MONOLITHIC STITCHING: ONE SENSOR GEOMETRY FOR MULTIPLE SENSOR CAMERAS

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ABSTRACT

Digital large forma aerial cameras typically use several cones and several sensors (CCDs) to achieve the large format. The sub images collected by the individual sensors are then stitched together to one large format image. The geometric accuracy of the final stitched image depends significantly on the quality of the stitching algorithm. This has been improved over the years and residuals of 20% of the CCD pixel size or better can be achieved under project conditions. The quality of the stitching depends on the content of the image. Unstructured terrain such as desert or water is difficult to stitch as the stitching algorithm does not find enough tie points between the sub images automatically. Super large sensors (CCDs) of with 100 to 200 Mega pixel would be the logical theoretical solution. But those super large sensors suffer from non-availability, bad price/performance ratio, and slow frame rate for example.

This paper introduces and discusses a new generation of stitching algorithms: the so called “Monolithic Stitching”. With Monolithic Stitching, the quality of the stitching can be improved by a magnitude. Furthermore, Monolithic Stitching allows also stitching reliably sub images which contain unstructured terrain. As a result, the new concept of Monolithic Stitching enables to achieve “one sensor accuracy” also with multiple sensor cameras. This makes the development of cameras based on super large CCDs obsolete and allows continuing to benefit from the advantages of multiple sensor cameras but with “one sensor accuracy” and “one sensor robustness”.

INTRODUCTION

Digital aerial cameras based on a multiple sensor/cone concept like the UltraCamD introduced in 2003 (see Leberl et al., 2003) and the more recent UltraCamX(p) series (see Gruber & Wiechert, 2009) rely on a sophisticated stitching algorithm to produce the high resolution virtual PAN image. The stitching algorithm used so far in the image post-processing procedure (OPC and UltraMap v1.x software, referred later on as ‘Standard Stitching’) has been proven to produce virtual PAN images of very high geometric accuracy and being robust under almost all possible project conditions. The analysis of many customer projects over the last five years has shown however, that there is still need for improvement mainly in two ways:

1. Standard Stitching completely relies on a valid camera calibration (cp. Kröpfl et al., 2004; Gruber & Ladstädter, 2006/2008) and the proper function of the temperature dependant correction (TDM) of the sensor positions. If calibration is lost due to mechanical stress on the sensor units (e.g. by damaging the camera during transportation) the Standard Stitching algorithm produces very inaccurate results (so the camera has to be re-calibrated immediately). On the other hand, TDM removes most of the sensor drift, but still some uncompensated, non-linear effects might introduce minor systematic errors (< 2μm) to the final image.
2. Under extreme project conditions (e.g. project flown at large image scale over coastline/sea) the number of stitching tie points in one or more overlap areas may fall under a critical value. Typically this is the case for a small number of images in the whole project only, but stitching errors might be visible e.g. in a derived orthophoto map.

In order to overcome these problems and to improve both the accuracy and the robustness, a new stitching algorithm has been developed called ‘Monolithic Stitching’ (Ladstädter et al., 2010). The basic idea of this new algorithm is to exploit the stable geometry of the monolithic green color channel (color master) and the support of additional, well distributed tie points matched between the color master and the PAN channel. The monolithic color

master allows using a more complex stitching algorithm called 'free mosaiking' which replaces the former layer transformation concept. This new mosaiking algorithm guarantees an optimal reconstruction of the inner orientation (IO) based on the calibrated sensor positions. A well known technique called 'free network adjustment' is used which ensures that inaccurate or even invalid calibration data has no negative influence on the stitching result.

In order to explain the new stitching concept, the first section provides some information on the image post-processing procedure and the Standard Stitching algorithm in more detail. After that, the Monolithic Stitching concept is presented and the new features of this algorithm are discussed. Finally, some results of some tests comparing the Standard and the Monolithic stitching algorithm are shown.

