Acquisition, registration and application of IKONOS space imagery for the World Heritage Site at Merv, Turkmenistan

Marek Ziebart, Department of Geomatic Engineering, University College London, UK
Peter Dare, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada
Tim Williams, Institute of Archaeology, University College London, UK
Georgina Herrmann, Institute of Archaeology, University College London, UK

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Abstract

A number of ancient cities existed on the Silk Road at Merv in Turkmenistan, and the remains were declared a World Heritage Site in 2000. Many archaeological excavations have been carried out on the site, but no means existed to place them all in one internally consistent spatial framework. No map base was available of either the ancient or modern landscapes. The solution to these problems is discussed in the paper.

Panchromatic 1 m-resolution imagery for the site area was acquired from the IKONOS remote sensing satellite during 2001. The acquisition epoch for the black-and-white data was selected to minimise masking due to vegetation and cloud cover. The precise locations of points of detail in the imagery, required for spatial registration of the remote sensing data, were determined by a Global Positioning System observation campaign. These locations were computed using the globally consistent International Terrestrial Reference Frame and projected using the appropriate Universal Transverse Mercator zone. The fieldwork, computational procedures and reasons for choice of reference frame and projection are described. The results of the spatial registration, and their implications for the accuracy of the mapping data are discussed. The relevance of this work in the context of World Heritage Site management is explored.

Contents

1.0 Introduction

The Merv oasis lies astride one of the main arms of the ancient Silk Roads that traversed half the world, from the Far East to Europe and Africa. The ancient cities of Merv, a succession of flourishing administrative and trading centres for nearly 1,700 years, became one of the most important cultural centres in the Islamic world. The Turkmenistan Ministry of Culture made the far-sighted decision in 1990 to establish an Archaeological Park to protect the walled cities and the principal outlying monuments within the oasis. This has already done much to improve the basic condition of the cities, removing modern agriculture from within the walled areas, and generally improving access to the monuments. However, there are daunting conservation issues facing the Turkmens. In 1999 the site was declared a World Heritage Site and in 2000 Merv was placed on the list of the world's 100 most threatened sites by World Monuments Watch – it remains on that list today.

