

Fusion of Three-Dimensional Data at Tiwanaku: An Approach to Spatial Data Integration

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Abstract

Between 2005 and 2007, a wide range of digital geospatial data were collected to document the pre-Columbian site of Tiwanaku, an actively excavated UNESCO World Heritage site on the Bolivian altiplano. Methods of data collection at this site include ground-based geophysics, terrestrial laser scanning, digital aerial photogrammetry, and total station surveys. In addition, existing sources of spatial information were collated and digitized. These data originate in various native formats, coordinate systems, and scales, and were collected during multiple epochs across several disciplines. This integrated geospatial model functions as a single spatial database in which information gathered at Tiwanaku across the last century, as well as data collection in the future, can be combined in a compatible and accessible manner. This paper summarizes the efforts of integrating geospatial data by co-referencing to a common coordinate system and converting to a universal file type for manipulation within a single software package.

Keywords

data integration, fusion, visualization, 3D

1. Introduction

Spatial data integration is quickly becoming an important topic for researchers employing high density survey methods (Alshawabkeh and Haala 2004, Lambers *et al.* 2007) and there are many organizations seeking methods for incorporating spatial data, collected through multiple sources, for both visualization (Waggott *et al.* 2005) and metric analysis (Miller and Nusser 2003). The analysis of spatial relationships, especially at high resolution, is evolving from the use of a handful of two-dimensional data sets at a time, to models that include a multitude of three-dimensional data sets, each containing a myriad of attributes. The integration of disparate data from multiple data sources, however, remains a significant issue in the creation of comprehensive spatial databases. With regard to this project, data

sources include terrestrial LiDAR surveys, shallow subsurface geophysical surveys, digital aerial photogrammetry, and total station surveys, as well as the digitization and incorporation of historical data sets. This paper will explore the types of data collected at Tiwanaku, some inherent differences between these data, and an approach used to integrate these data into a single, site-wide, three-dimensional model of Tiwanaku.

2. The Site of Tiwanaku

In collaboration with the Museum of Archeology and Anthropology and the General Robotics, Automation, Sensing and Perception (GRASP) Lab at the University of Pennsylvania, a team from the Center for Advanced Spatial Technologies (CAST) at the University of Arkansas has been involved in a multi-

year project at the pre-Columbian archaeological site of Tiwanaku. Situated high in the Bolivian Andes along a flat uprising of land referred to as the altiplano, the city of Tiwanaku consists of a series of mounds, platforms, and sunken courts that document over a millennium of ritual architecture. The people of Tiwanaku constructed these monuments to form the core of their city whose influence by the latter half of the first millennium stretched across the altiplano and into the Andes. So profound are these ruins that Tiwanaku was recognized as the birthplace for the people of the Andes when the site was rediscovered by Incan conquests in the 1500's.

At the core of Tiwanaku is the Akapana (*Fig. 1*), formerly a large stepped pyramid which likely housed a sunken court at its summit. To the north lies the Kalasasaya, a large platform temple with massive upright stones marking the annual solar cycle, and the adjacent *Templeté*, a semi-subterranean structure that represents one of the earliest monumental constructions at the site (Chávez 2004). To the east are the scattered ruins of the Kantatayita, a monument visible on the surface that has only recently been investigated via excavations (Koons 2006). One kilometer to the southwest are found the remains of the Pumapunku, a large platform mound similar to the Akapana (Vranich 1999, 2006). Surrounding this core of monumental architecture is a dense scatter of pottery, ash, and other artifacts that covers an area between four and six square kilometers (Parsons 1968), including the modern town of Tiahuanaco to the west of these ruins.

3. Spatial Data at Tiwanaku

The Tiwanaku data reported here were collected and processed as part of the Proyecto Arqueológico Pumapunku-Akapana (PAPA), directed by Alexei Vranich. For the past 12 years, this project has included an intense interest in exploring spatial relationships at Tiwanaku. The major goal of PAPA has been to collect and collate accurate spatial data in order to explore these relationships and gain a better understanding of Tiwanaku. In the summers of 2005 and 2006, PAPA team members conducted geophysical surveys, archaeological laser scanning surveys and photogrammetric surveys using historical aerial photographs to complement the traditional archaeological investigations that were being conducted at this UNESCO World Heritage site.

3.1. Data Collection at Tiwanaku

Prior to the most recent field seasons, some spatial data was collected at Tiwanaku during the early expeditions at the site, with the majority of this early data recorded by Arthur Posnansky in the early 1900s. Posnansky is responsible for creating the 1911 topographic map of the site (Posnansky 1945) which, prior to this project, was the most accurate published map of Tiwanaku.

