INTEGRATION OF STRUCTURED LIGHT AND DIGITAL CAMERA IMAGE DATA FOR THE 3D RECONSTRUCTION OF AN ANCIENT GLOBE

S. Sotoodeh, A. Gruen, T. Hanusch

Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland
{Soheil.Sotoodeh, Armin.Gruen, Thomas.Hanusch}@geod.baug.ethz.ch

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ABSTRACT:

An antique 300-year old wooden globe, preserved in the National Museum of Switzerland, had to be copied physically for delivery to another party. For this purpose a 3D computer model had to be generated. A structured light system and two digital frame cameras were employed, and the generated datasets were integrated to obtain both the geometry and the texture of the model. This paper reviews the whole workflow from data acquisition to the final geometrical surface and textural information. The results of the processes are presented and discussed and some conclusions regarding the exploitation of the two mentioned techniques are given.

1. INTRODUCTION

The 3D computer reconstruction of the St. Gallen Globe[1], an antique globe built in the 17^{th} century has been requested by the National Museum of Switzerland for the generation of a physical real scale copy. The object, which is now preserved at the museum, was built by Fürstabt Bernhard Mueller (1594-1630) in St. Gallen, Switzerland. The overall object dimensions are approximately 2x2x3 m^3 and the object consists of several parts that are covered by fine paintings and designs.

A physical reconstruction of the object requires architectural plans of all the parts (geometry) and the rectified images of its surfaces (texture) to be used for painting the copy. Thus the measurement of the object involving both the geometry and texture for all elements as a master copy was needed.

Photogrammetric techniques were applied for measurement since they do not need to touch the object and provide both the reconstructed geometry and texture during a relatively short acquisition period. Two different types of sensors were used for the measurements, a structured light system and digital frame cameras. The structured light system (Breuckmann OptoTOP-SE) was used to capture the geometry of the small pieces like the supporting legs, and images were taken to cover the texture and the missing areas that could not be measured by the structured light system.

In the following we will explain the procedure selected for data acquisition and the reconstruction of both geometry and textural information. A review of the project specifications and strategies adopted to record the object is presented in Section 2. Section 3 explains the data acquisition procedure. Then, the reconstruction procedure and the results are depicted in Section 4. Finally, the paper is summarized and concluded in Section 5 concerning the advantages and difficulties of the integration of both active (structured light) and passive (digital camera) sensors for cultural heritage preservation/documentation purposes of this kind of object.

2. PROJECT REQUIREMENTS

The object consists of several pieces. The central sphere, with approximately 0.6 m radius, is surrounded by two rings, one along its equator (equator-ring) and another along a meridian (meridian-ring) and all are held together by six supporting legs over a table (Figure 1). There are also some mechanical parts to rotate the sphere. Most of the parts are made of wood and are covered by various paintings. The surface of the sphere shows the map of the continents and the geographical boundaries of nations according to that era and is painted with figures of various creatures and other objects. Additionally, map features like mountains and settlements are symbolized by proper paintings and named by texts. There is also a geographical grid on the sphere with 10 degrees angular distance (along both latitude and longitude). The equator-ring and the supporting legs are painted to illustrate various seasonal events and famous figures. The surface of the table as well as the base of it is also covered by designs.

Since the object is quite old and sensitive, direct contact with the surface of the object or the attachment of any kind of material was not allowed. In addition, most of the pieces could not be measured easily due to occlusions. However, the object was dispatched into pieces for a short period due to a plan to move it to a preservation chamber.

The physical reconstruction of the object requires architectural plans with 1 mm accuracy. To paint the reconstructed copy, 1:1 scale images of each piece were requested. Particularly for the sphere the 1:1 scale images had to be prepared for each grid cell separately (according to the mapped geographical grid on the original sphere). These images are supposed to be used to paint the outline of the features on the reconstructed sphere. The images must be prepared in a way that a painter could attach them to the reconstructed sphere and perform a carbon copy. Additionally images were needed to contain all the details with diameter bigger than 0.1 mm, which were supposed to be applied to the final fine painting by eye-balling.

[1] http://www.musee-suisse.com

Figure 1. Left: The original complete globe before being dismantled. Right: The laboratory for image acquisition and the diffused lights to illuminate the globe.

