3D modeling and visualization of Cultural Heritage sites from high-resolution satellite imagery

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ABSTRACT: Today different satellites provide imagery with high potentials for applications in various fields of geomatics (e.g. DTM extraction, topographic mapping, GIS applications, Cultural Heritage documentation). The ground resolution of the satellite scenes is constantly increasing and the scenes can be acquired world-wide in different radiometric modes. In this contribution we present the modeling and visualization of the Cultural Heritage area of Bamiyan, Afghanistan, using high-resolution satellite imagery. The region, situated ca. 200 km north-west of Kabul, was one of the major Buddhist centres until the ninth century AD. The two standing Buddhas belonged to some of the most famous Buddhist monuments world-wide. They were a symbol for the region and they were destroyed in 2001 by the Taleban militia. In our previous reports we have already presented the 3D computer reconstruction of the Great Buddha and the Bamiyan cliff, while here we will describe the terrain modeling of the UNESCO World Heritage site from satellite images.

1 INTRODUCTION

Many cultural heritage applications require precise 3D reconstruction for documentation and visualization purposes and over the past decade it has become increasingly common to use 3D digitization and modeling techniques for these purposes. In particular, for the computer modeling of large sites, spaceborne images are requested and their choice mostly depends on the data availability for a specific location and time, their price and the required scale of application. The motivations that lead to the use of spaceborne data are different: (1) the available technologies for data acquisition, processing and visualization are continuously improving; (2) the increased availability and repeatability of satellite images; (3) the interest of UNESCO and other organizations in large site modeling and documentation; in fact UNESCO has started the ‘Open Initiative’ partnership with different space agencies to support and assist in the monitoring and documentation of World Heritage sites, natural hazards and for sustainable development using satellite data [Earth Imaging Journal]; (4) space images are often competing with traditional aerial photos in particular in problematic countries where aerial images are not available or no surveying company is operating.

Among the available satellite data, high-resolution imagery with a footprint smaller than 5 m are becoming increasingly available to the earth observation community and their clients. Spaceborne sensors like QuickBird, IKONOS, SPOT-5/HRG (High-Resolution-Geometry) and IRS-1C/1D provide not only for high-resolution (0.6–5.0 m) in panchromatic or multi-spectral mode, but also for the capability of stereo mapping, along or across flight direction.

In most cases the spaceborne imaging sensors use linear array CCD technology. The possibility and need for accurate 3D object reconstruction from linear array requires a suitable camera model, able to deal with such sensor geometry. In fact, unlike the traditional frame-based aerial photos,
each line of the linear array image is collected in a pushbroom fashion at a different instant of time. Therefore, the perspective geometry is only valid for each line whereas it is close to a parallel projection in along-track direction. Moreover, for each line, there is a different set of (time-dependent) values for the exterior orientation elements. Usually multiple view terrain coverage capability is available and the high quality image data results in a major improvement for image matching in terms of precision and reliability. Therefore the processing of these kinds of images provide a challenge for algorithmic redesign and improvement of many photogrammetric processing components, such as image enhancement, triangulation, orthophoto, DTM generation and object extraction. In recent years, a large amount of research has been devoted to efficiently use these high spatial resolution imagery data. Examples can be found in sensor modeling and image orientation [Baltsavias et al., 2001; Jacobsen, 2003; Grodecki and Dial, 2003; Fraser et al., 2002; 2003a; 2003b; Poli, 2004], automatic DTM/DSM generation [Jacobsen, 2004; Toutin, 2004; Poli et al., 2004; Zhang and Gruen, 2004; Toutin et al., 2004] and feature extraction [Shan, 2003; Hu and Tao, 2003; Di et al., 2003; Baltsavias et al., 2004]. Few packages are available for the complete processing of high-resolution satellite imagery, including sensor modeling, DTM/DSM and ortho-photo generation. We have recently developed a full suite of new algorithms included in the software package SAT-PP for the precision processing of high-resolution satellite image data. The software can accommodate images from IKONOS, QuickBird, ALOS/PRISM, SPOT-5/HRG and HRS, and sensors of similar type to be expected in the future. SAT-PP allows image pre-processing, orientation, matching, DTM/DSM generation and object extraction [Zhang and Gruen, 2004; Poli et al., 2004; Gruen et al., 2005].

