 km, LOS off-nadir angle at the aircraft less than 40 degrees), the difference due to refraction and the curvature of the earth between the LOS zenith angle at the aircraft and the zenith angle at the ground is negligible. A false color image of one of these files is shown in **Figure 9**. The 0 degree zenith angle spot is not located at the center of

the image due to the geometry of the collection including aircraft attitude, air turbulence, and the boresight alignment angle of the camera relative to straight down. These files are used to determine which image pixels are used to populate the mosaic image.
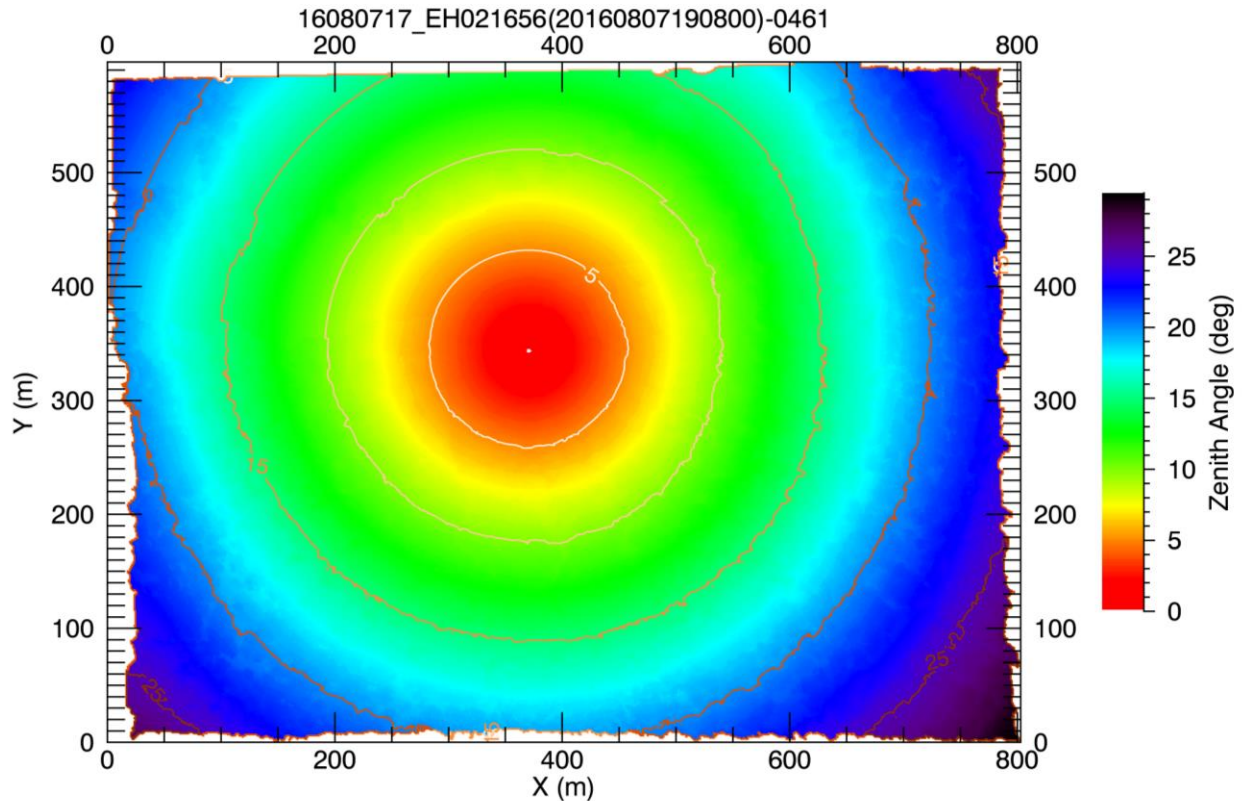

Figure 9. Contour plot of the LOS zenith angle for a representative image.