3. DATA ACQUISITION

To respond to the project requirements two types of measurements have been applied, structured light and digital camera imaging. Structured light has been applied to obtain the fine 3D model of all the object parts except the sphere. It has been used since it provides the pointcloud of the 3D model in an efficient and direct way and does not need any targeting or special texture on the object. That property was important because there are some parts that do not have enough detailed texture to be used by image matching techniques for the recovering of the geometry by images. However, using the structured light for measurement of the sphere was not applicable since (a) the surface of the sphere was too curved with respect to the field of view of the structured light system which would have led to too many scans (> 500) to cover the whole surface, (b) many dark colour areas could not be measured by the structured light system due to the low surface reflection, and (c) the textural information was more important than the fine geometry, since in the final physical reconstruction the geometry would be considered as a sphere. Also, the co-registration of the individual datasets of the sphere, just based of geometrical surface information, would have resulted in an ill-posed problem.

3.1 Structured Light System

A Breuckmann OptoTOP-SE structured light system[2] was used for the fine measurement of the geometry. To use the system in a proper condition the object parts were moved to a laboratory room where the ambient illuminations could be better controlled. Several measurement tests have been carried out to find the best illumination setup. The surfaces of the pieces were aged (aged wood, penetration of environmental dust, etc.) and did not reflect the projected light of the structured light system properly. Thus for every piece a different illumination was considered (either the projected light of the system with different exposures or using an extra light source).

For pieces larger than the field of view of the scanner, the measurements were done patch-wise with overlap coverage. The patches were registered, on the job, using the ICP algorithm of the OptoTOP software. Approximate registrations were done by measuring the minimal three common points manually on the fixed and floating surfaces and then the fine registration by the algorithm was activated. In addition, the full coverage of the object was checked while the measurement was still ongoing. All in all around 300 scans were taken to cover all 13 parts and the overall RMSE of the registrations was 44 micron. Figure 2 shows the system and the measured model of one of the mechanical parts of the object. Figure 6 illustrates the reconstructed geometry of some other parts as well. Also, Figure 7 shows the superimposed image of the wire frame of the reconstructed parts and the sphere.

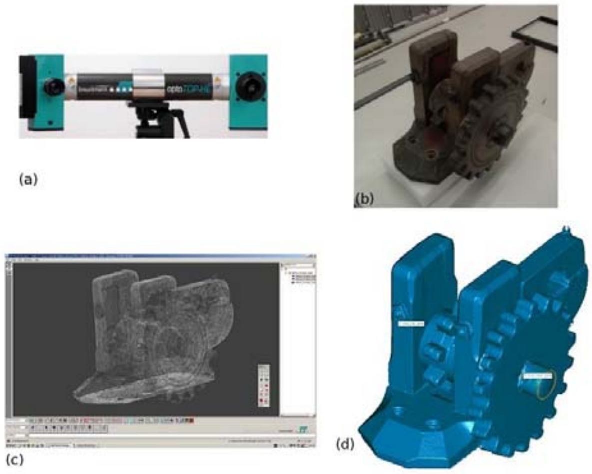

Figure 2. (a) The Breuckmann Opto TOP-SE structured light system; (b) a gear to rotate the object; (c) the measured point cloud by the structured light system; (d) the shaded model of the wire frame surface obtained by surface triangulation.

After the registration of the point clouds, the surfaces of the parts were generated by surface triangulation followed by hole filling and triangular surface decimation with the OptoTOP software. Finally, each modelled part has been handed over to an architect to generate the so called as-design maps.

Although the structured light system could measure most of the surfaces, the very dark coloured surface areas could not be measured completely, because the system cannot distinguish black and white stripes when the white ones are reflected dark as well. This problem could be solved in some cases by making the exposure longer or by adding external light sources. However, this was not always possible, and we had to recover the missing parts using the geometry generated by oriented digital camera images.

3.2 Image Data

A Canon EOS-10D (6 MP, 7.4 µm pixel size) with two objectives, 28 and 80 mm, and a Sony DSC-F828 (6 MP, 2.7 µm pixel size) with an 18 mm lens were used to capture the images. In the following sections the image sets with 18, 28 and 80 mm are named 18-lens, 28-lens and 80-lens image sets respectively. There are also separate sets of the same objectives which were taken from the sphere and the other parts of the globe. Using three objectives was necessary to take images with resolutions that could cover the project requirements (Section 2). The cameras had been calibrated for all the objectives off-line, over a calibration field at our Institute, and using the Australis software[3].

