

IMAGE-BASED MEASUREMENT OF THE MING GREAT WALL

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ABSTRACT:

The Great Wall is an ancient Chinese fortification against the raids of nomadic tribes and is the longest human building in the world, built over 2000 years and 10 dynasties in the Chinese history, and stretching over more than 10,000 km. It was made a UNESCO World Heritage Site in 1987. There are no precise and full recordings about the Great Wall, resulting in the difficulty of preservation, research, exploration and management of the Great Wall. It has important practical significance on how to measure scientifically the length of the longest human building in the world and issue the important geographic information related to the Great Wall such as the length, distribution, etc. The paper presents the method of measuring the Ming Great Wall based on image with the technology support of the field investigation and photogrammetry. The key technology of the method is to interpret and identify the Great Wall based on ortho-image database, testify the attribute and distribution by the field investigation, measure the surface length by the photogrammetry. The test result shows that the measuring accuracy of the surface length of the Ming Great Wall (5000km) will be 0.866km based on the method. The method has been used by the 10 provincial bureau of surveying and mapping along the Ming Great Wall.

1. INTRODUCTION

The Ming Great Wall (MGW) was built from the end of the 14th century until the beginning of the 17th century during the Ming Dynasty, with longer lasting materials (solid stone used for the sides and the top of the Wall). It stretches over more than 6000 km, from Shanhai Pass on the Bohai Gulf in the east, at the limit between China proper and Manchuria, to Lop Nur in the southeastern portion of Xinjiang Uygur.

Important geographic information relating the MGW such as the position, the distribution, length, attributes etc., is prerequisite to help the government to make the protect plan and carry out the protection of the MGW. However, there are no precise and full recording about the whole MGW up to now, resulting in the difficulty of preservation, research, exploration and management of the MGW.

In 1985, the Remote Sensing Center of the Geology and Mineral Resources investigated the resources of the MGW in Beijing using ways combined the interpretation of the aerial photo and field investigation, measured the projection length of the section of MGW through the 1:50k topographic map in Beijing (Guwei,1985). In 1990, the same way applied to Ningxia's part of the Great Wall, northwest of china. But the projection length and the paper investigation results can not fully meet the need of the current cultural heritage protection, preservation, research, exploration and management.

Hadrian's Wall built in AD 122 and was to cross the narrowest part of England, from the Tyne to the Solway, and served as the frontier for almost 300 years. The great British Ordnance survey made 1:10,000 scale DLG of Hadrian's Wall and measured the length (the total length is 117 km) with the help of the cultural heritage organization. At the same time, the close contour survey of the important forts has been done by the TC403 total station. The Close contour survey provides an accurate representation of both the surface terrain model and an accurate record of elevation (J A Biggins,2000). The successful

experience of Hadrian's Wall measurement is the cooperating between the surveying and mapping unit and the cultural heritage organization.

In order to complete successfully the resources investigation and measurement of the MGW, the State Bureau of Surveying and Mapping (SBSM) jointly with the State Bureau of Cultural Heritage (SBCH) decided to implement the task together. SBCH is in charge to investigate the attribute of the MGW, such as the building age, building materials, destroy status etc. SBSM takes charge of measuring the length of the MGW, capturing the base and thematic data of the MGW.

Three majors tasks need to be carried out by both SBSM and SBCH: mapping the spatial distribution of the MGW and deriving relevant statistics (such as length), investigating and recording the attributes and status of the entities and auxiliaries of the great wall, setting up the great wall geo-spatial information systems.

The paper will mainly introduce the method of image-based measurement of the MGW. The characteristic of the method is that utilizing the image to distinguish the distribution of the MGW and investigate in the field, expressing the attributes of the MGW on the image, capturing the MGW foundation geographical and thematic data using image, measuring the length of the MGW based on the image etc.

2. METHODOLOGY

There are some difficulties for measuring the length of the MGW. First of all, it is difficult to locate the MGW and decide the attribute without cultural heritage expert's knowledge such as building up age, classes of the wall due to the lacking of precise recording both in map and literature. Secondly, the MGW was built on different topography and the structure of the MGW is complicated. It is difficult to measure and map the MGW in the places such as the steep mountainous place wall,

river, streams and lake's natural blockade, and vanished wall, etc. Thirdly, the status of destroying makes it difficult to identify and map the MGW for some cases.

