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A Digital Survey Approach for Large-Scale Landscape Heritage Resource Exploration: Auxiliary Beacons, the Uncharted Signal Structure of the Great Wall in China

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Abstract: Following the completion of the Great Wall Resource Survey in 2012, numerous landscape heritage resources along the Great Wall remained undiscovered, highlighting the limitations of conventional survey methods. This study aimed to conduct in-depth investigations of Great Wall signal sites through digital fieldwork methods, unveiling a crucial signaling structure—the auxiliary beacon—and presenting genuine historical scenes of the Great Wall signal network. Through the retrieval of the image database of the entire Great Wall and the utilization of UAVs (drones) for low-altitude remote sensing surveys, 252 auxiliary beacon sites were identified in diverse environments (e.g., deserts, mountains, plains) in Xinjiang, Gansu, Inner Mongolia, Qinghai, Ningxia, and other 10 regions. These case studies enable the categorization of layout types and the proposal of reconstruction hypotheses for the signal network of the Great Wall of China. The findings demonstrate that the beacon fire signals are not lit on the beacon tower tops, but through the ignition of various signals by auxiliary beacons, expressing pre-arranged information. Beacon towers and auxiliary beacons together form an efficient signal network along the Great Wall. This study explores how to use digital survey methods to unearth unknown landscape heritage resources of the Great Wall, enhancing the accuracy of observation for cross-regional and large-scale cultural heritage.

Keywords: the Great Wall; auxiliary beacon; signal network; photogrammetry; image database

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1. Introduction

The application of digital technology to record cultural heritage has become an international trend in the field of heritage conservation in recent decades [1,2] The 19th International Council on Monuments and Sites (ICOMOS) General Assembly identified "protecting and interpreting cultural heritage in the age of digital empowerment" as one of the four core themes of the conference [3]. Digital technology provides unprecedented perspectives, details, and precision to observe and record cultural heritage, which has had a revolutionary impact on the workflow of heritage documentation and offered opportunities to explore innovative conservation and management approaches [4,5].

Many related projects have been conducted, most of which were for small-scale scenes and individual objects, such as statues of Buddha, sculptures [6], museum artifacts, etc. [7]. With the application of technologies such as unmanned aerial vehicles (UAVs), the scale of surveyed objects has increased significantly. More extensive digitalization projects for large heritage sites are being conducted worldwide (Table 1).

Table 1. The digitalization projects of cultural heritage sites at different scales.

Country and Region	Digital Technology	Surveyed Objects	Scale of Objects
Mantua, Italy	UAVs and terrestrial laser scanner (TLS)	Historical bell tower [8]	9 m × 9 m × 49 m
Fujian, China	UAVs and TLS	Temple with complex shapes [9]	30 m × 30 m
Amman, Jordan	Three-dimensional (3D) laser scanner and photogrammetry	Umayyad palaces [10]	30 m × 30 m; 20 m × 15 m
Zhejiang, China	Photogrammetry, UAVs, and mirrorless cameras	Historical settlements [11]	60 m × 30 m
Tivoli, Italy	Three-dimensional (3D) laser scanner	Emperor Hadrian's Baths [12]	60 m × 70 m
Trentino, Italy	TLS, photogrammetry, and computer-aided architectural design	Complex castles [13]	120 m × 50 m; 120 m × 40 m; 50 m × 40 m
Pompeii, Italy	Global Positioning System (GPS), photogrammetry, TLS, and aerial imaging	Roman Forum [14]	150 m × 80 m
Shaanxi, China	UAVs and photogrammetry	Historical military settlements [15]	300 m × 250 m
Queensland, Australia	Handheld 3D mapping system	Clustered settlement [16]	400 m × 250 m
Dolomites area, Italy	Oblique airborne laser scanning	Mountains [17]	2000 m × 800 m

Even though these methods are effective, they are not proper for large-scale heritage sites like the Great Wall. The Great Wall of China is the largest ancient military project in the world [18], including 21,196.18 km of walls and more than 29,000 individual buildings [19].