In this contribution we present the modeling and visualization of the Cultural Heritage area of Bamiyan, Afghanistan, a SPOT-5/HRG stereopair is used for DTM generation and a pan-sharpened IKONOS scene for texture mapping. The region is situated approximately 200 km north-west of Kabul and was one of the major Buddhist centres until the ninth century AD. The two standing Buddhas of Bamiyan belonged to some of the most famous Buddhist monuments world-wide. In 2001 they were destroyed with an act of vandalism by the Taleban militia and since 2003 the cultural landscape and archaeological remains of the Bamiyan valley are included in the UNESCO World Heritage List [http://whc.unesco.org/]. In previous reports [Gruen et al., 2004a, Gruen et al., 2004b] we have already presented the 3D computer reconstruction of the Great Buddha, its actual empty niche and the Bamiyan cliff. In this paper we report about the landscape modeling of the larger environment for documentation and visualization purposes. The photogrammetrically generated datasets are afterwards ported to a GIS platform and used for the generation of a cultural and tourist information system.

2 TERRAIN MODELING FROM SATELLITE IMAGERY

For the 3D modeling and visualization of the Bamiyan area, an accurate DTM is required. The contours of a Russian map 1:50 000 were available in digital form, but when we tried to map an IKONOS image onto the derived DTM we realised that its quality was not sufficient. Aerial images were not available to us and the idea to acquire them was unrealistic, due to the absence of any surveying company operating in that area. So space-based image acquisition and processing resulted as the only alternative to the aerial photos or any other surveying method. Nowadays space images are competing successfully with traditional aerial photos, for the purpose of DTM generation or terrain study in such problematic countries as Afghanistan. Moreover, the resolution and availability of world-wide scenes taken from satellite platforms are constantly improving and those scenes are available in different radiometric modes (panchromatic, multispectral) and also in stereo mode.

2.1 The available satellite images

The HRG sensor carried on SPOT-5 since May 2002 was suitable for our tasks [http://www.spotimage.fr]. The sensor can acquire stereo images in across-track direction at 2.5 m ground resolution in panchromatic mode. The time difference between two successive acquisitions in
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stereo mode of the same area depends on the incidence angle, with a minimum of one day difference. The satellite flies at a mean height of 832 km, along a quasi-polar and sun-synchronous orbit. Due to the scientific, social and cultural interest of the Bamiyan project, a panchromatic SPOT-5/HRG level 1A stereo pair (radiometrically but not geometrically corrected) over the UNESCO cultural heritage area was provided at special conditions by the ISIS Program [http://medias.obs-mip.fr/isis/]. The two scenes, overlapping across flight direction, have been acquired on 18th December and 19th December 2003, at 10:40 a.m. and 10:20 a.m. local time respectively. The scenes are 24,000 \times 24,000 pixels large and cover a mountainous area of approximately 60 \times 60 km, centered at (34°50′ N, 68° 7′ E) and (34°50′ N, 67°48′ E). The cloud cover was zero and the ground resolution is 2.5 m (supermode). Furthermore, a colour Geo level IKONOS image mosaic over the Bamiyan area was provided by Space Imaging [http://www.spaceimaging.com] (Figure 1). The scene was acquired on 15th December 2001 and covers an area of 13 \times 20 km, centred at (34°46′ N, 67°49′ E). The image size is 13,957 \times 21,118 pixels and the ground resolution is 1 m.

![Figure 1. The two empty Buddha niches as observed by IKONOS (courtesy of Space Imaging, Inc.) from 650 km of altitude. Left: the Great Buddha empty niche. Right: the Small Buddha empty niche.](image)

### 2.2 GPS measurements

For the georeferencing of the satellite images, seven GPS points were measured during our field campaign in August 2003. Two Trimble GEO Explorer receivers logging carrier phase data (C/A code) were used; one receiver was set as ‘master’ (fix position) and the other served as ‘rover’. The points were identified on the IKONOS image and then measured in C/A mode. After the data collection, the observations were post-processed to generate more accurate positions. It was not possible to perform absolute differential corrections, as the closest master station was ca. 1500 km away. Table 1 summarises the GPS measurements.