[2] http://www.breuckmann.com

[3] http://www.photometrix.com.au

Images of the parts except the sphere were acquired in the illumination isolated laboratory, in manual mode and with the use of external diffused light. The light-controlled environment allowed us to capture relatively homogeneous images in terms of colour, brightness and contrast. The diffused light was necessary to avoid specular reflections in the images (Figure 1).

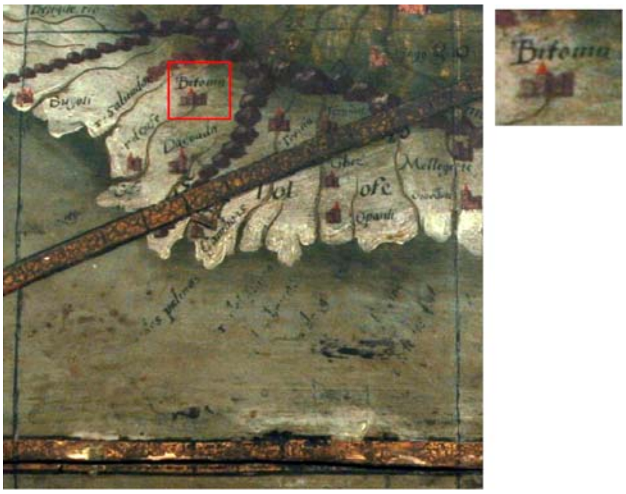

Figure 3. Left: An image of one of the grid cells of the sphere. Right: Zoom-in of the red rectangle of the left image. All the details had to be seen in the final rectified images to perform a carbon copy on the physically reconstructed sphere.

Concerning the sphere only the 18-lens image set was used to measure the geometry. This lens was used to cover the object with less images and a scale bar which was put beside the sphere was measured. These images were taken only for the geometry reconstruction of the sphere (Section 4.1.1).

Having the grid lines of the latitude and longitude of the sphere map on the sphere for every 10 degrees, it has been decided to use the grid cells as reference frames for the painting procedure and so 1:1 scale rectified images have been asked to be prepared for each grid cell for the overlay carbon copy. This implied that images should be oriented and rectified according to the geometrical surface of the sphere.

To prepare such rectified images of the sphere we used the 28-lens. According to the project specifications details larger than 0.1 mm had to be seen in the images. If we assume that value as the maximal acceptable uncertainty of the points in the object space, plus assuming one pixel uncertainty for image measurements, then using a simplified network design criterion (Fraser; 1984) the distance of the camera stations to the sphere surface would be approximately 650 mm. So the images were taken over a hypothetical sphere, co-centric to the globe sphere and with approximately 650 mm offset. The camera was always pointing to the center to keep the images as parallel as possible to the tangential planes at each grid cell center point. This was required since finally the images had to be rectified according to those tangential planes (Section 4.1.2).

We have also recorded each grid cell of the sphere using the 80-lens. This image set was necessary to have the detail of painting at very high resolution. Since after the recording period the object parts were supposed to be mounted and so there would be no proper access any more to the object for measurements. Figure 3 shows a grid cell and a zoom to one of the fine features.

4. RECONSTRUCTION

The reconstruction of the master copy includes geometry and rectified images. Since the procedure taken for the reconstruction of the sphere and the other parts are slightly different due to the project needs, we explain them separately. Apart from the geometry obtained by the structured light system, the general workflow of the generation of the rectified images is

- Image orientation
- Surface approximation
- (Ortho)Rectification and stitching
- Contrast enhancement

The details are explained in the following paragraphs.

4.1 The Sphere

The image sets obtained by the three lenses were used as follows. The 18-lens data set for geometry reconstruction included 30 images. The 28-lens image set, containing over 100 images to cover the whole sphere, has been used to provide the rectified images of its surface. The 80-lens data set contains more then 1500 images and will be used as a reference for the detailed painting of the sphere.

4.1.1 Geometry of the sphere: Tie points were measured manually on the 18-lens images. A conventional bundle adjustment method (scale bar constraint and inner constraints to compensate translation/rotation deficiencies, because no object control point could be attached to the sphere), followed by a mathematical sphere fitting the object points, provided us with the model of the sphere.

After the bundle adjustment more then 200 object points, spread over the whole sphere, were obtained. The RMSE of the sphere fitting was 0.8 mm, which is in the range of the requested 1.0 mm accuracy. This model was employed as the reference geometry of the sphere later on.