It is always a great challenge to investigate the Great Wall heritage site, since it covers huge areas in harsh environments. The scales of the objects in the aforementioned projects are much smaller than that of the Great Wall, and their environments are relatively homogeneous. If the same digitization methods are applied, a larger number of personnel is required, and the process is time-consuming. This issue has manifested in existing digitalization projects related to the Great Wall. According to the comprehensive investigation carried out in reference [20], these projects mostly target specific sections of the Great Wall sites. The Chinese government initiated the "Great Wall Resource Survey" (GW Resource Survey) and employed digital survey methods such as handheld GPS devices and 3D laser scanners [21]. However, due to the enormous scale and complex environment of the Great Wall, the survey is still not comprehensive and in-depth. For example, the smallest architectural type included as an object of this survey was beacon towers, with even smaller structures falling into the ambiguous categories of "ancillary facilities" or "related remnants" [22]. This may have led to the omission of some small-scale site types during the field surveys, reflecting the limitations of traditional survey methods in conducting comprehensive and in-depth investigations into the details of large-scale sites.

This paper takes beacon signal sites as a starting point, exploring a new digital method that may solve this problem.

1.1. "Multi-Beacon Signals" and Auxiliary Beacons

Beacon signals are an important cultural landscape resource along the Great Wall of China, and the signal network also plays an important role in ancient large-scale military projects [23]. The beacon signal does not merely signify a simple "safe" or "dangerous" message; instead, it has the capability to convey pre-arranged information, including the quantity and location of the enemy. The specific method involves igniting varying numbers of beacon signals to represent the quantity of the enemy, while the direction of the signal indicates the enemy's location. This method, referred to as "multi-beacon signals", constitutes a crucial approach in ancient Chinese military signal networks [24]. An auxiliary beacon is a facility used to ignite beacon signals, typically arranged in groups of three or five and positioned near watchtowers [25].

1.2. The Gap between the Rich Records and Contemporary Site Research

The history of auxiliary beacons can be traced back to the document Mozi-zashou by Mo Di (476–390 B.C.), which recorded the methods of using auxiliary beacons [26]. Many historical documents contain records of auxiliary beacons. Using a full-text search, we searched for Ding-Xiu and Unihan (Ding-Xiu and Unihan) using the keywords "auxiliary beacon" and its historical names in different dynasties, respectively, and selected records relating to beacon signal facilities from the returned items (Figure 1). The earliest document was Mozi-zashou, and the use of these terms was observed in documents up to and including those created in the Republic of China. A significant proportion of the literature was related to the Great Wall. Therefore, auxiliary beacons and the corresponding military considerations have a long history and were an integral aspect of the beacon signal network in China.