4.2.2.3   Create the Tile Boundaries

The maximum extent of the mosaicked image is determined from the files selected in the previous step. This extent is expanded to fall on even 1 km UTM boundaries. The 1 km by 1 km mosaic tile boundaries are extracted from this overall extent. This process may include tiles along the outer boundary that do not actually include any overlapping images: these no data tiles are deleted. **Figure 10** shows the outlines of the tiles for BLAN 2016, as displayed in Google Earth.
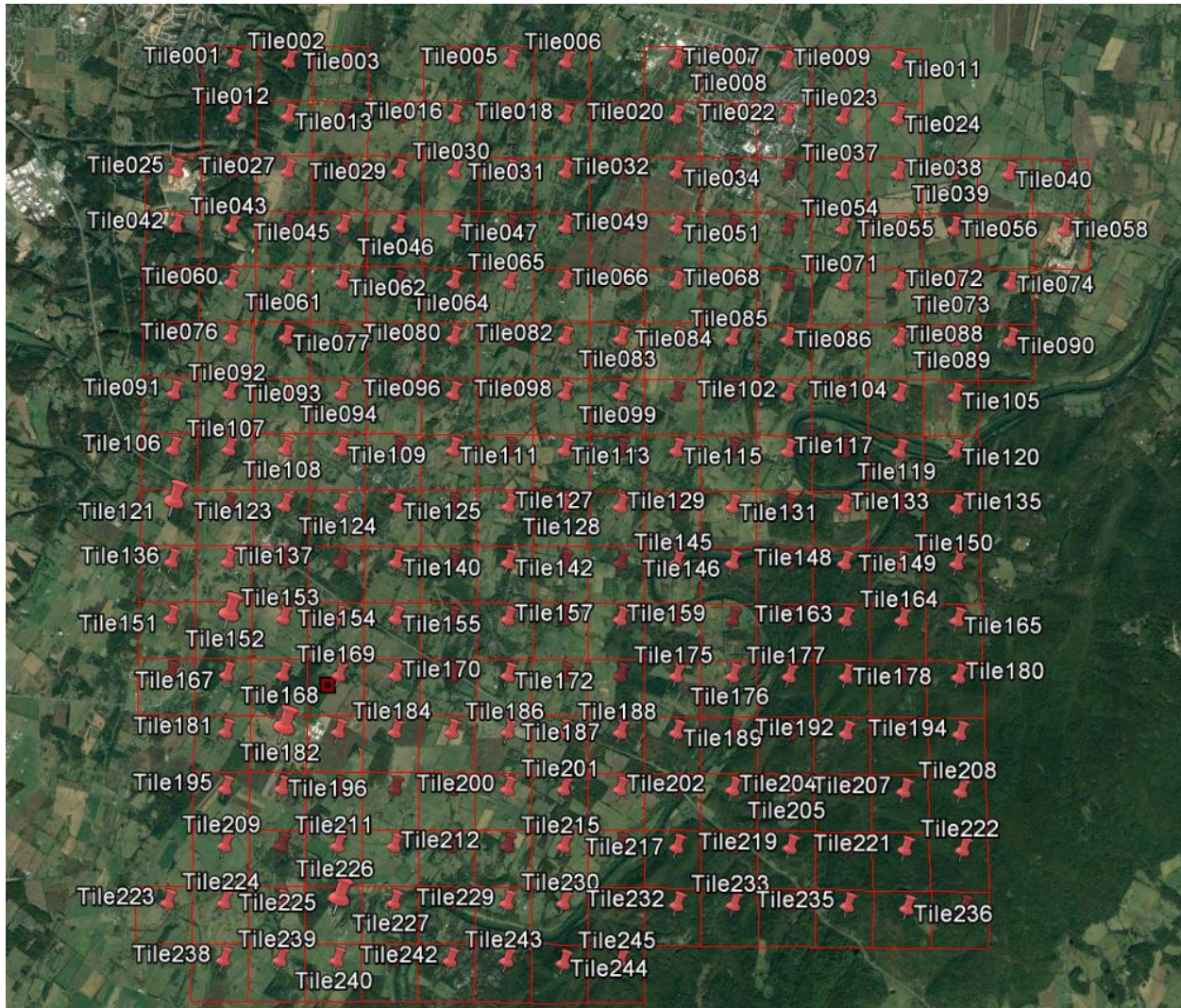
Figure 10. Plot showing the outlines of the tiles for BLAN 2016, as displayed in GoogleEarth.

4.2.2.4 Fill in the Tiles
For each tile, the process is as follows:

1. Find all the individual images that overlap the tile
2. For each tile pixel, use the image pixel with the smallest zenith angle to populate the tile pixel.
3. Create a 5-meter resolution browse image of the full mosaic. This image is used for reference and for quality assessment. **Figure 14** shows this image for BLAN 2016.

Figure 11 shows the regions occupied by each of the 23 images that contribute to tile 0146. Some images may overlap the tile but not contribute pixels to the tile.