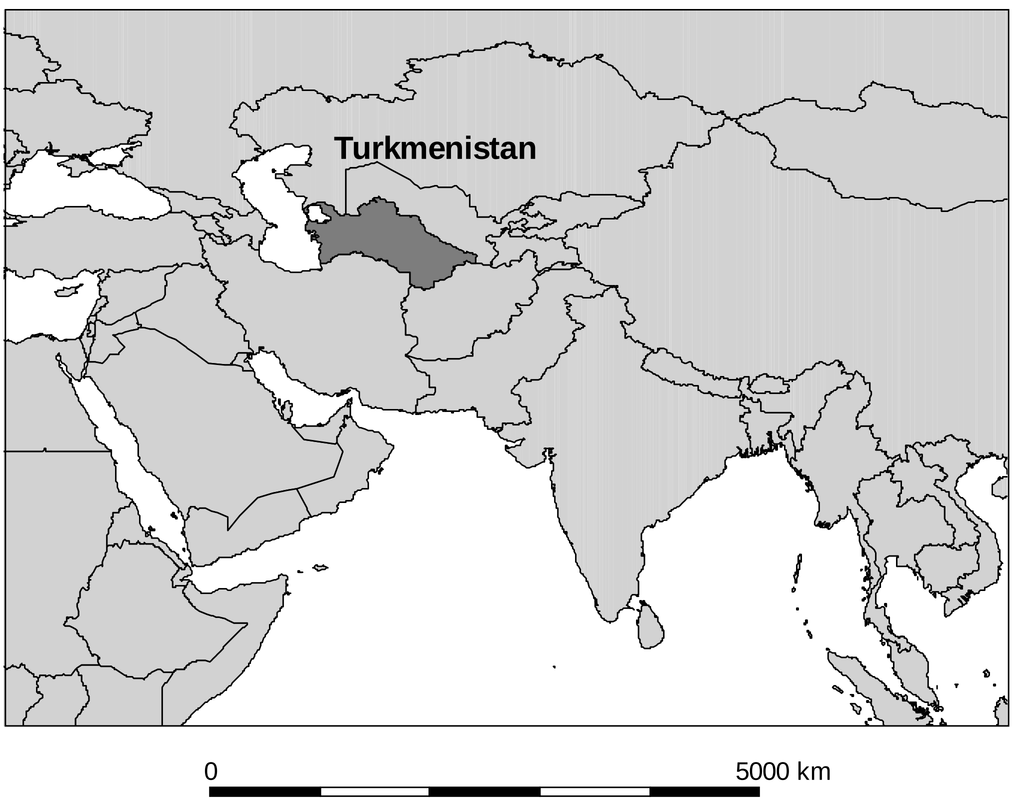

Figure 1.1: Turkmenistan

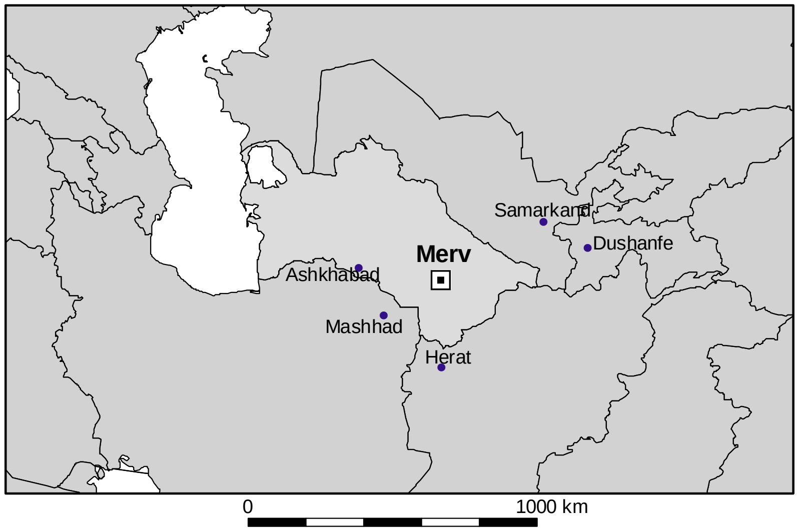

Figure 1.2: Merv and adjacent cities

1.1 Problem statement

A substantial amount of archaeological fieldwork had been carried out over a number of years at Merv. For one reason or another, there was no one consistent spatial framework within which to register and integrate this work, nor was there a base map against which to overlay the archaeological material. Survey work had been carried out by various groups (Barratt et al., 1997; Herrmann et al., 2001) but this had failed to come to terms with the scale of the problem and had not provided a mapping and control dataset that was usable by other project personnel. Moreover, in late 1999 time was running out. An existing block of funding was coming to an end, and if investigations were to continue, then the existing work had to pulled together into a consistent dataset to enhance the credibility of the project. Fortunately, two waves of new technology could be brought to bear on the problem: high precision coordinate estimation using the Global Positioning System (GPS) and relatively inexpensive space-borne remote sensing at very high resolutions.

1.2 GPS geodesy and the International Terrestrial Reference Frame

GPS is a 24 hour a day, all weather satellite navigation system developed primarily by the United States Air Force that enables users to determine their position in real time over most of the Earth's surface. It consists of a number of satellites in orbit about the Earth (the space segment), a master control station, a small number of globally distributed tracking and uplink stations (the control segment), and the receivers used to determine position, velocity, attitude and time synchronisation (the user segment).

In the past ten years GPS has evolved from what was essentially a navigation system enabling civilian users to establish their position at the level of +/-100m to a precise surveying tool through which position in a geocentric reference frame with a repeatability of a few millimetres can be achieved. We list here a few organisations and concepts that are required to understand the content of this paper in a relatively self-contained manner:

The International GPS Service (IGS): this umbrella organisation, run by NASA's Jet Propulsion Laboratory, is responsible for a global network of over 300 GPS tracking stations that continually record GPS data, and make it available free of charge to analysts via the internet.