<table>
<thead>
<tr>
<th>No. of points</th>
<th>Average satellites</th>
<th>Average PDOP</th>
<th>Horiz. accuracy</th>
<th>Vert. accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>6</td>
<td>2.78</td>
<td>0.11 m</td>
<td>0.3 m</td>
</tr>
</tbody>
</table>

### 2.3 Scenes orientation

Most of the high-resolution satellite cameras use linear arrays to acquire a single image line at an instant of time, each with its own positional and attitude data. The imaging geometry is characterized
by nearly parallel projection in along-track direction and perspective projection in across-track direction. A rigorous model can be used to reconstruct the physical imaging geometry and to model transformations between the object space and the image space. Due to the dynamic nature of satellite image acquisition, this kind of model is more complicated than in the single frame acquisition case. A sensor model, based on the collinearity equations and the use of different forms of trajectory models could be applied [Gruen and Zhang, 2002; Poli, 2004]. Alternatively, Rational Function Models (RFMs) have recently drawn considerable interest in the remote sensing community [Tao and Hu, 2001; Fraser and Hanley, 2003; Grodecki and Dial, 2003]. This is due to the fact that some commercial high-resolution satellite imaging systems, such as IKONOS, are only supplied with Rational Polynomials Coefficients (RPCs) instead of rigorous sensor model parameters. A RFM is generally the ratio of two polynomials derived from the rigorous sensor model and the corresponding terrain information. These models do not describe the physical imaging process but use a general transformation to describe the relationship between image and ground coordinates.

In our application, the images were oriented within the SAT-PP package. The IKONOS mosaic orientation was based on the rational function model: we first used the available RPCs to transform from object to image space and then using these values and the known pixel coordinates we estimated the six 6 parameters of a 2D affine transformation. For SPOT stereopair orientation, a rational function model was also employed. Using the camera model, the calibration data and the ephemeris contained in the metadata file, the software estimates the RPC (Rational Polynomial Coefficients) for each image and applies a block adjustment in order to remove systematic errors in the sensor external and internal orientation. The scenes’ orientation was performed with the help of the GCPs measured with GPS. Table 2 shows the image orientation results.

Table 2. Image orientation results.

<table>
<thead>
<tr>
<th>Source</th>
<th>RMSE East (m)</th>
<th>RMSE North (m)</th>
<th>RMSE Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKONOS</td>
<td>0.56</td>
<td>0.48</td>
<td>–</td>
</tr>
<tr>
<td>SPOT Image Pair</td>
<td>1.22</td>
<td>2.01</td>
<td>1.50</td>
</tr>
</tbody>
</table>

2.4 DTM generation

The algorithm of SAT-PP for DTM/DSM generation has the ability to provide dense, precise, and reliable results. The approach uses a coarse-to-fine hierarchical solution with a combination of several image matching algorithms and automatic quality control. The new characteristics provided by the linear array imaging systems, i.e. the multiple view terrain coverage and the high quality image data, are efficiently utilized in this approach. It essentially consists of several mutually connected components: the image pre-processing (enhancement, pyramids generation, etc.), the multiple primitive multi-image matching of different features (feature points, grid points and edges), the refined matching through the image pyramid and the system performance evaluation. A TIN from the DSM is reconstructed from the matched features on each level of the image pyramid by using the constrained Delauney triangulation method. Then the TIN is used in the subsequent pyramid level for the approximations and adaptive computation of the matching parameters. Finally, least squares matching methods are used to achieve more precise matches for all the matched features and for the identification of some false matches.

The oriented SPOT stereo pair was subjected to the automated DTM/DSM generation and a point cloud of approximately 8,500,000 points was obtained. Then a 20 m raster DTM for the whole area and 5 m raster DTM for the area covered by the IKONOS image were interpolated from the original matching results (Figure 2), using also some manually measured breaklines near the Buddha cliff.
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3 DTM DATA VISUALIZATION

The visualization of the produced DTM is a very important element, as for the external world it is usually the unique and possible contact with the 3D model. Visualization packages and tools are available in different forms. For DTM visualization (often called 'geovisualization'), more than 500 packages are available, while many other developed software packages are not widely known and public. The packages can be classified according to their real-time performances, the rendering quality of geometry and texture, the anti-aliasing function, the input data, the level of detail (LOD) properties, etc.

For the photo-realistic visualization of the whole Bamiyan area (49 km x 38 km), a 2.5 m resolution SPOT-5 B/W ortho-image and a 1 m resolution IKONOS pansharpened ortho-image were generated. The textured 3D models (rendered with Erdas-Virtual GIS) are shown in Figures 3, 4, and 5.

The Bamiyan dataset has a size of ca 640 MB (SPOT) and 1.4 GB (IKONOS) and it requires very powerful visualization software for interactive use. We employed Skyline (IDC AG), Erdas Virtual GIS and ESRI ArcGIS-ArcScene for data rendering, real time demos and video generation and in the following sections a short comparison is reported. All the software allows interactive or user-defined flythrough animations.
Figure 4. Closer view of the Bamiyan valley modeled and textured with a SPOT-5 image.