4.1.2 Rectified Images: As explained in Section 2, the rectification must provide images of each grid cell of the sphere that when printed on a paper, the painter could easily attach them to the physically reconstructed sphere based on the grid crossing points and start painting. This rectification resembles a local stereo-graphic projection that will be explained in the following paragraphs. However, first the orientation of the image set was necessary. We took the following procedure to avoid tedious manual work and we have found it practical and accurate enough.

The 28-lens image set (>100 images) that had been taken for this purpose (Section 3.2) was measured and oriented to be rectified. Tie point measurement was done semi-automatically using a SIFT operator (Lowe, 2004). The 128-element feature vector of the operator for each point was used to find correspondences through the images. Note that a kind of task was considered during the image acquisition phase, so finding the correspondences was limited to some certain neighbouring images. Although the matching procedure is not very accurate and has some blunders, it does not need particular target shapes or any approximations. Besides, the redundancy of measurements was mostly high enough to help detecting the blunders during the orientation by conventional blunder detection methods after the adjustment. Using this operator we have saved considerable amount of time by avoiding manual tie point measurement.

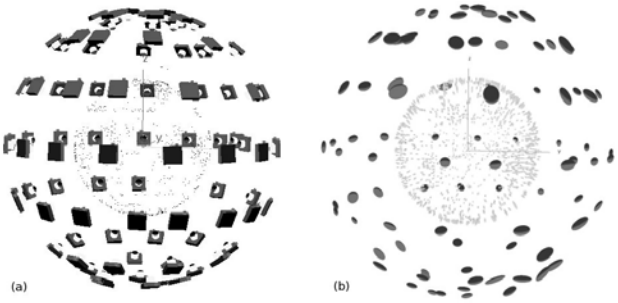

Figure 4. Left: The network of camera stations and the object points after the bundle adjustment of the 28-lens images. Right: The final error ellipsoids of the camera stations and object points. The scale is exaggerated to emphasize the relative sizes.

No. of observations	> 7100
No. of object 3D points	> 1300
Avg. number of rays per point	~5.4
RMSE of image residuals	1.58 µm (~ 0.2 pixel)
σ_0	1.06

Table 1. Statistics of the bundle adjustment of the 28-lens images network

The orientation of the images has been done with the Australis software, using the relative orientation of image pairs followed by a conventional bundle adjustment. The approximation values of the parameters and the scale are obtained according to the geometry of the adjusted sphere. Figure 4 illustrates the configuration of the camera network, object points and their error ellipsoids. Table 1 presents some statistics about the network and the adjustment results.

The RMSE (~0.2 pixel) relates to the precision of the image measurements. The blunders of the measurements were removed carefully by automatic and manual detection. Please note that the image measurements were done with a little manual work on images with no distinctive targets. However, it has to be pointed that the images were taken in convergent mode and with relatively short base lines.

After the orientation of the images, the rectification is straight forward. Since the final painting has to be performed on a mathematically defined sphere surface (the reconstructed sphere), its geometry was used for rectification.

A local stereo-graphic projection for each grid cell was used to project the texture on a local plane (the final rectified image which will be the printing paper). The projection is local since we have considered the tangential plane to the sphere at each grid cell center point separately, and each grid cell is projected to the corresponding plane locally. Figure 5 illustrates the relation of a projection plane and the sphere. The error of projection was computed (0.1 mm) and with respect to the project specification it was in the acceptable range.

Therefore, the rectification contained two projections. To avoid aliasing effects an indirect rectification was performed. Each point in the rectified image plane was first projected back to the mathematical sphere using the inverse of the stereo-graphic projection function T, X = T(X';O,C,R), afterwards it was projected back to the corresponding images using the inverse of the perspective projection function P_s, $x = P_s(X)$ (parameters are defined according to Figure 5).

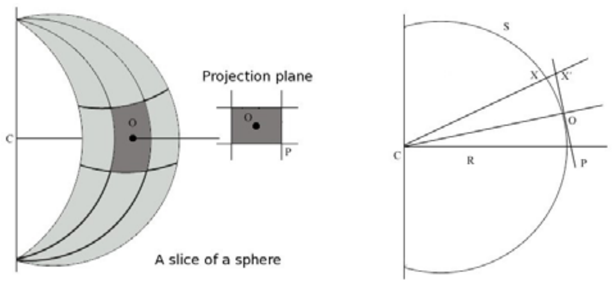

Figure 5. Left: A slice of a sphere, the gird lines and a grid cell patch with its center. Right: A section of the sphere and the local tangential plane. The parameters are as follows: (C, R) are the center and the radius of the sphere respectively, P is the tangential plane to the sphere in O, X is a point on the surface of the sphere and X' is the projection of X onto the plane P via transformation Ps.