Precise Orbit Determination (POD): the IGS data is pooled on a daily basis and used by a number of analysis centres to calculate ultra high precision trajectories of all the GPS satellites. A relatively crude model of the satellite trajectories can be decoded directly from the satellite signals, but in order to achieve high precision position the orbits must be calculated by a sophisticated combination of range observations and mathematical models of forces acting on the satellites.

The International Terrestrial Reference Frame (ITRF): a reference frame can be thought of as a three-dimensional co-ordinate system, with an origin at the earth's centre of mass. The Z-axis is co-incident with the Earth's spin axis and the X-axis is in the plane of the Earth's equator, roughly running through the Greenwich meridian. Finally the Y-axis completes the right-handed system. This frame is realised by the co-ordinates of tracking stations that have a number of co-located space geodesy sensors such as GPS receivers, satellite laser rangers (SLR), very long baseline interferometry (VLBI) radio dishes and Doppler Orbitography System (DORIS) receivers. Data from these observation technologies are combined to calculate both the positions and velocities of the tracking stations. This is known as the International Terrestrial Reference Frame. It is maintained for the purposes of numerous scientific analyses such as monitoring plate tectonic motion, measuring post-glacial rebound and determining global sea level changes. Access to the frame is freely available to anyone, whether for private, public or commercial use. Using GPS data and appropriate scientific processing software it is possible to determine the position of points on the surface of the Earth with a repeatability of a few millimetres. That is, if a GPS receiver were placed over a stable mark on the ground on successive days, and a solution for that point were computed daily, using IGS precise orbit and clock products, then the time series of those solutions would show small random fluctuations of 10-20 millimetres.

1.3 The IKONOS Remote Sensing satellite

The IKONOS satellite is a passive remote sensing platform launched in 1999, orbiting the Earth at a mean altitude of 481 km. The satellite moves at about 7 km/second, and orbits the Earth once every 98 minutes. The orbit is designed such that the satellite passes over the same point on the Earth's surface every three days. The nominal swathe width imaged directly below the satellite (the nadir direction) is circa 11 km. Imagery of the Earth can be captured by the satellite in a number of resolutions and types. For this particular application the authors used 1 m pixel resolution panchromatic imagery. In 2000 this was the highest resolution remote sensing data commercially available. Despite this the data are relatively affordable, at about £3-5K for a 13 by 13 km tile.

2.0 Proposed methodology

The approach to solving Merv's problems was threefold. First, a GPS field campaign was organised to:

- Establish a number of monumented points around the site to form the basis of a control network for a project co-ordinate system
- Occupy these points with GPS receivers such that the network could be related to the ITRF
- Use GPS receivers to determine the coordinates of points of detail in the landscape that would appear in the remote sensing imagery in order to register[1] the data in the ITRF

Second, arrangements were made for the retrieval of IKONOS data whilst the satellite made a pass over the site when there would be a low risk of cloud cover and minimal vegetation on the ground to mask the archaeological features.

In the third stage the coordinate system, and the digital map base derived from the remote sensing data, would be used to spatially register the various disparate elements of fieldwork into one consistent dataset.

GPS data processing was to be carried out independently at University of New Brunswick (UNB) in Canada and University College London (UCL), in the UK. The results would then be used to publish a list of coordinates for the control stations and points of hard detail, using the Universal Transverse Mercator mapping projection. This projection was chosen as a representation for two reasons:

- The numbering system would be in terms of eastings and northings with which archaeologists are used to working, instead of geocentric Cartesian or Geodetic co-ordinates, which are generally less intuitive for non-specialist users

- UTM is a standard mapping projection that is both well documented and accessible within geographic information system (GIS) software.

The hard detail list would be used to carry out the spatial registration of the IKONOS data.