In order to resolve the above problems, the method has been developed based on the test and the theory's support of stereo measurement, and can be summarized as 4 steps:

- 1) Data collection and processing: During this period, aerial photos, high resolution satellite images, digital maps, analog maps and MGW related documents will be captured and sorted out;
- 2) Interpretation and identification of the Great Wall based on ortho-image: Firstly, 1:10k DOM and 1: 50k DOM covering the Great Wall and the vector data which be derived from digitizing the Great Wall elements based on 1:50k DRG are sorted in the computer to set up the Great Wall base imagery database. Secondly, existence, the status of preservation, other auxiliary elements, such as watch towers and battle forts, and attribute classification will be interpreted and identified with the support of the experts;
- 3) Stereo measuring: based on the results of field investigation and control, the stereo measure of the Great Wall will be carried out.
- 4) Length calculation and accuracy assessment: the surface and the projection length of the MGW for total and segments will be calculated by the photogrammetric approach through defining the length of the MGW and stereo measurement and the measuring accuracy will be assessed by the accuracy model.

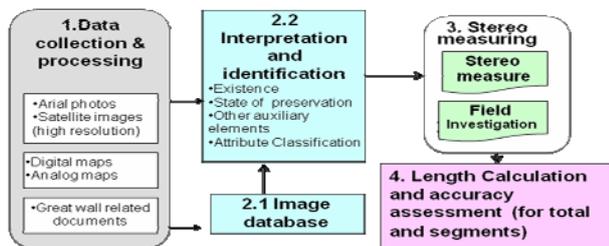


Figure 1. The method of Image-based Measurement of the MGW

3. IDENTIFICATION AND AFFIRMING OF THE MGW

3.1 Identifying the MGW Based on Ortho-image Data Base

The Great Wall made by human being according to definite regulations, such as height, width, structure, materials, function, etc. The most MGW in Beijing, Hebei, Tianjin, Shanxi, Shanxi, Neimengu are the stone and brick structure and built on the top of the mountains and the most MGW in Ningxia, Gansu, Qinghai are sand and fence structure and built on the surface of the plain.

In national foundation data base, there are the part of Great Wall thematic vector data in the 250k data base. Extracting the thematic vector data from 250k data base can get the Great Wall's base data, then get 1:50k base map guiding by the 250k data base. Digitizing the Great Wall element from 1:50k DRG, can get the 1:50k Great Wall vector data. The ortho-image database has been set up based on the Great Wall vector data, 1:10kDOM and 1:50kDOM, etc.

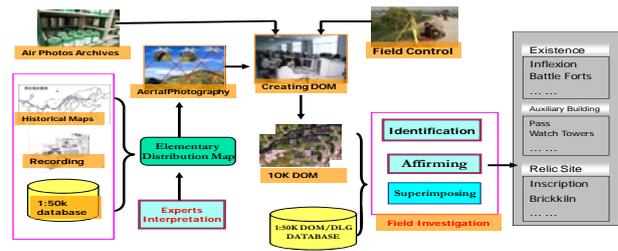


Figure 2. The Work Flow of Identifying the MGW

Using the references such as Cultural Heritage historical map, document, and recordings, and 1:10k base map, Cultural Heritage and surveying and mapping experts identify and affirm jointly the Great Wall based on the ortho-image database, generating the Ming Great Wall elementary distribution map (see figure 3).



Figure 3. The MGW Elementary Distribution Map

3.2 Affirming the MGW in the Field

During the process of the MGW resources investigation in the field, guiding by the Ming elementary distribution map, the field investigator will locate the main inflexion of the MGW by the GPS handset, describe the investigation information on the aerial enlarge photo, fill in 10 kinds of resources investigation forms to record the attribute of the wall and battle forts and watch towers, etc, such as wall registration form describing building up age, location (x,y,z), building materials of the wall, and GPS registration form describing the numbering, coordination, relations, and name etc.