IMAGE POST PROCESSING

In the geometric post-processing step, the high resolution virtual PAN image (Lvl02) is composed by stitching the nine individual sensor images (Lvl00). The low resolution color channels (RGB and NIR) cover the whole virtual image plane with a single sensor with a PAN-Sharpening ration of 1:3.The registration of the color channels onto the PAN channel and the generation of the high resolution color image are separate steps in the image post-processing pipeline. In the following we will only concentrate on the stitching of the PAN channel because this is the most critical part concerning geometric accuracy for photogrammetric evaluation. In the following, the Standard Stitching algorithm is explained in detail, the new Monolithic Stitching approach is discussed in the next section.

In the first step of the Standard Stitching algorithm, all sensor images of one single cone are transformed into the corresponding layer image (e.g. the four sensor images of the master cone are transformed into layer 0). This is done by using the information stored in the camera calibration data and applying TDM corrections to compensate for sensor drift. After that, tie points are matched in the overlapping regions of the nine PAN sensors (see figure 1). Finally, layer transformations (2D projective transformations, 8 parameters) are calculated to transform each of the three layers 1, 2 and 3 onto layer 0. Note that this algorithm is very robust because it uses a very limited number of transformation parameters (in total only 24 parameters). On the other hand, small deviations of the actual sensor positions from the calibrated sensor positions will propagate into the layer images and will cause some systematic errors in the final virtual PAN image.

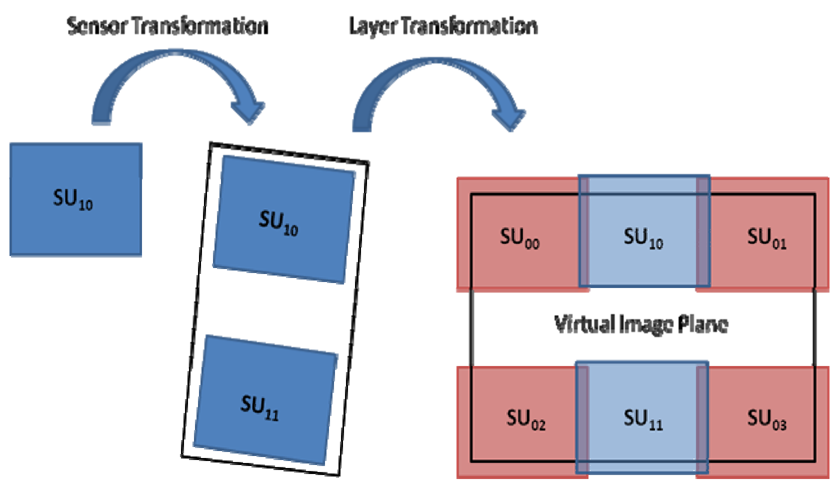

Figure 1. Standard Stitching is a two step procedure: First, the sensor image is transformed into the specific layer (here: layer 1) using the information stored in the calibration data. Second, the layer is transformed onto the master layer (composed of four sensor images) using tie points measured in the PAN sensor overlaps. Layers 2 and 3 (holding additional 3 sensors: SU_{20}, SU_{21} and SU_{30}) are not shown here for simplicity.

MONOLITHIC STITCHING

The new stitching algorithm does not use a two step (sensor and layer) transformation procedure as described above. Instead, a more flexible image mosaiking algorithm is used (called free image mosaiking), which transforms

each sensor image individually into the virtual image plane (see figure 2). In addition, tie points are matched not only between PAN sensors but also between PAN sensors and the green color channel. The accuracy of those color tie points is reduced by the factor 3 (due to the lower resolution of the color channels) but they are very well distributed over the whole virtual image plane (see figure 3, right side) and the number of tie points is increased by a factor of about 2.7.