Part of the rationale behind relating the network to the ITRF was that in places like Turkmenistan there is a strong possibility that any monumentation established during the GPS field campaign would be destroyed or 'recycled' by the local population. Although decoy earth anchors were installed and substantial earth anchors were used as the control points their removal would in no way make it difficult to re-instate the co-ordinate system in future seasons. All that would be required would be to set up a GPS receiver at

[1] See section 4.0 for an explanation of this process

the site and collect observations for around twelve hours in order to add new control points consistent with the ITRF co-ordinate system at the level of 1-2 centimetres.

Finally, the registration and formatting of the remote sensing data to make it compatible with desktop GIS packages was to be carried out at UCL

Figure 2.1: head of earth anchor used as a control point

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3.0 Data acquisition

3.1 IKONOS

The imagery was acquired from the IKONOS satellite in April 2001. The 13 x 13 km tile of raw data had no cloud coverage at all and was supplied with a coarse registration to the appropriate UTM zone. The extent of the raw data supplied is illustrated in figure 3.1.

Figure 3.1: Extents of the main block of imagery

3.2 GPS

3.2.1 Equipment

The GPS equipment used consisted of three Leica System 500 dual frequency antennas and receivers, mounted on tripods. Centering over ground marks was carried out using optical plummets. Data were downloaded and pre-processed each day on a laptop computer.

3.2.2 Observation period and monumentation

All GPS observations were carried out during September 25-29, 2000. Detailed location sketches were made for the control points with photographs and hand drawings. Figure 3.2 shows the primary control network established.

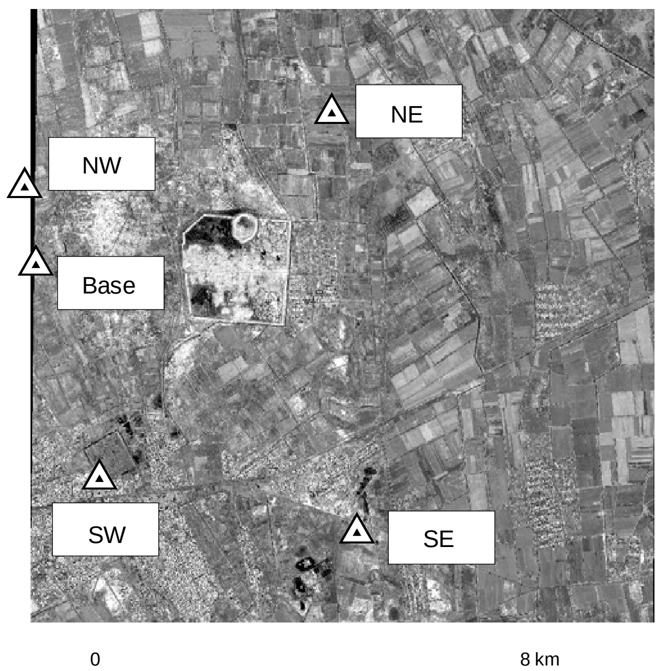

Figure 3.2: Approximate location of primary control points

Physical monumentation was established in the area by using submerged earth anchors. Most of these were outside the immediate area of interest, plus one close to the accommodation (point ‘Base’). This is in keeping with the nature of GPS control points – there is no need to maintain clear lines of sight between the control points in order to use them, although this can cause problems if other technologies are to be used in conjunction with GPS as will be shown in the discussion. Decoy, slightly-raised earth anchors (left visible on the surface) were also established to improve the chances of the submerged earth anchors not being removed.

3.2.2 Observations to link local control to ITRF via IGS:

Observations were made at the Base point on each day for between 2 and 10 hours — this being the primary point connected to the ITRF. In addition, points NW and SE had observations carried out over a six-hour period on one day to improve the ITRF link.

3.2.3 Coordination of Ground Control Points for IKONOS imagery:

The registration of the remote sensing data required the coordination of ground control points (GCPs) that were anticipated to be clearly visible in the IKONOS imagery to be obtained in April 2001. Usually the selection of suitable GCPs would be carried out after the imagery had been obtained (so that suitable GCPs can be identified in the imagery) but the logistics made this impossible in this case.