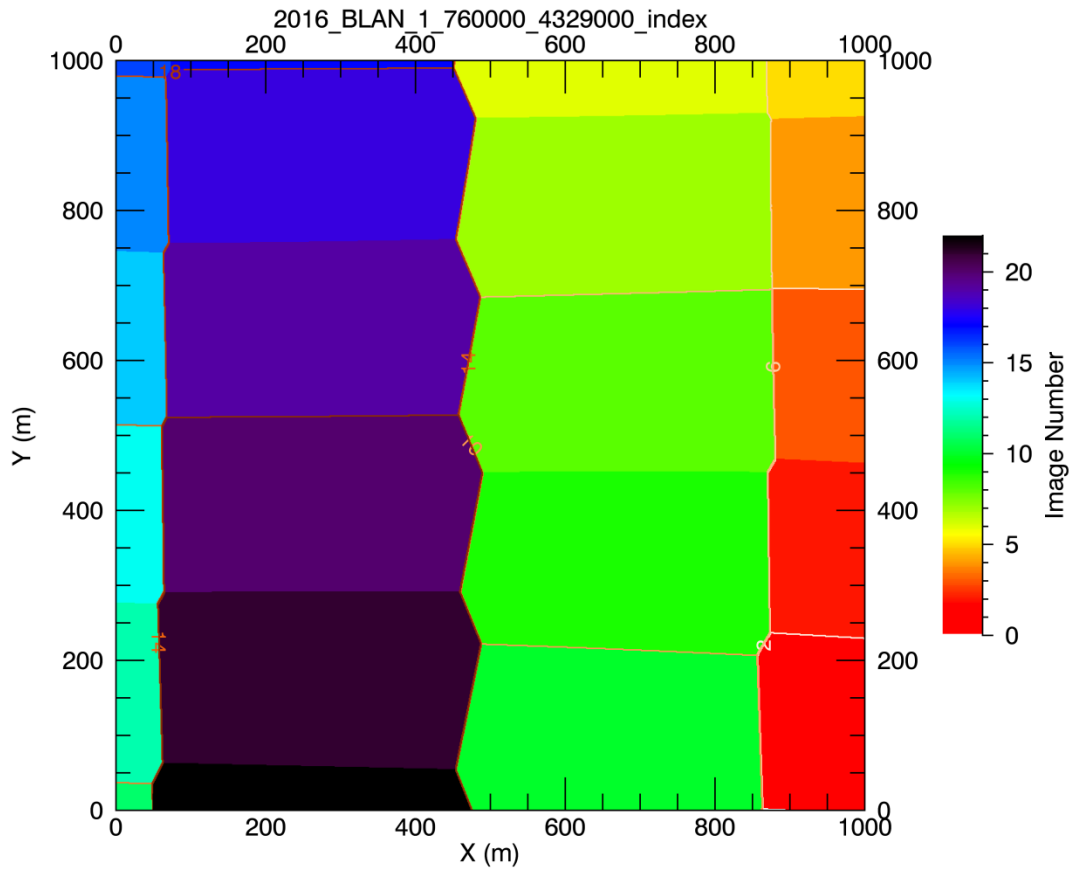**Figure 11**. Plot of the regions of tile 0146 populated by different images. Each colored area represents the region covered by a different image.

Figure 12 shows the off-zenith angle of each pixel in the tile. The maximum off-zenith angle is about 15 degrees. However, for tiles on the outer boundary of the full mosaic, the extreme off-zenith angles may be used, up to about 35 degrees.