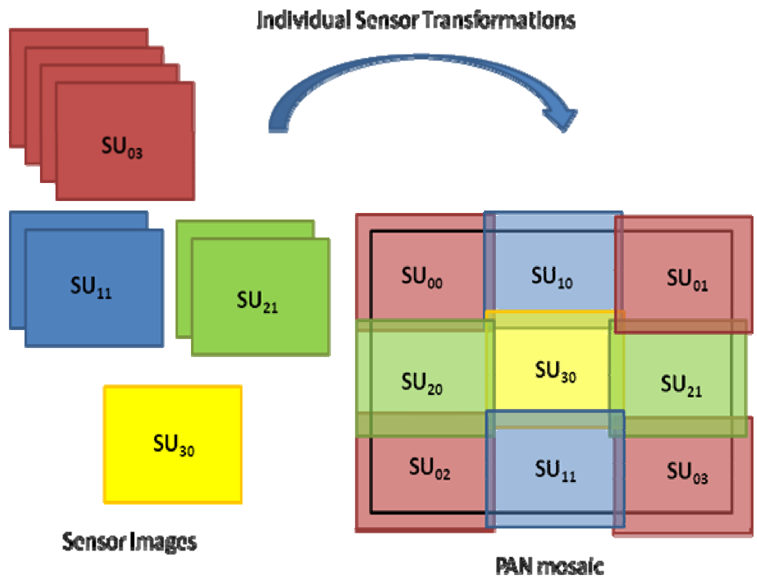

Figure 2. Monolithic Stitching uses individual transformations of each sensor to get a best-fitting image mosaic in the virtual image plane. Calibration data is used to reconstruct the inner orientation of the camera (scale orientation, orthogonality of the camera coordinate system) but does not constrain the absolute position of the sensor images within the PAN mosaic.

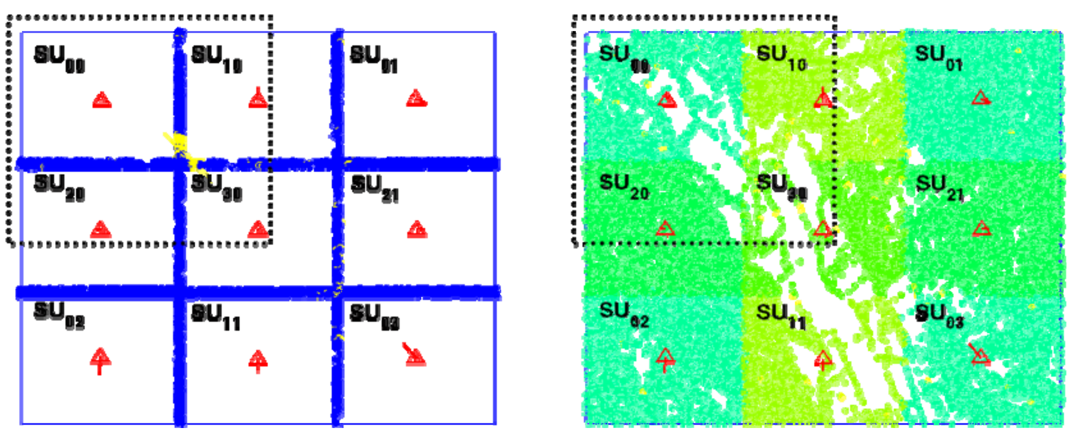

Figure 3. Distribution of PAN (left side, in blue) and color tie points (right side, in green) in the virtual image plane of an UltraCamXp camera system. Calibrated positions of the nine PAN sensors SU_{ij} are marked by red triangles. The area bounded by the dashed line is enlarged in figure 4 and 5.

The most important property, however, is that the green color channel consists only of a single, monolithic sensor with an absolute stable geometry (that's why we call it "monolithic Stitching"). Using those color tie points in the mosaiking process of the high resolution PAN image therefore allows us to determine 2D Helmert transformations (4 parameters: shift x, shift y, rotation scale) for each individual sensor without running into problems with over-

parameterization. A total set of 64 parameters is actually used in the mosaiking algorithm, consisting of four parameters each for the nine PAN sensors, eight parameters for the registration of the green color channel onto the PAN channel and additional correction parameters to compensate for small projective distortions of the four PAN cones. Additional constraints are used to guarantee an optimal reconstruction of the inner orientation of the camera (see section below) which reduce the degree of freedom of the normal equation system to 52.