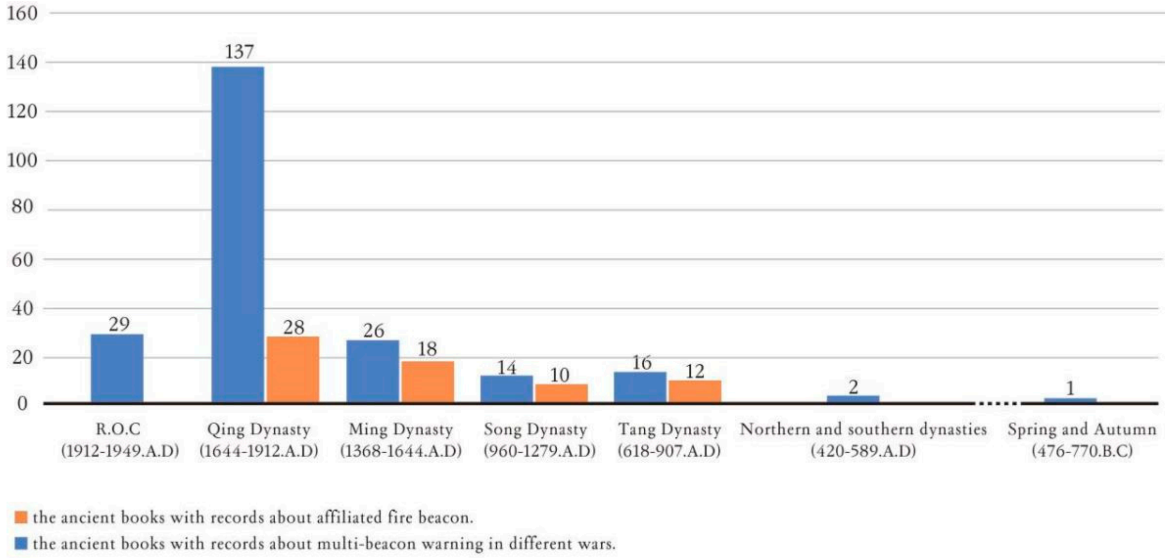


Figure 1. Date distribution of ancient books with information related to "auxiliary beacons".

Compared to the watchtowers, walls, and other structures found along the Great Wall, auxiliary beacons are small in scale and can be easily destroyed or buried. Surviving sites are scattered across a vast geographical region divided by complex terrain. Therefore, the GW Resource Survey rarely involved auxiliary beacons, despite the large number of historical records that document them. Only Inner Mongolia [27], Qinghai [28], and other regions of the GW Resource Survey reports mentioned the existence of auxiliary beacon sites. The lack of basic investigation has led to less research on auxiliary beacons. Few archaeological and historical studies relating to the auxiliary beacons have been published to date. Gao and Wei found three auxiliary beacon sites in Hebei Province. Based on historical documents, they confirmed that these three auxiliary beacon sites date from the Ming Dynasty and were used to burn beacons to send signals [25]. Zhang Kun discovered twelve auxiliary beacon sites of the Qing Dynasty in Xinjiang and analyzed the multi-beacon signal system of Hami city [29]. Li Xiaoming conducted a preliminary study on the function of auxiliary beacons based on field research in Inner Mongolia and historical materials [30]. Chen, Du, and Cui classified the architectural forms of 116 watchtowers of the Ming Great Wall in Qinghai Province, and the combination of the watchtowers and auxiliary beacons was classified as one architectural form [31]. These results were mainly based on archaeological reports and historical background interpretation of partial cases, answering the two questions of "what is it?" and "what is its function?" of the auxiliary beacon.

In-depth and systematic research on auxiliary beacon sites and their related historical scenes from the perspective of the Great Wall as a whole has remained lacking prior to this study. This situation reflects the problems of fragmentation and loss of detailed site information due to the large geographical scale of the wall and the shortcomings of previous research efforts in terms of digital information collection and management methods [32]. These factors have hindered a comprehensive grasp and observation of heritage information from specific perspectives.

1.3. Research Questions

This paper is focused on the following research topics:

New digital survey methodology: How can a comprehensive and in-depth observation and recording of auxiliary beacon sites be conducted along the entire Great Wall using new digital survey methods?

Understanding auxiliary beacons: What did these look like? Where are these sites distributed? What are the characteristics of the sites' locations? The answers to these questions form a crucial foundation for comprehending the cultural landscape of Chinese beacon signals.

Mechanisms of the Great Wall signal network: How was the beacon signal transmitted from the watchtower on the wall to the military settlements? The specific modes and scenes of signal transmission through auxiliary beacons have not been thoroughly studied.

2. Materials and Methods

To address the first research question, this study implemented a rapid survey method for heritage information at a macro-geographic scale:

2.1. Efficient Localization of Auxiliary Beacon Sites Based on the Image Database of the Entire Great Wall Line

The GW Resource Survey completed the first nationwide survey of the location and length of Great Wall relics, including a survey of the location and length of the entire site, the collection of 5 m grid digital elevation model (DEM) data within 1 km on both sides of the wall and 1 m resolution digital orthophoto model (DOM) data, and other digital mapping results [33]. However, the spatial scale and form of earlier survey results are still unable to show the site's three-dimensional details, such as site diseases, facility remains, and so on.