In 1996, under the direction of Vranich, a total station survey project was initiated to document archaeological features and excavations as well as the corners of many *in-situ* monument stones at

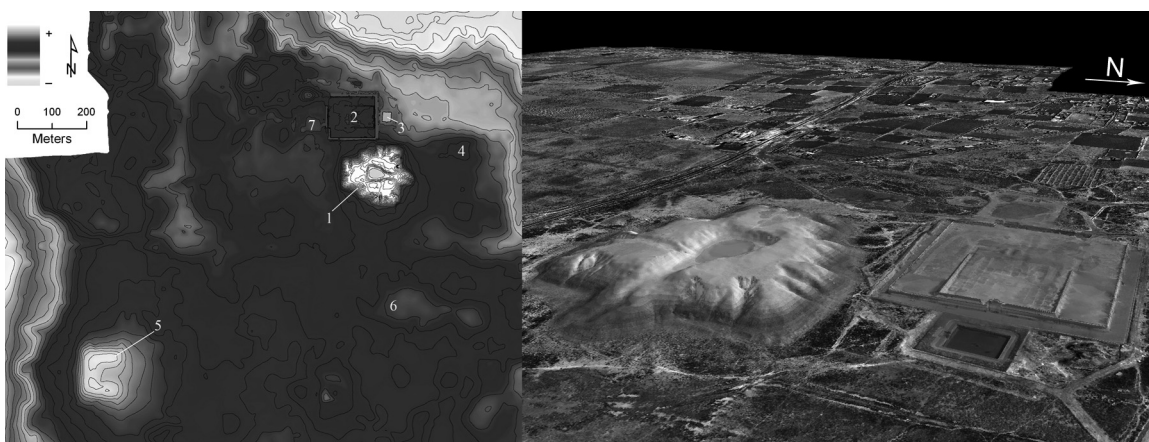


Fig. 1. (left) Topographic map showing principle Tiwanaku monuments mentioned in the text (contour interval = 1 m).

Key: 1. Akapana; 2. Kalasasaya; 3. Templeté; 4. Kantatayita; 5. Pumapunku; 6. Mollo Kontu; 7. Putuni. (right) 1972 orthophoto of Tiwanaku draped over digital surface model extracted from 1972 photogrammetric block with major monuments highlighted by elevation.

the site. This survey used a local coordinate system aligned to astronomical north, a local origin, and meter units. Survey results were compiled into a CAD database each year and served as the single most comprehensive survey for the site.

Digital photogrammetry was performed on two groups (or blocks) of analog black and white aerial photographs taken from above Tiwanaku’s monumental core (Table 1). Group 1 consisted of ten photos from 1972 with an average scale of 1:5,150. From these photographs, a digital surface model, with an average point density of two points per square meter, and an orthophoto, with a resolution of 6.5 cm, were derived (Table 2). Group 2 consisted of two photos from 1992 with an average scale of 1:16,100. From this group, a digital surface model, with an average point density of one point per square meter, and an orthophoto, with a resolution of 20.4 cm, were derived (Barnes and Cothren 2007).

	Average Scale	Average Flying Height (m)	Ground Sample Distance (cm)
1972 Photos	1:5 150	782	6.5
1992 Photos	1:16 100	2470	20.4

Table 1. Average scale, flying height (m), and ground sample distance (cm) for the 1972 and 1992 photogrammetric blocks.

	Resolution	Area of Coverage	Contour Interval	Core Area RMSE
1972 Ortho Mosaic	6.5 cm	360 ha		0.57 m (H)
1992 Ortho Mosaic	20.4 cm	710 ha		0.83 m (H)
1972 DEM	0.5 m	330 ha		0.45 m (V)
1992 DEM	1.0 m	550 ha		0.86 m (V)
1972 Contour Lines		330 ha	1 m	
1992 Contour Lines		550 ha	2 m	

Table 2. Resolution and area of coverage for photogrammetric products.

Terrestrial laser scanning was carried out at Tiwanaku during the summer field seasons of 2005 and 2006 (Goodmaster and Payne 2007; Goodmaster *et.al.* 2007). In 2005, the goals of the survey were to collect high resolution digital data using an Optech ILRIS-3D system of several structures and monoliths within the monumental core of the site. Specifically, these included the Kalasasaya, Templete, and Putuni monuments. A return visit in 2006 served to collect data for areas missed during the 2005 survey, as well as many recently excavated trenches around

the Akapana. The 2006 field season also provided an opportunity to field test a Konica-Minolta VIVID 9i for scanning monoliths and artifacts at sub-millimeter resolution. Specifically, the Minolta scanner was used to document the frieze of the Puerta del Sol monolith, one of the most well known Andean archaeological artifacts.