Free Image Mosaiking

The function of the free image mosaiking algorithm is shown in figues 4 and 5. An iterative adjustment procedure is used to minimize residuals of the PAN and color tie points, respectively. In each iteration, tie points are transformed into the virtual image plane and residual vectors are calculated. By adjusting the transformation parameters, the residuals are minimized and the algorithm converges quickly.

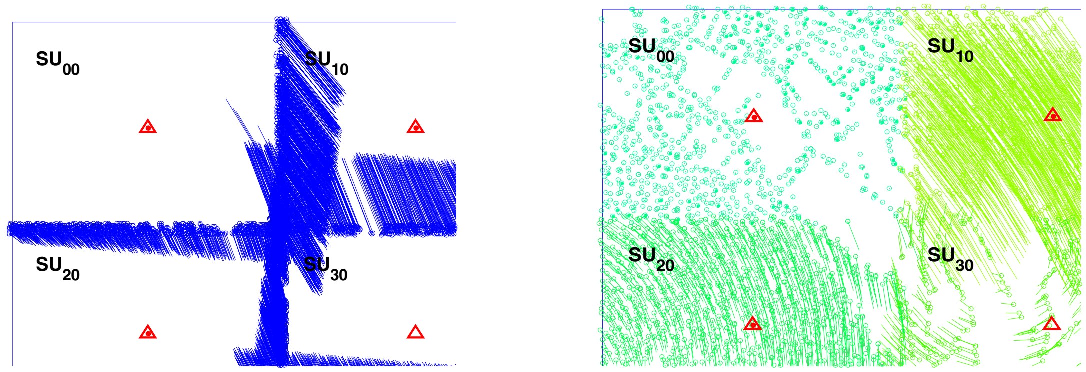

Figure 4. Residuals of PAN (left side, in blue) and color tie points (right side, in green) after the first iteration of the monolithic stitching algorithm.

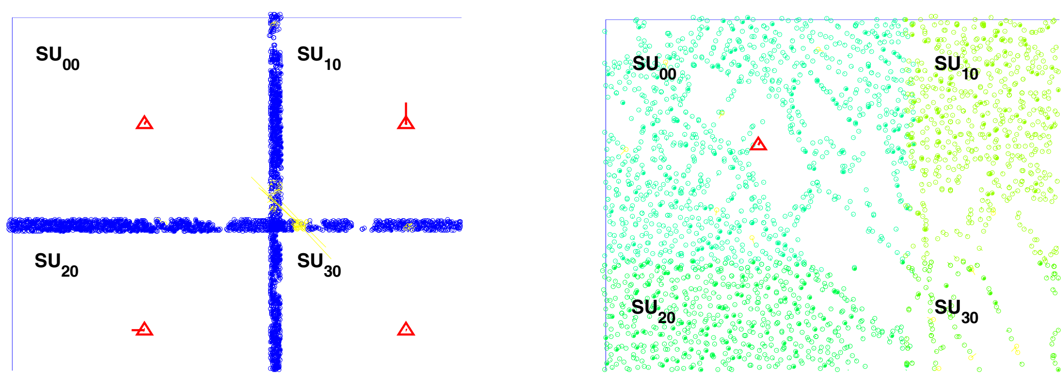

Figure 5. Residuals of PAN (left side, in blue) and color tie points (right side, in green) after three iterations of the monolithic stitching algorithm.