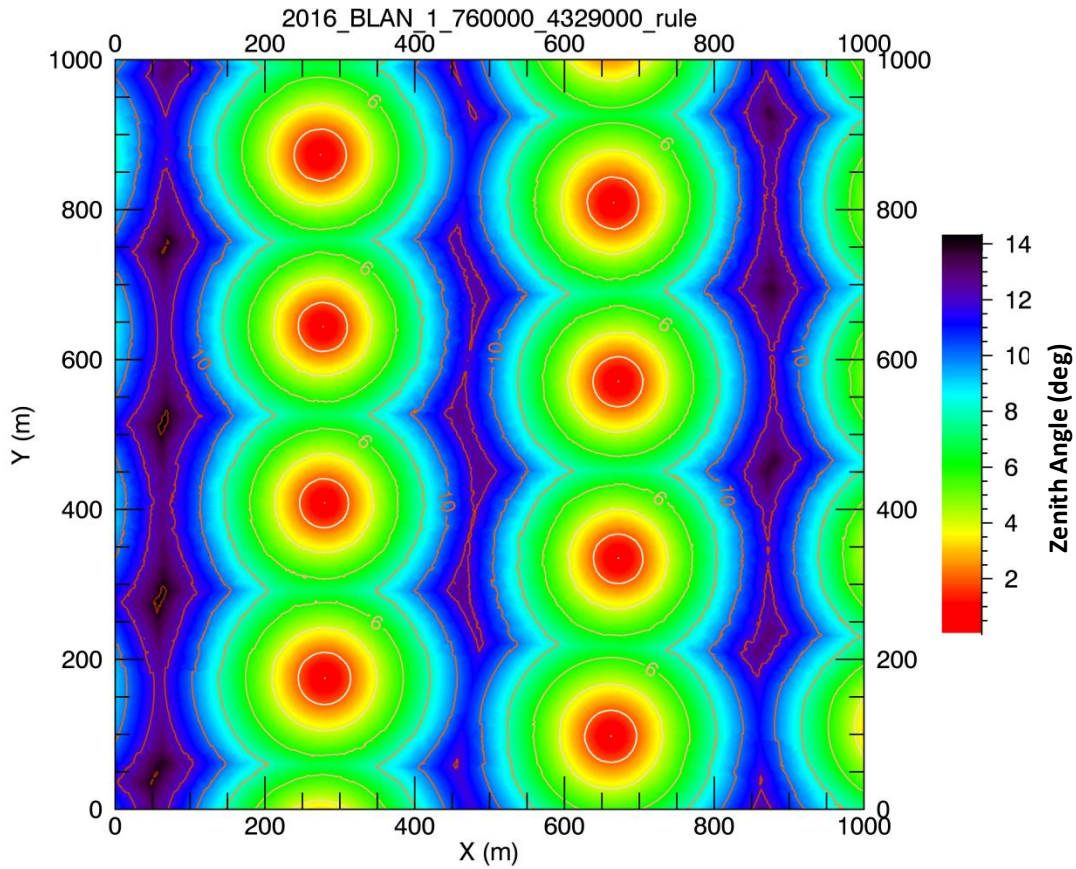**Figure 12**. Plot of the LOS zenith angle for each pixel in tile 0146.

Finally, **Figure 13** shows the resulting tile 0146 image and Figure 14 shows the 5 m resolution browse image for the entire site mosaic.
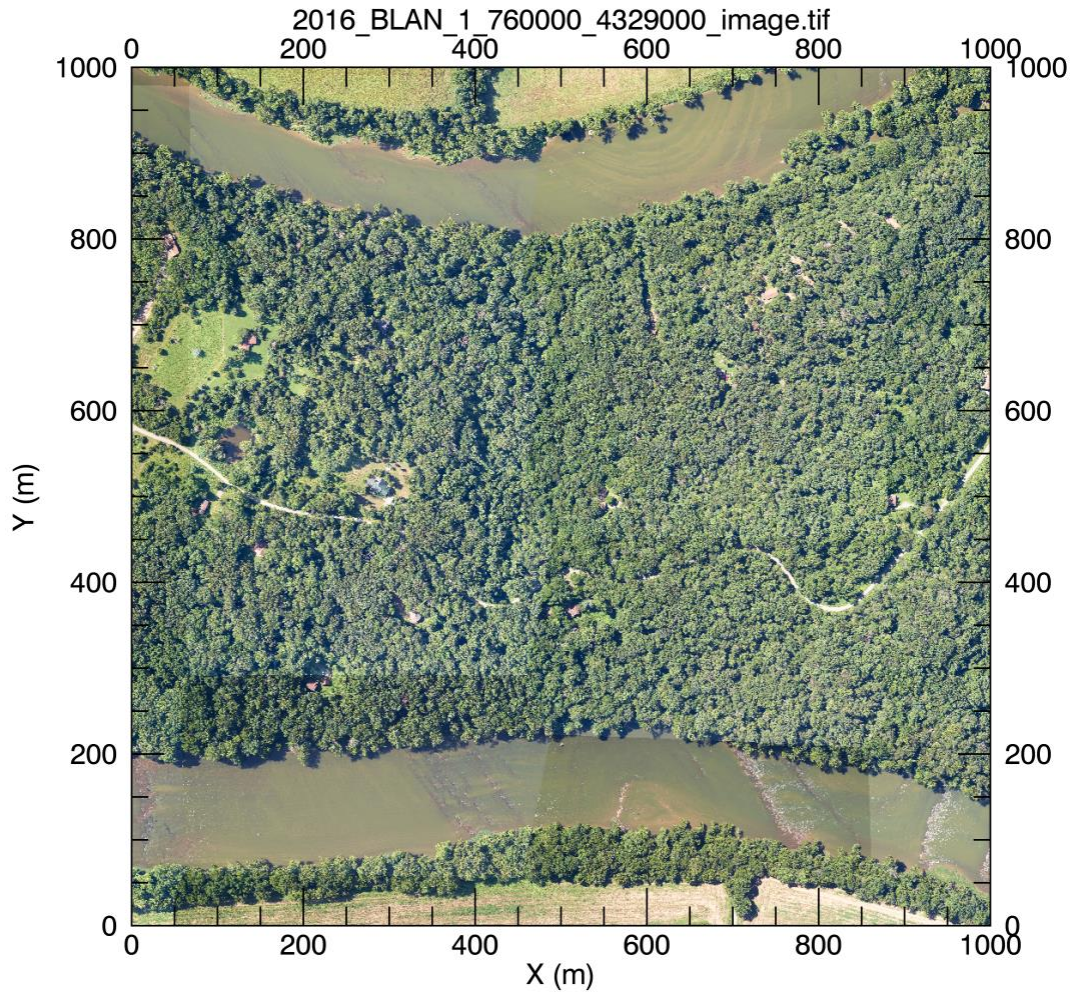
Figure 13. Mosaic tile 0146.