In 2018, our research team initiated a whole-line digital survey of the wall, with the aim of collecting detailed 3D image information pertaining to the whole-line ruins and compiling an image database of the entire Great Wall line. The method of information collection involved the use of drones for segment-wise, ultralow-altitude, low-speed flights along the Great Wall (approximately 15–25 km/h). Photographs were taken from three positions—top, inner, and outer sides—at a relative height of 30–50 m. This process was intended to capture a continuous set of high-resolution images along the same flight path, with a minimum overlap of 70% between adjacent images. Subsequently, the GPS coordinates embedded in the drone images, along with photogrammetric techniques, were employed to achieve three-dimensional measurements of both the wall itself and the localized terrain on the inner and outer sides.

Due to the complex terrain changes along the Great Wall and the presence of obstacles such as power lines, tree trunks, and mountains along the flight path, we opted for manually piloting the drone for the survey. In the initial stages of our practical work, we experimented with various drone models and ultimately chose the DJI Mavic 2, which has four main advantages:

Photography capabilities meet requirements: The DJI Mavic 2 features a 1/2.3-inch CMOS sensor with an effective pixel count of 12 million, supporting 2× optical zoom (equivalent focal length of 24–48 mm) and 2× digital zoom (48–96 mm).

Obstacle awareness: The DJI Mavic 2 is equipped with 10 sensors, applying computer vision technology to environmental perception in six directions—front, rear, left, right, up, and down—assisting in flight safety.

Long-distance and high-speed flight: The DJI Mavic 2 has a maximum flight speed of 72 km/h and a maximum image transmission distance of 8 km. Theoretically, it can complete a survey of the Great Wall spanning 10–16 km from the same location.

Cost-effectiveness: Due to the higher safety risks associated with flying in complex environments, the possibility of drone crashes exists. The DJI Mavic 2 can fulfill the aforementioned survey requirements at an affordable price.

At present, the image database contains ultralow-altitude aerial image data for about 8000 km of the Great Wall, watchtowers, military settlements, and other individual sites from several dynasties, including the Han, Ming, and Qing Dynasties. On this basis, we conducted preliminary database management and image retrieval using the Web GIS platform. Using this database, we were able to quickly retrieve and screen out no less than 530 potential auxiliary beacon sites from more than 1,150,000 images. After calibrating these positions on the map, we conducted searches and investigations of auxiliary beacon sites along the Great Wall (Figure 2).