Optimal IO-Reconstruction

So far, the PAN mosaic has not been related to the camera coordinate system, established during camera calibration. This process called "reconstruction of the inner orientation" has lost importance when analogue film cameras have been replaced by digital camera systems. In the new Monolithic Stitching algorithm however, we want to re-use this concept by applying a similarity transformation of the PAN mosaic onto the calibrated sensor positions of the master cone and calculating the residual vectors to the adjusted positions (see figure 6). This is exactly the same concept used in the free network adjustment of geodetic networks, which prevents that possibly inaccurate control points (here: calibrated sensor positions) decrease the high internal accuracy of the network (here: the PAN image) which is based on very accurate measurements (here: PAN and color tie points).

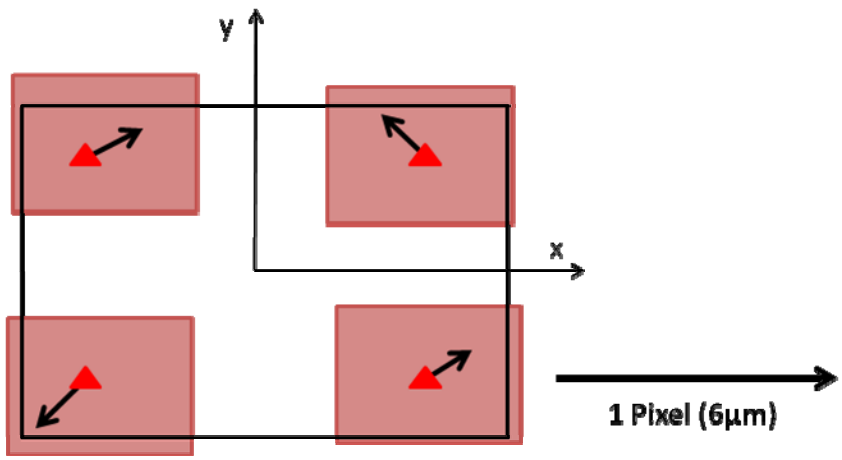

Figure 6. Residual vectors between calibrated and adjusted sensor positions in the virtual image plane. According to the theory of free network adjustment, the sum of the residuals in x-/y-direction has to be zero to avoid any systematic shift, rotation or scale of the PAN mosaic and thus an optimal reconstruction of the inner orientation is achieved. Note that for a well calibrated camera, the residuals are typically in the sub-pixel range (~0.2-0.3 pixels).

This new feature of the Monolithic Stitching algorithm allows to validate the camera calibration data by analyzing the stitching results of a single image frame. If, by any reason, the calibration is not valid any more, we will observe large residuals in the inner orientation process but still get reasonable stitching results.

TEST RESULTS

In order to prove the potential for higher geometric accuracy and increased robustness of the Monolithic stitching algorithm, some tests project have been evaluated. Images of UltraCam test and production flights have been processed using both the Standard Stitching approach (using OPC 3.2.x) and the new Monolithic Stitching algorithm (implemented in UltraMap v2.0). Aero-triangulation has been performed using UltraMat AT and bundle adjustment results have been further analysed using the BINGO software package.

UltraCam$_{Xp}$ Test Flight

The first test was done using image data from an UltraCamXp test flight. This means that the time period between camera calibration and flight mission is very short (less than a week). As we can see from the figures below, some minor systematic effects (less than 1.6µm) can be observed in the images processed with the Standard Stitching algorithm. Monolithic Stitching greatly reduces systematic image errors as expected (being less than 1.3µm in the image corners).