The same GPS data collection methodology was used for the control network and the GCPs. The mask angle (the elevation below which the receiver is set to stop tracking the GPS satellites) was 15˚, a 10 second epoch rate[2] was used and 10-15 minutes of observations were made at each point.

The ideal GCPs are 'cultural features'. These include road and sidewalk intersections. These features should have well defined edges with high contrast. Because of a lack of these ideal GCPs, most GCPs were the intersection of bridge edges (marked with concrete blocks) with canals (see figure 3.3). Although only five GCPs were needed, each point was doubled up to increase the likelihood of having five usable GCPs visible in the image. In addition, to assist with the location of the GCPs on the image, a kinematic track map was made.

Figure 3.4: GPS receiver placed over image registration point on concrete bridge

[2] The epoch rate determines the frequency with which the observations of the GPS satellite signals are stored within the receiver

4.0 Data Processing

4.1 GPS data processing

The processing of the GPS data to fix the network of control points to the ITRF was carried out independently at UNB and UCL using different processing strategies and software. UNB used its own scientific software package called DIPOP, whilst UCL used JPL's scientific software package GIPSY OASIS II. Thereafter the computation of all other surveyed points was carried out at UNB relative to Base using Leica's Ski-Pro software.

4.1.1 DIPOP/Baseline approach

DIPOP uses what is known as a 'Baseline' approach to determine the coordinates of points. We can think of a baseline as a vector, whose coordinates at one end are known, but whose lengths in the X, Y and Z direction (denoted by ΔX, ΔY and ΔZ) in the ITRF are unknown. DIPOP determines the values of ΔX, ΔY and ΔZ. We can then work out the unknown coordinates of the other end of the baseline through the simple formulae:

$X_{UNKNOWN} = X_{KNOWN} + \Delta X$
$Y_{UNKNOWN} = Y_{KNOWN} + \Delta Y$
$Z_{UNKNOWN} = Z_{KNOWN} + \Delta Z$

To enable DIPOP to determine the coordinates of the primary control points Base, NW and SE, GPS data were obtained via the Internet for the 4 IGS points closest to Merv. Necessarily, the data were those collected at the same time as the GPS data were collected at Merv. In addition, the ITRF coordinates of the IGS were obtained via the Internet. Thus DIPOP was able to determine the X, Y and Z values for the coordinates of Base, NW and SE. These values were then converted to latitude and longitude, and subsequently eastings and northings by use of well-documented formulae.

4.1.2 GIPSY/Precise Point Positioning

The processing strategy at UCL made use of the 'precise point positioning' (PPP) concept [Zumberge et al., 1997]. In this approach a network of circa 40 globally distributed GPS receivers is used to calculate the orbits of the GPS satellites for each particular day, along with models of the behaviour of the satellite clocks (all GPS positioning is essentially based on timing through atomic clocks carried on-board the satellites) and a set of transformation parameters relating the orbits to the ITRF for that day. These data are then combined with the GPS observations from the receiver location that is to be determined. As at UNB the results were then converted to latitude and longitude, and finally into the UTM mapping projection coordinates.

4.1.3 Relative positioning processing

The scientific software packages DIPOP and GIPSY OASIS II were used for processing the IGS GPS data as the baselines were at the inter-continental scale. A rigorous scientific approach to dealing with error sources in GPS is essential under the circumstances of having very long baselines. However, the baselines between the primary control points were short enough (maximum length was 9 km) to enable standard commercial GPS processing software (in this case Leica's Ski-Pro) to be used to determine the coordinates of the points. This produces a substantial saving in processing time and an increase in the ease of processing.