Note: the actual tile filenames that correspond to a tile number are described in Section 5.2. For example, tile 0146 corresponds to the file 2016_BLAN_1_760000_4329000_image.tif.

Figure 14. 5-meter resolution browse image of the full mosaic for BLAN 2106.

4.2.2.5   Create a KMZ

For convenience in accessing the tiles and individual images, a kmz file is generated that can be loaded into Google Earth. When loaded, the kmz displays the outline of each tile with a red pushpin at the center. Right clicking on a pushpin reveals the name of the tile file. By clicking on the boxes on the Google Earth toolbar on the left, the user can also display:

1. the location of the individual images (green pushpins). Right-clicking on a green pushpin reveals information about that image: the date/time, lat/lon of the center, the altitude AGL and true heading of the aircraft trajectory
2. the 5-meter browse image
3. the DTM boundaries, without and with backfill

See RD[05] for a detailed guide to the kmz's. **Figure 15** shows the kmz for BLAN 2016 loaded into Google Earth. **Figure 16** shows a screen shot of Google Earth expanded around tile 0146 with the browse image and image pushpins displayed.
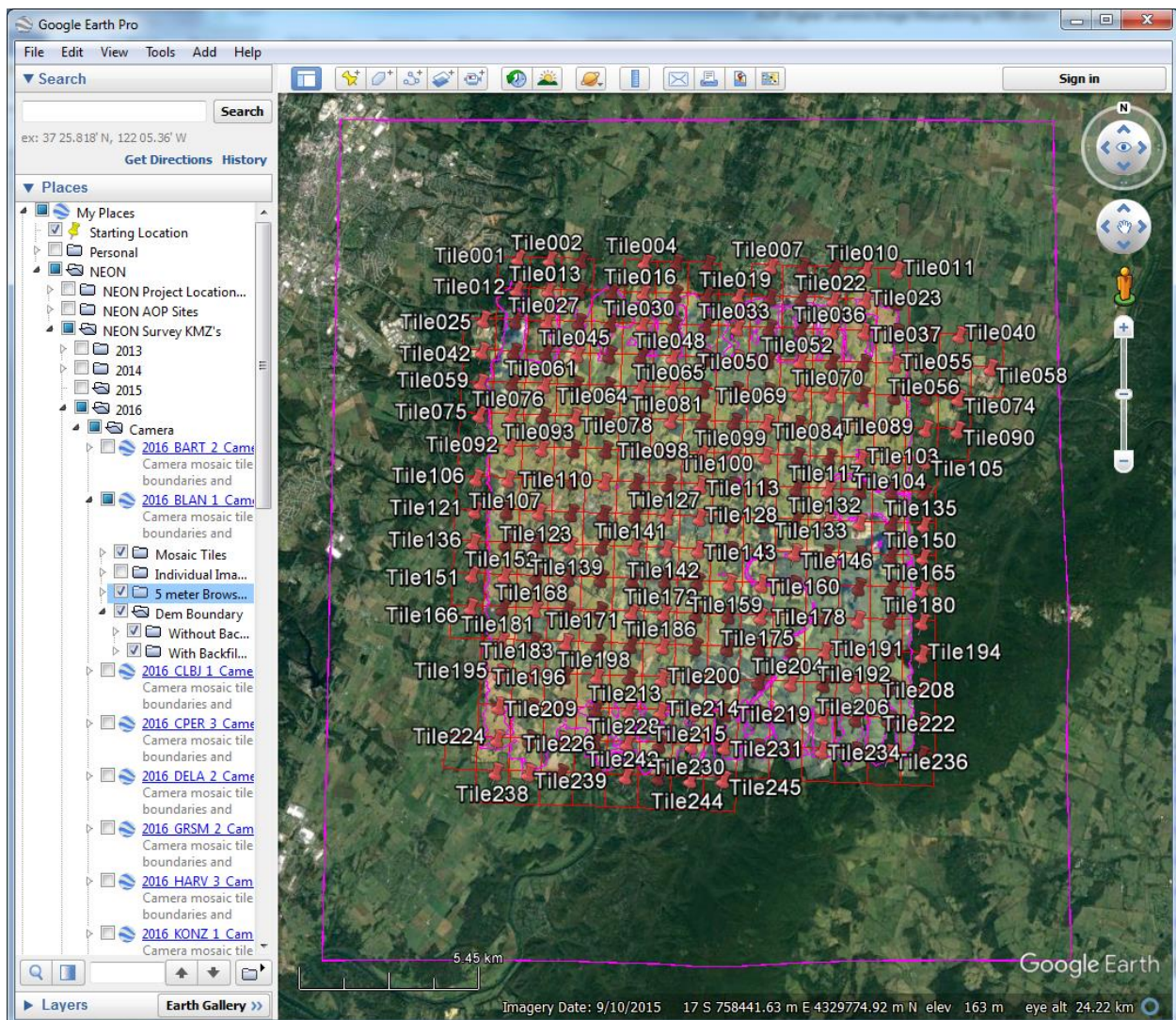

Figure 15. A screen shot of Google Earth showing the kmz for BLAN 2016.
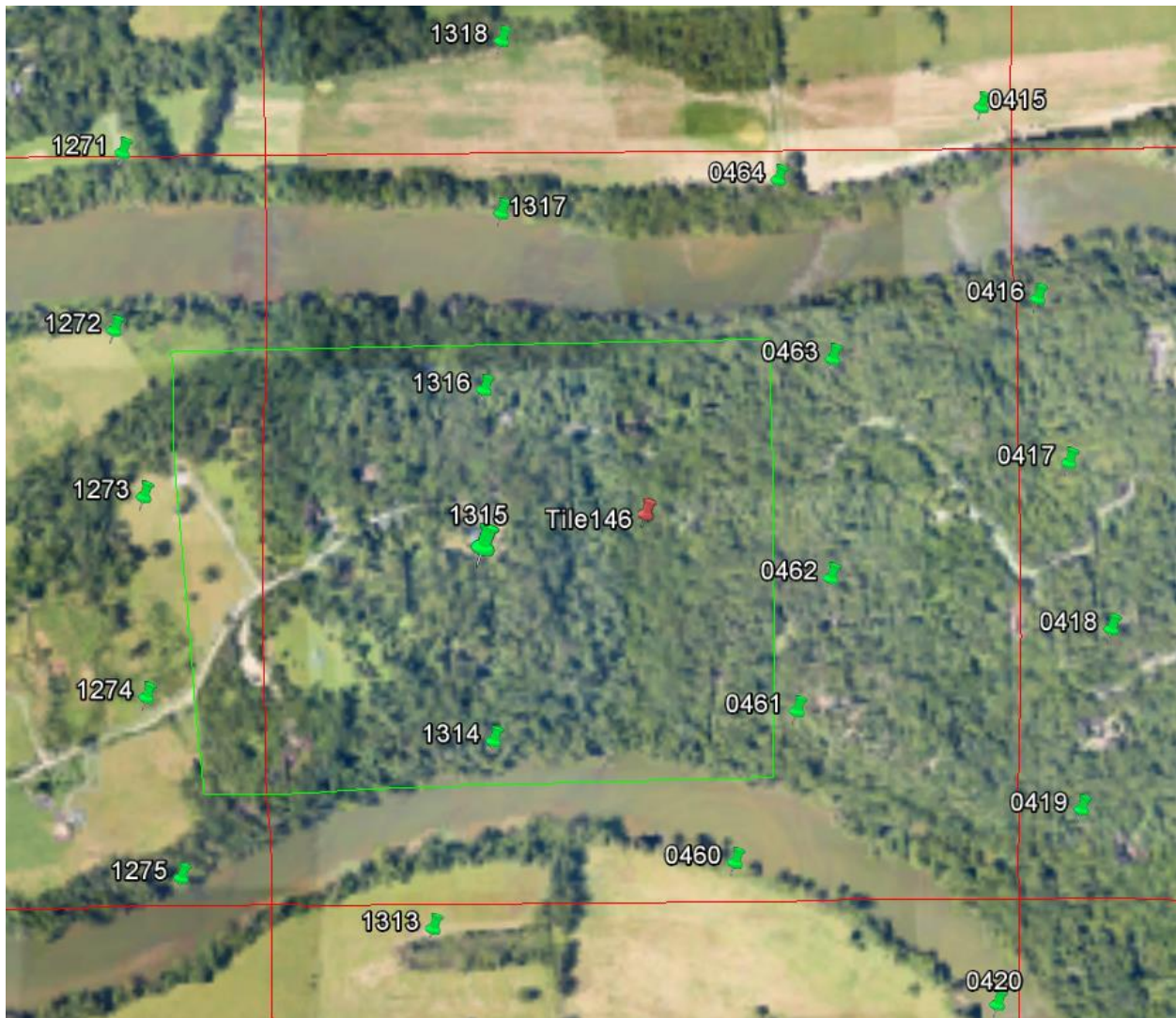
Figure 16. A blowup of **Figure 15** centered on tile 0146 (red pushpin and red boundary). The green pushpins show the center locations of the individual images. The green boundary shows the extent of image 1315. The cursor (not shown) is hovering over pushpin 1315.