Empty niche of the Great Buddha

Empty niche of the Small Buddha

Rock cliff with Buddha niches

The new ‘bazaar’

Shahr-i-Ghulghulah, the old Bamiyan city

Figure 5. Zoom into the 3D Bamiyan terrain model textured with an IKONOS ortho-image. The rock cliff with the two empty niches (above), the pyramid-type hill (Shar-i Ghulghulah) where the old city was located and the Bamiyan cliff and the new ‘bazaar’ of the village (below).
3.1 Erdas–Virtual GIS 8.6

The package works with its own internal file format (IMG), reducing considerable the file size. The LOD can be only statically applied to the whole scene. A dynamic LOD can be applied generating a ‘Virtual World’ where the model is divided in different sectors and, for each sector, the software constructs a pyramid of detail for geometry and texture. In the generated virtual world, the user can easily navigate through the scene while the details are automatically adapted according to the model’s distance from the viewer.

3.2 Skyline–Terra Builder

The software converts all the data (geometry and texture) in its own internal and binary file format (MPT), which can reduce the total data size by a factor 4. The interactive and offline navigation is very easy, due to the dynamic LOD. Unfortunately different aliasing artefacts are presented in the rendered model and the LOD resampling produces a noticeable reduction in the image texture quality.

3.3 ESRI ArcGIS – ArcScene 8.3

ArcScene is mainly a 3D GIS tool of ArcGIS. The DTM data are imported as regular grid and then a TIN is generated in an internal binary format. The software cannot perform real-time rendering of big data sets, it has a static LOD control but it can easily display different vector information without aliasing effects. The ‘extrude’ function can display in 3D features from 2D vector data sources and generate lines, walls or solids.

4 TOURIST INFORMATION SYSTEM

A GIS is a software used to map, collect, manage and analyze geographical other related kinds of geometrical and attribute data. GIS records the geometry and location of features in layers and the combination of layers of information related to a place gives a better understanding of the area. The GIS technology allows database operations like queries and statistical analysis together with the visualization and geographic analysis of maps. The use of GIS in heritage management has been also underlined by UNESCO, as a GIS allows (1) historical and physical site documentation, (2) the assessment of physical condition, cultural significance and administrative context, (3) the preparation of conservation and management strategies, (4) the implementation, monitoring and evaluation of management policies [www.unescobkk.org/culture/gis/]. Furthermore, a GIS tool generates permanent records of heritage sites, including also text documentation, virtual flight-over and 3D models.

The information extracted from the high-resolution satellite imagery was ported to a GIS platform (ArcView and ArcGIS) for further analysis, visualization and topographic information generation. The UNESCO ‘cultural landscape and archaeological remains of the Bamiyan valley’ includes 8 locations, identified with an area of interest and a buffer area:

1. Bamiyan Cliff including the niches of the 38 meter Buddha, the seated Buddhas, the 55 meter Buddha and surrounding caves;
2. Kakrak Valley caves including the niche of the standing Buddha;
3. Qoul-I Akram Caves in the Fuladi Valley;
4. Kalai Ghamai Caves in the Fuladi Valley;
5. Shahr-i-Zuhak;
6. Qallay Kaphari A;
7. Qallay Kaphari B;
8. Shahr-i-Ghulghulah.

The 8 protected areas as well as man-made objects (e.g. streets and buildings) and rivers were identified and measured manually from the ortho-images. A total of 243 objects were extracted and then overlapped onto the recovered DTM and ortho-image (Figure 6 and Figure 7).
Furthermore, from the DTM raster grid, the contour lines of the area could be computed and displayed together with the man-made objects, to generate a new plan of the Bamiyan village (Figure 8).

5 CONCLUSIONS

The reported work has shown the computer modeling of the entire UNESCO area of Bamiyan, Afghanistan, using high-resolution satellite imagery. Nowadays space images are competing successfully with traditional aerial photos, for the purpose of DTM generation, terrain study and visualization. Their availability, repeatability and resolution is still increasing and they can contribute in the monitoring and documentation of many Cultural Heritage areas. For the photo-realistic 3D
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digital models of the entire Bamiyan area different commercial packages have been used, but the management of large terrain data sets is still problematic, in particular for real-time rendering. In addition, the DTM and other topographic data have been imported into a GIS software to create an information system of the protected area, which may serve for technical, scientific and tourist purposes in the future.

ACKNOWLEDGEMENTS

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REFERENCES