4.2 IKONOS data processing

When the imagery was initially supplied by the vendor (Space Imaging) it was approximately positioned in the appropriate UTM zone. In order to improve the accuracy of the position of any features visible in the scene[3], the process of *registration* must be carried out. In this process the position of several points of detail visible in the imagery must be determined accurately in an appropriate co-ordinate system. The positions of the points of detail are then used to calculate a mathematical transformation mapping each pixel in the raw image to its equivalent position in the registered image. Any point of detail in the registered image is then (within certain accuracy limits) in its true position on the mapping projection used.

As explained in the methodology section ten points were available for the process of the registration. These points were converted from latitude and longitude to UTM zone 41 eastings and northings. The physical mark for each point was then identified in the raw IKONOS image, and the coordinates of these points under the coarse registration of the supplied dataset were extracted from the digital data. A four parameter mathematical transformation was then computed using least squares analysis that would transform the raw image into ITRF under the UTM projection. The minimum number of points required to carry out this parameter estimation would be two, hence it can be seen that the mathematical model was strongly over determined (that is, far more than the minimum number of observed points were available to use in the least squares estimation). It should be borne in mind that the image pixel resolution was at best 1 m. It would be largely impossible to resolve any feature to a finer resolution, and this naturally sets a limit on the process of extracting the coordinates of points of detail from the raw data. The ITRF coordinates of the corresponding points of detail on the ground were precise at the level of 1-2 cm, but the actual nature of the physical features themselves make it all but impossible to find a centering point to better than circa 5 cm.

The process of computing the transformation parameters involved balancing out obtaining the best possible transformation using as much of the available data as possible whilst not including some of the points to use as an independent check on the quality of

[3] In remote sensing terminology a 'scene' refers to a block of topographic data captured by the sensor and combined into one image.

the transformation. Held against this was the possibility of points being affected by systematic biases and gross errors, thus necessitating removal from the data set, and the requirement for a good spatial distribution of control used in the transformation.

The quoted accuracy of the imagery once registered using ground control according to the vendor’s specification was:

- 2-meter horizontal and 3-meter vertical accuracy with ground control
- These are specified as 90% CE (circular error) for the horizontal and 90% LE (linear error) for the vertical

The adopted strategy was to use 5 points in the registration, retain 4 as check points and reject one as an outlier. The results are summarised in tables 5.1 and 5.2.

5.0 Results

5.1 Comparison of two GPS processing strategy results

Although observations were made at NW and SE as part of the primary control, only Base had observations on more than one day – it was thus only at this point that the ITRF coordinates were adopted.

The two approaches produced results of startling closeness. The differences between the two solutions were:

Latitude	10 mm
Longitude	1 mm

The closeness is even more impressive when one realises that the non-trivial computational process was carried out with no discussion of processing strategies used.

5.2 Estimates of GPS position accuracies and precisions

Estimates of GPS position accuracies and precisions are notoriously difficult to assess to a reasonable confidence level from GPS processing software. Therefore, a number of approaches were adopted in this work:

1. Comparing the repeated ITRF coordinates computed each day at Base
2. Determining the difference in coordinates for the start and end point in a loop
3. Evaluating the residuals resulting from a least-squares estimation procedure
4. Comparing the DIPOP derived coordinates and the Leica measured NW-SE baseline

For (1), the daily agreement was <3 cm, for (2) the loop misclosure was 8 cm, for (3), the residuals were < 3 cm, for (4) the difference was 4 cm.

5.3 Results for Registration of IKONOS imagery

Table 5.1: Control points used to derive the image transformation

	ITRF coordinates		Position in Registered image		Differences	
Point number	**Eastings**	**Northings**	**Eastings**	**Northings**	**ΔE (m)**	**ΔN (m)**
2	424869.831	4169737.755	424870.507	4169738.490	-0.676	-0.735
4	428647.260	4171328.243	428647.296	4171328.340	-0.036	-0.097
5	426204.391	4165812.834	426204.664	4165812.559	-0.273	0.275
7	429544.054	4165121.732	429544.012	4165122.133	0.042	-0.401
10	427347.253	4167346.733	427347.646	4167346.677	-0.393	0.056