The important job will be carried out in the field investigation is to resolve the location and the extent of the steep mountainous place wall, river, streams and lake's natural blockade, and vanished wall, etc. Through consulting the obvious surface feature around, the field investigator needs to express the result judged in field on the aerial enlarge ortho-photo, meanwhile; record the corresponding characters in detail by filling in the investigation forms .

4. STEREO MEASURE OF THE MGW

4.1 The Length Definition of The MGW

The vertical profile of the MGW can be defined as the curved surface which the central axis through the MGW intersects vertically the horizontal plane, the track line of the MGW can be defined as the three-dimensional space curves which the vertical profile intersects vertically the surface of ground, the track line length can be defined as the length of the earth's surface or the surface length of the MGW. The red line in figure stands for the surface length of the the MGW.

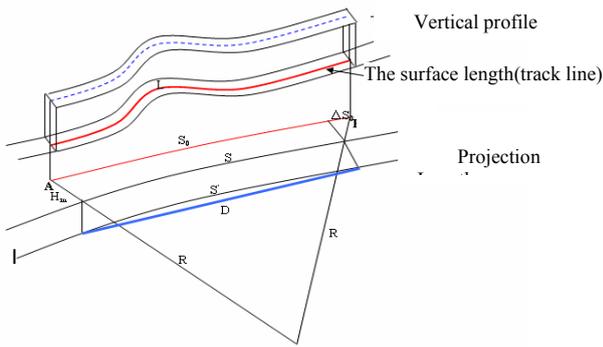


Figure 4. The Length Definition of the MGW

4.2 The Length Measurement of the GW

According to the MGW resource field investigate results, accurately measure the three-dimensional coordinate of each inflex point on the surface centre line of the MGW under the MGW stereo pairs with the 1:10k specification precision.

The quantity of the measured inflexion point must be enough to guarantee to reflect the distribution characteristic of the surface centre line of the MGW, at the same time, in order to reduce the measurement mistake, the same section of the MGW need to be measured twice by different operators along the positive and negative direction, when the difference of the two times's length measurement result is less than 0.001m, the average of the two times's length measurement result will be the final measurement length.

4.3 Value Assignment

The MGW length includes surface length, projection length and categorised lengths. According to the attribute of the MGW, such as the wall's building up age, building up materials, protection status, administrative division, etc, categorised lengths can be the length of the vanished MGW, the length of the Gansu province's MGW etc.

During the stereo measurement of the MGW, the attribute value should be assigned to the MGW section in order to count the different length of the MGW. The attribute include function of the wall (first line or second line), building up materials (stone, clay, etc), protection status (good, vanished, etc), administrative division, building age, etc. At the same time, in order to assess the length measurement precision, X, Y, Z direction aero-triangulation adjustment precision also need to be assigned to the MGW section respectively.

4.4 Length Calculation Formula

The track line of The MGW is a three-dimensional curve, the surface length of the MGW is the curve length of three-dimensional.

Using of digital photography method to obtain inflexion point coordination of the MGW, calculating the curve length between the adjacent inflexion points, the surface length of the MGW is the cumulative length of each curve length.

The Formula of calculating the surface length of the MGW is:

$$L = \sum_{i=1}^{n-1} S_0(P_i, P_{i+1}) = \sum_{i=1}^{n-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \quad (1)$$

Where P_i, P_{i+1} is inflexion points, $(x_i, y_i, z_i), (x_{i+1}, y_{i+1}, z_{i+1})$ is P_i, P_{i+1} three-dimensional coordinates, L is the curve's surface length of the MGW.

4.5 Accuracy Assessment Model

During the stereo measurement of the MGW inflexion points, each measuring is independent of each other, the measuring error of three directions should also be independent of each other, in the same time, in every triangulation densification network, the accuracy of each measuring point can be assumed to be equal. That is, $\sigma_x = \sigma_{x1} = \sigma_{x2} = \dots = \sigma_{xn}$, $\sigma_y = \sigma_{y1} = \sigma_{y2} = \dots = \sigma_{yn}$, $\sigma_z = \sigma_{z1} = \sigma_{z2} = \dots = \sigma_{zn}$.