Since the grid cells were getting small near the poles of the sphere, instead of one projection for each cell, only one tangential plane at each pole was considered and the projection was done once for all the cells near each pole.

The colour of each pixel was picked from the image that has the smallest deviation from being parallel to the tangential plane. Saturated areas and areas with specular reflections were masked in the images manually. Figure 8 shows the rectified images of a section of the sphere.

4.2 Other Parts

The 28-lens image sets of parts other than the sphere have been applied to (a) complete the surface geometry of pieces that could not be measured by the structured light system due to the surface low reflection or occlusions and (b) the generation of the rectified images that could be employed to paint the outline of the figures and designs. Finally, the 80-lens image sets of these parts are planned to be applied in the fine paintings.

According to the different shapes, sphere vs. planar objects, the processing of these parts differs from the processing of the sphere. This concerns the surface approximation and the projection function which is basically an ortho-rectification.

4.2.1 Orientation of the images

The number of images, used for the processing, depended on the size and the resolution of the acquired images. It varied between 3 for the supports, up to 30 images for the meridian ring. Each part was processed separately within a local coordinate system. The image orientation was done using manual measurements and a bundle adjustment with the PhotoModeler software [4]. The scale was introduced using distances, measured on the original object or in the geometry data, acquired during the structured light measurements. The correctness of the scale was confirmed using control distances for each object. The RMSE of the bundle adjustment was less than one pixel in the image space.

[4] http://www.photomodeler.com

4.2.2 Rectified Images

To do the ortho-image rectification the necessary elevation model or surface was generated using additional manual measurements. The point density was defined according to the curvature of the object, the relative pose between the images and the required accuracy. According to these parameters the point density was specified to one point per ten square centimetres, homogeneously distributed.

First, the camera distortions were corrected using the parameters, determined during the camera calibration. The height or Z-values were interpolated with an inverse distance weighting algorithm using the closest three points. Because of the smooth curvature and the sufficient point density, a higher approximation, e.g. polynomial or spline functions were not necessary. Each image was processed separately. According to the use of the full set of orientation parameter and generation of the ortho-images in the local coordinate system, the final ortho-images for each part were oriented in the same reference system. Therefore, the stitching could be conducted using two shift parameters. An introduction of additional rotations was not necessary.

According to different illumination conditions during the image acquisition the brightness of the images differed partly significantly. To reduce this effect, the brightness and the colour of the images were adjusted to each other using an in-house developed algorithm, presented in (Hanusch, 2008).

4.3 Contrast Enhancement

In the previous steps, rectified images were generated to paint the object. However, in some regions the original object is very dark and shows low contrast. This makes it difficult to recognize fine details, e.g. rivers, borders or letters, in order to copy them from the rectified images to the physically reconstructed object. Therefore, the customer demanded a set of rectified images, with fine details and good contrast, even if the colour information does not correspond to the original colour. To fulfil this requirement, adaptive histogram equalization was performed to brighten the dark regions and to reduce the brightness in over-exposed regions in a patch-wise manner.

Finally, each part was delivered either in one stitched image or in separate images in the size of DIN A3/A4 to enable an easy printing to this format on the customer side. The geometric correctness was proved comparing the overlaying images on the original object. A deformation between the object and the rectified images was not recognizable. Therefore, the required accuracy, specified as one percent in geometrical fitting between original and the copy were fulfilled.

5. CONCLUSIONS

The reconstruction procedure to generate a master copy of an ancient globe is presented in the paper. Two image-based techniques have been employed to record the object, namely multi-image network and structured light measurements. The strength of each technique has been exploited to fulfil the project requirements with minimal manual effort.

Structured light systems can provide the 3D point cloud of the surfaces almost independent of the texture quality of the surface. The original measurements were processed on the job and the final geometric results were available after some post processing (triangulation, hole filling, smoothing, etc.), to transfer the point clouds to surfaces, in a few days.

Multi-image networks were used to obtain the textural information and the geometry of the sphere. The images were processed following the conventional orientation and rectification processes. The rectification was done with different geometries (spherical and planar surfaces) and finally the images were corrected for the brightness variations and enhanced to some extent.