Table 5.2: Check points used as validation of transformation

	ITRF coordinates		Position in Registered image		Differences	
Point number	**Eastings**	**Northings**	**Eastings**	**Northings**	**ΔE (m)**	**ΔN (m)**
1	425521.820	4170487.709	425522.475	4170491.319	-0.655	-3.610
3	428244.955	4170632.682	428247.389	4170635.223	-2.434	-2.541
6	426309.502	4165960.801	426309.677	4165962.208	-0.175	-1.407
8	429750.121	4165161.551	429749.359	4165164.529	0.762	-2.978
9[4]	427572.197	4168665.430	427580.965	4168670.066	-8.768	-4.636

The RMS of the residuals for the points contributing to the transformation was 0.384 m. For the check points the RMS value of the residuals was 2.159 m.

The raw image data file (see figure 3.1) covering the complete tiling supplied by the vendor was 141 Mbytes in volume. This was too large to be comfortably handled by all the envisaged users, and also contained much information of only limited value to the archaeological analysts. Therefore, a subset of the imagery was cropped from the main image with a file size of 38.6 Mbytes. This subset covered all the main areas of archaeological features visible in the main dataset.

[4] Point 9 was rejected from the dataset as an outlier

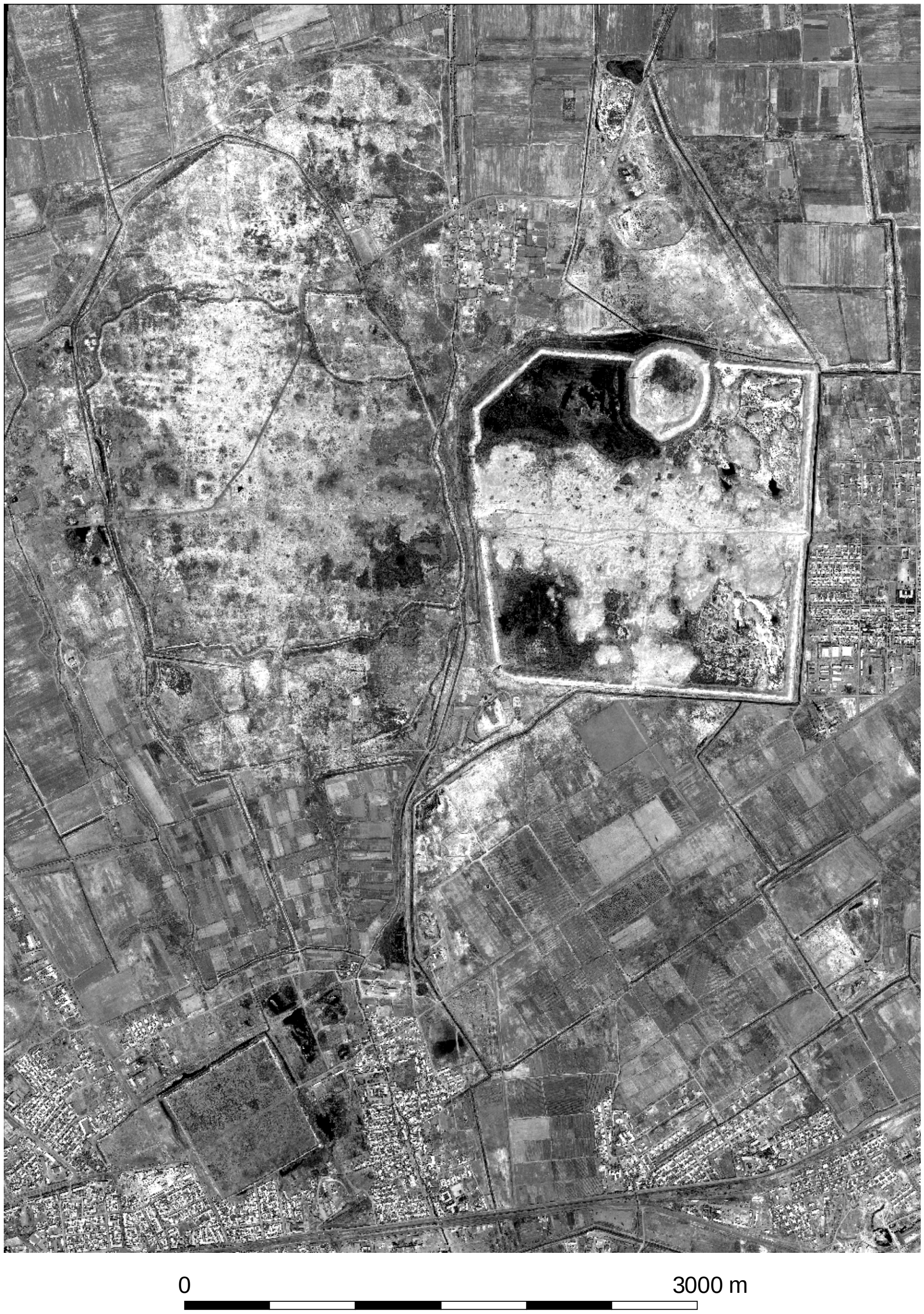

Figure 5.1: Extent of the imagery subset

Discussion

One outstanding issue remains, and that concerns the *heighting* system that is to be used on the site. At present all the control point heights are referenced to the WGS84 ellipsoid. This is a mathematically defined surface, and the heights of points above it impart no intuitive information concerning the hydrology of the site. It is conventional in archaeology to use *orthometric* heights. These are essentially related to some concept of mean sea level. Now, strictly speaking, such height systems are only of limited value in archaeology due to the fluctuating nature of the water table and sea level over the history of a site. However, archaeologists are used to using such systems, and may be less comfortable using ellipsoidal heights. It is possible to convert the GPS-derived ellipsoidal heights in the control network to a form of orthometric height using NIMA (the US national imaging and mapping agency) gravity field data. This calculation could be done without any further fieldwork in Turkmenistan, but it would be preferable to back this up with some levelling measurements between the control points to verify that the heighting was internally consistent.

Conclusions