Geophysical techniques utilized at Tiwanaku include ground-penetrating radar (GPR), magnetic gradiometry, induced electromagnetic conductivity, and magnetic susceptibility. This multi-sensor approach has proved to be very useful in discovering several subsurface features, and distinguishing the depth and nature of construction materials. The geophysical survey at Tiwanaku included one of the largest GPR surveys known to date, with a total survey area of approximately six hectares. Ground-penetrating radar proved to be the most useful and versatile method because it detects the majority of subsurface features and allows their depths to be estimated. Magnetic gradiometry provided a powerful complement by distinguishing between igneous rock (e.g. andesite) and other common rocks used in construction (e.g. sandstone and limestone). Magnetic susceptibility and electromagnetic conductivity (both collected with an electromagnetic induction instrument) provide additional insight for feature interpretation (Ernenwein and Koons 2007; Herrmann *et al.* 2007).

4. Data Integration

While each of these surveys are individually informative, the integration of multiple spatial datasets is widely acknowledged (cf. Wang *et al.* 2006) and essential for a holistic understanding of this large and complex archaeological site. Geophysical survey provided insight as to the shallow subsurface features of Tiwanaku while digital photogrammetry provided a large-scale perspective of topographic relief, lending a site-wide context. Terrestrial laser

scanning data provided a near-horizontal, high-resolution perspective necessary for documenting the monumental architecture present at the site (cf. Lambers *et al.* 2007, 1705). Traditionally, the common method of analyzing three-dimensional spatial data is through the use of a Geographic Information System (GIS). Although many GIS software packages contain powerful tools for many types of spatial analyses, the ability to efficiently handle massive amounts of three-dimensional data (i.e. several million points) is often lacking. Furthermore, geospatial databases, compiled within specialized software packages, are oftentimes difficult to distribute to researchers and collaborators, or disseminate to the larger scientific community, because these individuals often lack the specialized software necessary to view and analyze such data. A solution for this problem should be a software package which can be freely distributed, handle large three-dimensional data sets, and allow researchers to perform multi-scale dimensional analysis. Below is an outline of how the above data sets were co-referenced into a common coordinate system, converted into a common file format, and integrated within a single three-dimensional digital environment (Cothren *et al.* 2007).

4.1. Issues with Integration

Table 3 summarizes the above mentioned data sets and estimates the number of data “points” associated with each (in the case of raster data sets, the number of points equals the number of cells). In total, geospatial information collected at Tiwanaku is comprised of approximately 500 million data points. There are many challenges inherent in integrating seemingly disparate three-dimensional data sets, including not only the vast number of points associated with them, but also the multiple scales of the data, fundamental differences in the data types, multiple data epochs, incompatible data formats, and multiple coordinate systems. Of these issues, the question of coordinate systems is one of the more difficult to solve. Very often, digital data is collected in an arbitrary coordinate system. Each phase of data collection introduces a new coordinate system that must be “aligned” or

“referenced” to another phase in order to produce a single model. This can be relatively straightforward for overlapping data collected by a single instrument, but can be much more difficult between datasets collected with multiple instruments. In the case of Tiwanaku, instruments collecting data (or methods of data creation) over a common area had very little in common. Not only were data collected in different formats, scales, time periods, and coordinate systems, but in the case of geophysics, the data include characteristics of subsurface locations. All of these factors can contribute to the difficulty in identifying common points between data sets (Cothren *et al.* 2007). In the end, a relatively small number of common points were identified across as many of the data sets as possible. However, even the common points did not represent the same “point” on the surface in each data set. The laser scanner, while it rapidly collects densely spaced data points, substitutes density for precise pointing and thus may not directly measure interesting corners and edges (cf. Marshall and Gilby 2001). Similarly, data collected by the geophysical surveys, as well as those extracted through digital photogrammetry, represent data generated at fixed intervals. Therefore, the common points used for alignment and error assessment are thus interpolated in all but the total station survey. By virtue of its manual collection, the total station survey was the only survey to directly measure corners and edges of objects. Thus, errors include actual differences in the object as they change in time, instrument biases, common point interpolation effects and, finally, random errors.