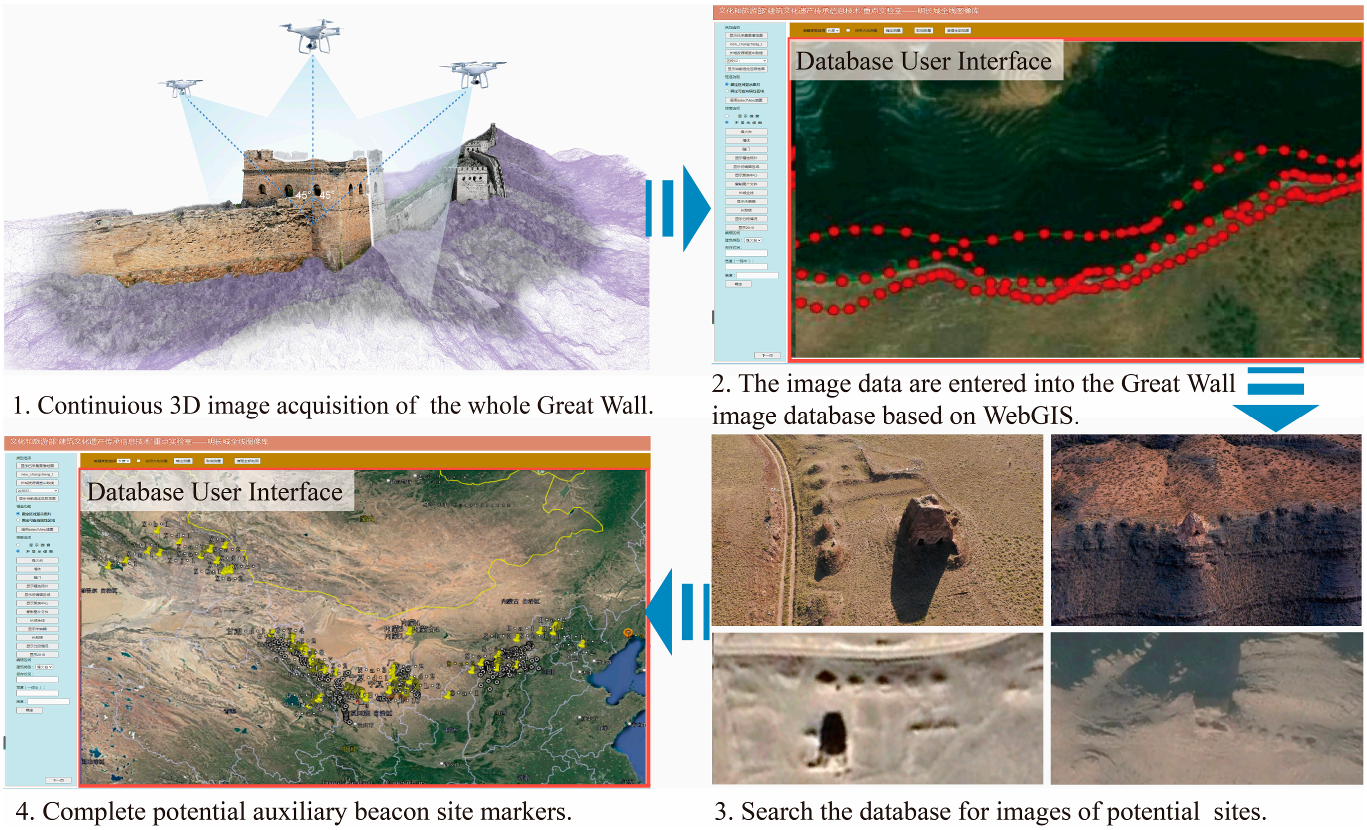


Figure 2. The workflow for locating potential auxiliary beacon sites.

2.2. Field Survey Based on Low-Altitude Remote Sensing Technology

The aforementioned potential auxiliary beacon sites were located in Xinjiang, Gansu, Inner Mongolia, Qinghai, Ningxia, and 10 other regions. However, faced with the extensive target range and complex topographies, traditional archaeological survey methods proved ineffective for in-depth investigations. In comparison, low-altitude remote sensing technology has various advantages, as reflected in the workflow.

Rapid access to map calibration locations: Most of these locations are situated in high mountains, or in the Gobi or other deserts, making it challenging and time-consuming for surveyors to approach them. Drones (e.g., the DJI Mavic 2) can overcome terrain restrictions, swiftly reaching calibration points and initiating the search and assessment of the sites. If confirmed as an auxiliary beacon site, further mapping is conducted; otherwise, the drones can swiftly return, significantly enhancing the efficiency of the survey.

Lower omission rates: Most of the auxiliary beacon sites have collapsed into piles of soil and stones, some obscured by vegetation, which are easily overlooked by ground surveyors. Aerial remote sensing perspectives are more effective than ground perspectives in discovering auxiliary beacon sites. From the aerial perspective, the piles of soil and stones are distinctly recognizable, arranged in groups of three or five. Additionally, through pseudo-color analysis, auxiliary beacon sites that are difficult to discern with the naked eye can be identified.

Rapid acquisition of comprehensive 3D data: The DJI Mavic 2 can conduct photogrammetric measurements of the site and topographic environment at a relative height of 1–3 m using the aforementioned method. The resulting high-overlap photos can be utilized to construct a three-dimensional model of the site using DJI Terra. This method enables the recording of scale, topography, and other information of auxiliary beacon sites with centimeter-level accuracy within a 10-minute timeframe (Figure 3).