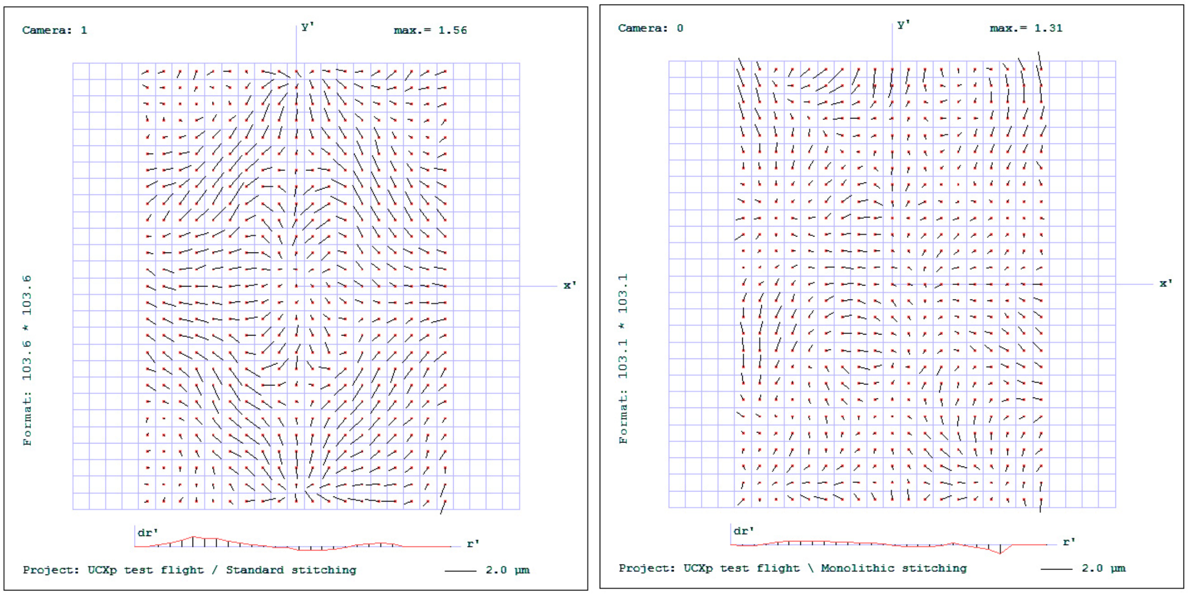

Figure 7. Image residual plots of an UltraCamXp test flight. Left side: Image post processing using the standard stitching algorithm. Right side: Monolithic stitching used (UltraMap v2.0).

UltraCam$_X$ Production Flight with Damaged Camera (calibration lost)

The second experiment shows the result of a camera that had been damaged before a production flight.