5   ALGORITHM IMPLEMENTATION

5.1   Algorithm Program

The mosaicking algorithm is coded in the IDL (ED[02]) program run_aig_dms_mosaic.pro. The instructions for obtaining and running this program are given in detain in RD[04].

5.2   Filenames

The mosaic tile images are jpeg-encoded geotiff files in the UTM WGS84 projection. The tile sizes range from 3 MB (for tiles on the mosaic boundary that are mostly empty) to 110 MB for complex scenes. For reference, a non-compressed geotiff file would be 150 MB in size. The number of tiles for a site varies from about 190 for LENO to 628 for GRSM.

The tile names are of the form:

year_site_xxx000_yyyy000_image.tif

where:

year is the year of the survey

site is the 4-character site code

xxx is UTM X (easting) coordinate in km of the upper right corner of the image

yyyy is UTM Y (northing) coordinate in km of the upper right corner of the image

For example, tile 0146 from BLAN 2016 has the file name:

2016_BLAN_1_756000_4329000_image.tif

6   UNCERTAINTY

6.1   Analysis of Uncertainty

The horizontal location uncertainty of the orthorectified image is 0.5 meters or better, which translates to five pixels in the mosaic. This uncertainty is the RMS value over the image. The location errors tend to be greater near the edges of an image.

6.2   Reported Uncertainty

This uncertainty can be seen in the mosaic as offsets at the boundaries between contributing images, as seen in **Figure 17**. Here there is an obvious break in a straight line (a highway lane marker) at the boundary between two contributing images. Here the displacement is estimated to be 1 meter. The boundary between the two images is near the edges of both images resulting in a large displacement.

Figure 17. A section of the tile 341 (2016_ORNL_2_737000_3973000_image.tif) from ORNL 2016 showing image-to-image mis-allignment.

7   VALIDATION AND VERIFICATION

There are no numerical values associated with this product. Validation consists of visually examining the 5-meter browse image in Google Earth to verify that:

1. the image tiles fully cover the area enclosed by the lidar DTM, and
2. the image tiles are properly located relative to the Google Earth background to within several meters.

8 FUTURE PLANS AND MODIFICATIONS

The overlapping images that contribute to a mosaic tile may show large differences in color and brightness as seen in **Figure 18**. This image shows tile 0309 from Great Smoky Mountain National Park (GRSM) in 2016. The contributions of images taken on different days are seen in the alternating light and dark green regions. The white balance and exposure corrections are performed when processing the raw images into tiff images and before orthorectification. (This process is described in detail in RD[04]). The process is performed separately for each flight.