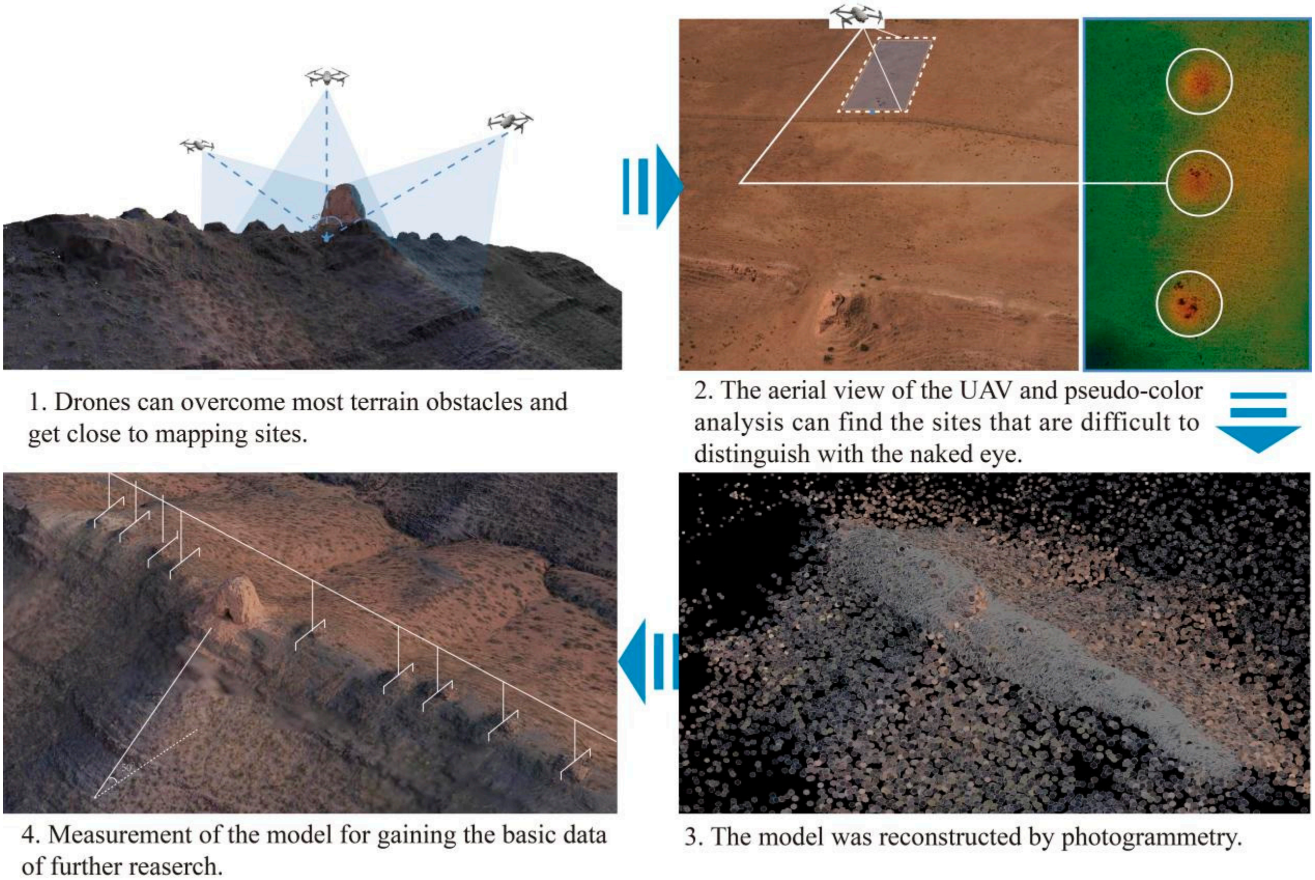


Figure 3. The workflow for confirming and mapping auxiliary beacon sites.

2.3. Mutual Verification of Historical Documents, Archaeological Reports, and Site Investigation Information

During the GW Resource Survey, archaeologists conducted verification of the construction dynasties for each wall segment and beacon tower. In the process, a small number of auxiliary beacon sites were discovered in Gansu [34], Qinghai [28], and Hebei [35], and they were identified as ancillary facilities from the same historical period as the Great Wall. Based on the above archaeological information, we believe that auxiliary beacon sites found in other regions, when adjacent to beacon towers or walls, belong to the same historical period. Further confirmation was conducted by combining local historical literature.

Historical documents record the formal characteristics of the auxiliary beacons and related historical events. Using traditional historical textual research methods, we synthesized the fragmented auxiliary beacon information and conducted historical interpretation based on the actual space of the site to confirm the authenticity of the historical information and enhance our understanding of the artifacts' authenticity.