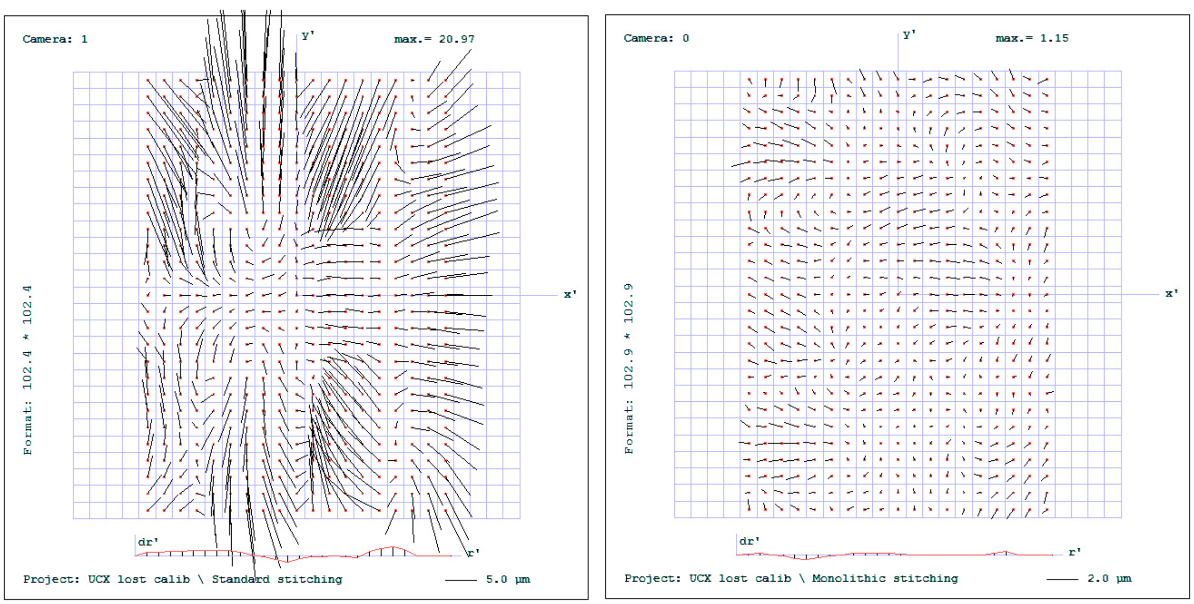

Figure 8. Image residual plots of an UltraCamX project where calibration was lost (damaged camera). Left side: Image post processing using the standard stitching algorithm. Right side: Monolithic stitching used (UltraMap v2.0).

Therefore, the calibration data was no longer valid and the camera would have had to be re-calibrated. Processing the images with the old calibration using the Standard Stitching algorithm produces very large errors (> 20µm) in the image, which is not acceptable for a customer. Using the new Monolithic stitching algorithm we do not observe large systematic errors anymore, however the principle point is lost and has to be determined in the bundle adjustment. We also observe very large residuals in the inner orientation process of about ten pixels (~72µm) indicating that the calibration data is not compatible with the adjusted PAN mosaic.

UltraCam$_X$ Production Flight Over Low Textured Desert Area

Another production flight performed over a desert area offering a very low image texture. Out of about 6000 images, 20 images had very low tie point numbers in at least one of the three PAN layers. One of those images shown in the figure below, failed to have a sufficient number of tie points for layer 2. In the Standard Stitching algorithm this resulted in a very inaccurate layer transformation so that an offset of about 10 pixels is visible on a road crossing sensor borders. Monolithic Stitching (see right figure) avoided this problem because of having additional color tie points that could be found for this image area (sensor SU$_{10}$).

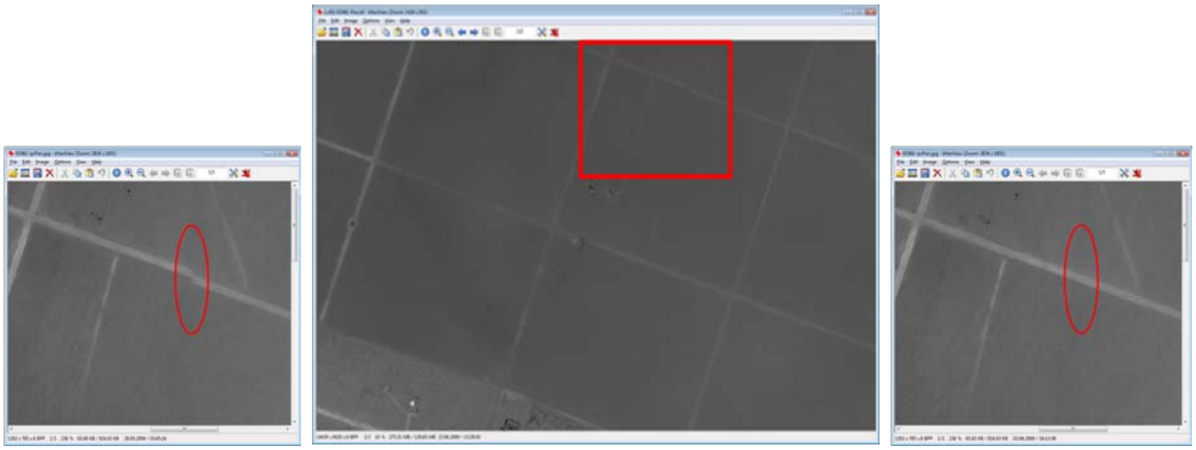

Figure 9. Visible stitching error in an extremely low textured (desert) area. Area marked by the red rectangle is enlarged. Left side: Standard stitching algorithm, right side: Monolithic stitching used during post-processing.

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