The cities of Merv have been the subject of many years of investigation, including fieldwalking, geophysical surveying, detailed archaeological excavation, and building recording. Future work will include further excavation, geophysical and topographic survey, aerial photography, conservation and monitoring. The satellite imagery provided the basis by which all the disparate elements undertaken thus far could be integrated into a single spatial framework, and a means by which all future work could be co-coordinated.

The site coordinate system has been set up within the International Terrestrial Reference Frame. This is adds great value to the coordinates of the points in the network in that even if all physical monumentation is lost or removed the coordinate system can still be re-instated to a precision of 20-30mm. Thus the coordinate system provides not only for a spatial framework for all archaeological mapping and surveying on the site from season to season, but also a means by which long term monitoring of monument erosion can be realised.

The image provides an important record of the condition of the site at an instant in time. Given the scale of the ancient cities of Merv (c 1,000 ha of enclosed urban space, with additional extensive suburban activities), the field monitoring of every track, pathway, drainage channel, field, erosion gully, etc, would be a huge undertaking. The satellite image provides a comprehensive base map that enables these aspects to be rapidly and accurately documented, and future changes to be measured. The geo-referenced image has provided, for the first time at Merv, a base map capable as acting as the platform for integrating and acquiring spatial data, providing the platform for the development of a GIS for the Archaeological Park.

This project demonstrates how several rapidly developing branches of technology can be brought to bear on the management and analysis of a site of international importance in a cost-effective and efficient manner. These technologies are great enablers, and although the acquisition and registration of the data are quite complex tasks, the final product, in the form of a digital map base, is readily accessible to archaeologists and other heritage management professionals.

Acronyms and abbreviations

GPS	Global Positioning System
IGS	International GPS Service
ITRF	International Terrestrial Reference Frame
UCL	University College London
UNB	University of New Brunswick
UTM	Universal Transverse Mercator

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