According to the length calculation formula(1), respectively x_i, y_i, z_i from derivatives, measuring section 's error (σ_L) formula is as follows:

$$\begin{aligned} \sigma_L^2 &= \sum_{i=1}^n \left(\frac{\partial L}{\partial x_i} \right)^2 \sigma_{x_i}^2 + \left(\frac{\partial L}{\partial y_i} \right)^2 \sigma_{y_i}^2 + \left(\frac{\partial L}{\partial z_i} \right)^2 \sigma_{z_i}^2 \\ &= \left(\frac{x_2 - x_1}{L_1^2} \right)^2 + \sum_{i=2}^{n-1} \left(\frac{x_i - x_{i-1}}{L_{i-1}} - \frac{x_{i+1} - x_i}{L_i} \right)^2 + \left(\frac{x_n - x_{n-1}}{L_{n-1}^2} \right)^2 \sigma_x^2 \\ &+ \left(\frac{y_2 - y_1}{L_1^2} \right)^2 + \sum_{i=2}^{n-1} \left(\frac{y_i - y_{i-1}}{L_{i-1}} - \frac{y_{i+1} - y_i}{L_i} \right)^2 + \left(\frac{y_n - y_{n-1}}{L_{n-1}^2} \right)^2 \sigma_y^2 \\ &+ \left(\frac{z_2 - z_1}{L_1^2} \right)^2 + \sum_{i=2}^{n-1} \left(\frac{z_i - z_{i-1}}{L_{i-1}} - \frac{z_{i+1} - z_i}{L_i} \right)^2 + \left(\frac{z_n - z_{n-1}}{L_{n-1}^2} \right)^2 \sigma_z^2 \end{aligned}$$

Where $\sigma_x, \sigma_y, \sigma_z$ is three direction's measurement accuracy under the stereo measuring environment, that is the densification precision of every triangulation densification network.

Using the formula (2) to calculate the MGW each section's length measurement accuracy, and using the formula (3) to calculate the overall length measurement accuracy of the MGW, the overall error (σ_{Lall}) formula is as follows:

$$\sigma_{Lall} = \sqrt{\sum_{i=1}^n \sigma_{L_i}^2} \quad (3)$$

Where i is the MGW serial number of each section's length measurement, n is the total number of sections.

5. TEST

5.1 Measurement Method Test

One of the main purpose of the test is to validate the method to obtain the surface length of the MGW. The ways, such as RTK-GPS, Photogrammetry, and measuring the length of the MGW based on the 1:50k DRG and DEM, had been tested in Beijing, Hebei and Gansu. The result of the test is as follow:

	INSTUMENT /SOFTWARE	PROCESS	Main RESULTS
RTK-GPS	ASHTECHZ-12/Trimble4000sse	Selected the main inflexion and change-point of the MGW and surveyed 58 GPS points by the RTK-GPS	It is difficult to select GPS point to describe the MGW and to reach some points such as the watch towers and to set the tripod. RTK-GPS is not suitable for measuring the MGW
Photogrammetry	VirtuoZo	1:8000 aerial photos, 22 stereo pairs, 1:10k control points	under the stereo model, it is easy to select the points to measure the MGW and the operation is reproduced with the support of the theory
1:50k DRG and DEM	Arcgis	Digitizing the MGW elements based on DRG, getting X, Y from the DRG and Z from the DEM	The MGW elements of the DRG is being synthesized during the map compilation. The precision of the 1:50k DRG and DEM can not meet the need of the MGW resource investigation. Using 1:50k DRG and DEM is not suitable for measuring the wall

Table 1. The Comparison of the Main Measuring Ways

	PROJRCTION LENGTH	SURFUCE LENGTH
RTK-GPS (L1)	2309.93	2445.25
PHOTOGRAMMTRY(L2)	2359.09	2481.64
L1-L2	-49.16	-36.39
(L1-L2)/L1	-2.13%	-1.49%

Table 2. The Length Comparison Between RTK-GPS and Photogrammetry

The chart shows the difference by comparing RTK-GPS and photogrammetry, the result proves the use of RTK-GPS to survey the length of the MGW is not feasible.