Data Set	Date	# Data Points (approximate)
Total Station Survey	1996–2004	2000
Posnansky Topographic Map	1911	Hundreds
Low-altitude image block	1972	20 Million
High-altitude image block	1992	10 Million
Geophysical Survey	2004–2006	1 Million
Optech Laser Scanner (long range)	2005–2006	300 Million
Konica-Minolta Scanner (short range)	2006	200 Million

Table 3. An approximation of the number of points found within each data set.

4.2. Co-referencing data sets

In this case, the organized point clouds reside in a local coordinate system set up in 1997 for the site-wide total station survey. This system has a local origin and is oriented with respect to astronomic north. Because

it is the most accurate survey to date, all successive data have been tied to this coordinate system. Within the integrated site model, it is possible to make very accurate relative measurements. For example, a researcher may measure the width of a structure wall with centimeter accuracy and the distance between an anomaly visible in the geophysics surveys and architecture visible in Posnansky’s 1911 survey with decimeter accuracy (Cothren *et al.* 2007). However, care must be taken when measuring across data layers to ensure that integration errors (described in Section 4.1) are taken into account. The integrated model can facilitate this assessment by reporting which data layers measurements are using.

4.3. Converting to a Common File Format

Raster data sets (orthophotos, geophysical data, and digital elevation models) were converted into three-dimensional point files containing x, y, z, and i values for each point. This process, shown in *Figure 2*, included several steps. First, raster files were converted to point files containing x, y, and i values based on the centroid of individual raster cells. These points were then given z values by evaluating their spatial location relative to an overlapping DEM. The resulting file, containing x, y, z, and i values for each

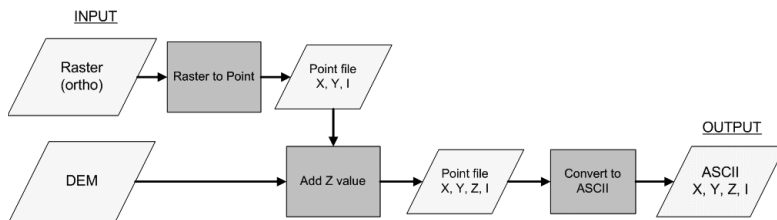


Fig. 2. Method used for converting raster images to point clouds.

point, was then converted to an ASCII format and treated as a point cloud (Cothren *et al.* 2007).

5. The Present 3D Model

The present 3D model of Tiwanaku includes multi-scale, multi-temporal, and multi-source “organized” point clouds co-existing within a single coordinate system, and containing hundreds of millions of points. This model is a dense collection of three-dimensional observations describing the topology and morphology of Tiwanaku’s monumental core. Each point in the cloud contains attributes (i) that describe additional properties of the surface (e.g. color as measured by digital cameras, reflectivity of infrared light from the LIDAR source, geophysical properties of the soil). This “organized” point cloud contains additional information in the form of connectivity among points in the cloud. For example, points in the Tiwanaku site model “know” which points they are closest to and whether they belong to the same surface as those points. This organizing information facilitates efficient processing of the huge dataset, but more importantly, provides guidance in automated feature extraction, analysis and model query (Cothren *et al.* 2007).

The degree to which these data sets were aligned was determined by measuring the amount of offset between two layers at approximately 20 locations chosen at random, and computing a least squares root mean squared error (RMSE). *Table 4* shows the values found between the total station survey data (the common dataset for co-referencing) and each of the other data sets. Also included is the vertical RMSE

RMSE (meters)	Total Station Survey	Laser Scanner	1972 Surface Model	1992 Surface Model	1972 Orthophoto	1992 Orthophoto
Total Station Survey		0.064	0.45	0.86	0.57	0.83
Laser Scanner			NA	NA	NA	NA
1972 Surface Model				0.92 (vertical)	NA	NA
1992 Surface Model					NA	NA
1972 Orthophoto						0.72 (horizontal)
1992 Orthophoto						

Table 4. Error matrix containing Root Mean Squared Error (RMSE) values describing data set alignment.

found between the two surface models, and the horizontal RMSE found between the orthophotos.

6. Conclusions

The integrated model of Tiwanaku described was produced using a variety of software, both off-the-shelf and special purpose written by team members. The final integrated model is stored in a format compatible with InnovMetric's Polyworks, because of this software's ability to efficiently manage and manipulate large, organized, 3D data. One component of the Polywork's suite is IMView, a free viewer which allows manipulation and measurement. The software viewer, datasets, and fieldwork summaries are available on the website: <http://www.cast.uark.edu/projects/tiwanaku/>, which provides an opportunity to not only virtually explore this World Heritage site, but also propose and test hypotheses about spatial relationships among its surface and sub-surface features.

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