We have done all the measurements in a laboratory environment to control the illumination conditions for both types of measurements. However, the structured light approach was not always successful because of the low reflection of the projected stripes over the aged dark wooden surfaces. In addition, the tight field of view of the system would have led to the need of many scans, which was not possible due to working time restrictions. To measure these missing parts we have used images as well.

Although the result we obtain was satisfactory for the customer, there are some issues that have to be addressed for further considerations. Although we have used laboratory illumination, often the common areas in different images had severe brightness/contrast and sometime colour differences. This was due to (a) the curvature of the object, (b) the movement of the illumination during the image capturing because of the object size, and (c) the change of the brightness gain of the camera during image capturing. We have already tried some algorithmic colour/brightens/contrast corrections, but the results were not really satisfactory. Therefore, obtaining a high-resolution homogeneous textural information needs more efforts (see Figure 8 for a typical problem).

Even though we have measured quit dense and high quality data of both geometry and texture, the use of the information was not easy due to the volume of the data. For example, delivering the surface model to an architect had to be done after a significant decimation of the data. In addition, since the quality of the textural information is very high, thus its volume (>1.5 GB image data), the visualization of the 3D model of the sphere with texture is very expensive and requires customized advanced visualization software. The software should load the images in tiles and performs Level of Detail (LOD) techniques which imply more efforts and software development.

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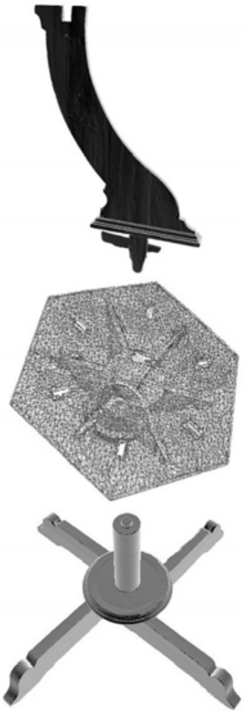

Figure 6. From top to bottom: The reconstructed surface of one of the supporting legs, the wire frame of the table surface and the base of the table.

Figure 7. The textured globe model and the reconstructed wire frame of some of its parts.

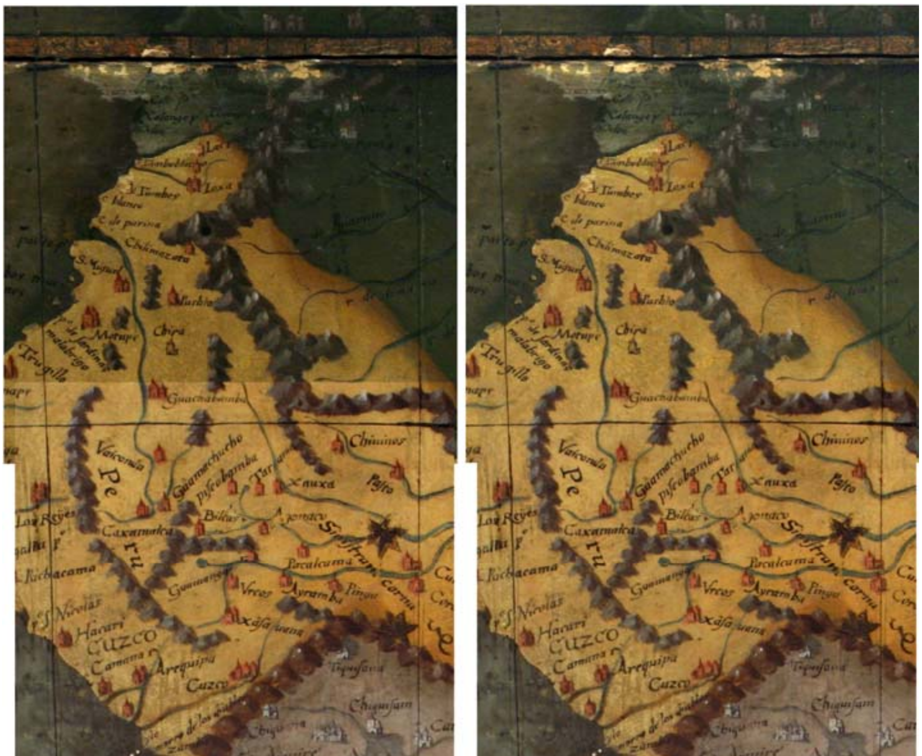

Figure 8. Left: A stitched mosaic of parts of three rectified images of a slice of the sphere. In the upper part a clear seamline is visible. Right: The radiometrically corrected image.