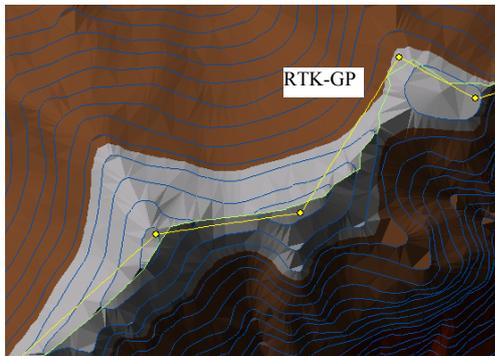


Figure 5. The Comparison Between RTK-GPS and Photogrammetry

The test result shows that the Photogrammetry is the best way to measure the slope length of the MGW.

5.2 1:10k Specification Precision

In order to compare the impact on the length using different scale aerial images to measure the same section of the MGW, the pilot uses respectively 1:8000 and 1:35000 scale aerial photos to measure two categories of the MGW (plain and mountain type) according to the Specifications for aero photogrammetric office operation 1:10k topographic maps, the test results in table 3.

	1:8000(L1)	1:35000(L2)	L1-L2	(L1-L2)/L1
Mountain	3,300.19	3,302.02	-1.83	1/1803
Plain	2,495.37	2,493.56	1.81	1/1379

Table 3. The Surface Length Comparison Between 1:8000 and 1:35000 Scale

Table 3 shows the differences between the two kinds of aerial scale (1:8000 and 1:35000) measuring the surface length of the MGW based on the different terrain conditions

By analyzing the results of the trial, the measuring length's difference of the two scales relative to the length can basically ignored, the MGW length measurement accuracy mainly depends on the specification's accuracy indicators rather than the scale of the Aerial photos, but large-scale aerial photos of the MGW can improve the identification and measurement capability.

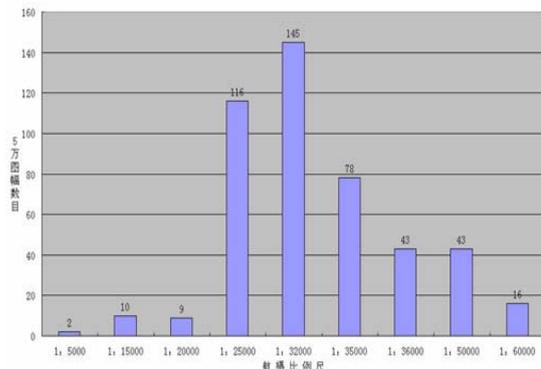


Figure 6. Existing Air-photos Statistics Covering The MGW

The figure6 shows the scale series of aerial photos covering the district of the MGW mainly focused on the scope of 1:25000 to 1:35000.

To make full use of existing aerial photos, the Specifications for aero photogrammetric 1:10k topographic maps eventually has been determined to measure the length of the MGW on basis of trial.

5.3 Length Measurement Precision Test

The test had been done in the Beijing Badaling section of MGW (mountain type, about 2.5 kilometers), densification points (mountain type) plane mean square error is 5.0 meter, elevation mean square error is 2.0 meter, the calculating surface length accuracy of the MGW is ± 19.37 meter according to the accuracy evaluation formula(2).

Provided that the total length of the MGW were 5,000 km, the total measuring times were 2000 and the each section's measuring accuracy were the same as the above test's accuracy, the expected length measurement accuracy of the MGW can be achieved ± 0.866km.

6. CONCLUSIONS

This paper discussed the measurement method of the MGW based on image, which is to Interpret and identify the elementary distribution of the MGW based on ortho-image

database, affirm the distribution and attribute of the MGW in the field by field investigation, such as locating the main inflexion of the MGW by the GPS handset, expressing the investigation information on the aerial enlarge photo, etc., fill in 10 kinds of resources investigation forms to record the attribute of the wall, and measure three-dimensional coordinates of each inflexion points on the surface centre line of the MGW by photogrammetry with the 1:10k specification precision.

The technological test results being done in Hebei, Beijing and Gansu, show that the technological method is effective and feasible. Now, 10 provinces along the MGW has been using the method to carry out the measurement of the MGW.

The expected measurement results obtained by the method will include the length of the MGW, such as surface length, projection length and categorised lengths, the stripe geo-image with 1m resolution, DEM with 5m grid interval, the MGW thematic data, the MGW thematic image map, etc.

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