Future modifications to the camera processing workflow may include additional steps for blending the color and exposure across flights, either before or after orthorectification, to reduce the large contrasts seen in the mosaic.
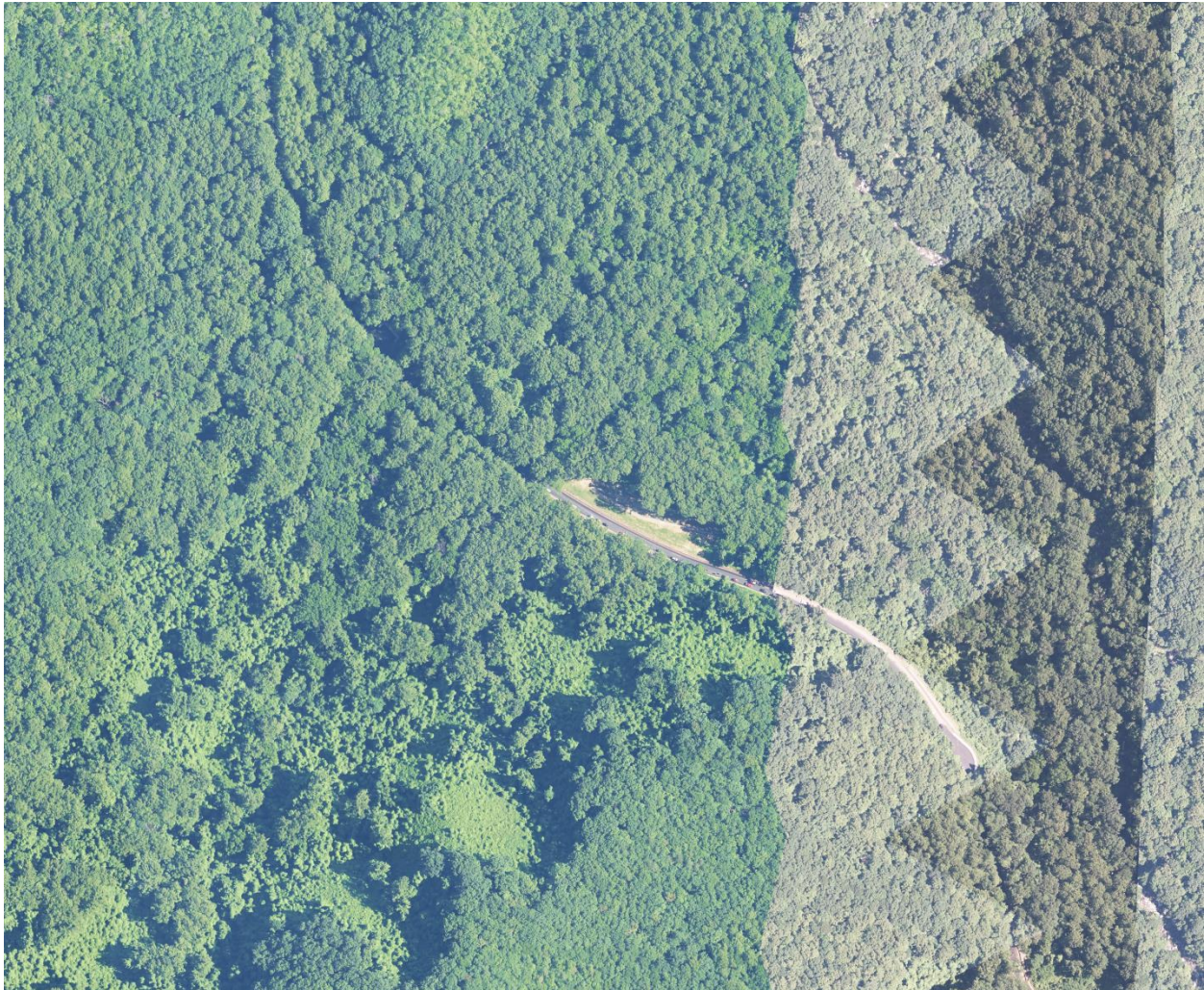

Figure 18. Tile 0309 (2016_GRSM_2_271000_3949000_image.tif) for Great Smoky Mountain National Park (GRSM) in 2016 showing the brightness contrast among images taken on different days.