3. Survey Results and Analysis

3.1. Distribution of Auxiliary Beacon Sites

Following the digital survey, 252 auxiliary beacon sites were identified out of the 530 potential sites, challenging the existing understanding.

The widespread continuous distribution of auxiliary beacons along the whole line of the Great Wall was confirmed for the first time (Figure 4). The number of auxiliary beacon sites found in the survey far exceeds the record of the GW Resource Survey, including 18 Han Dynasty auxiliary beacon sites, 211 Ming Dynasty sites, and 23 Qing Dynasty sites. These sites span across 10 provinces/autonomous regions, including Xinjiang, Gansu, Qinghai, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Hebei, Tianjin, and Liaoning.

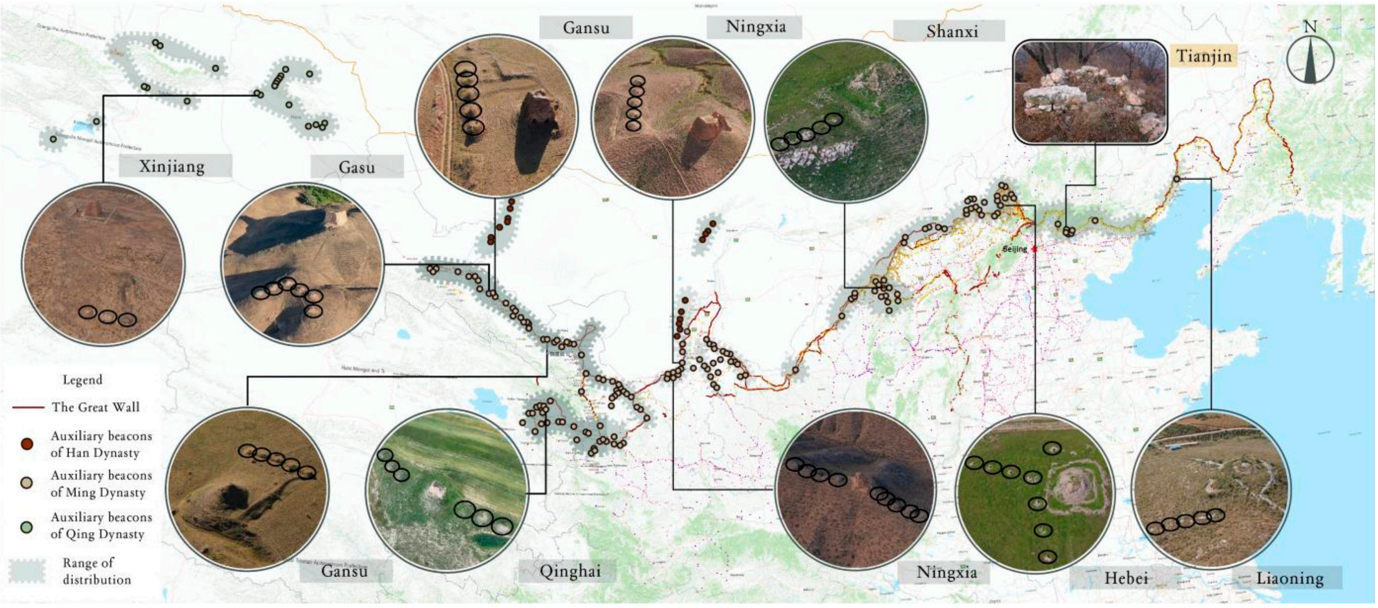


Figure 4. Distribution of auxiliary beacon sites along the Great Wall of China.

The discovery of these sites validates the extensive use of the "multi-beacon signals system", indicating that the auxiliary beacons should be recognized as crucial structures in the Great Wall's signal network.

3.2. Location Types of Auxiliary Beacon Sites

3.2.1. Location Types of Auxiliary Beacons Combined with Watchtowers

Watchtowers can not only store grain and firearms but also ensure the safety of soldiers [36]. Consequently, many auxiliary beacons are strategically positioned near these watchtowers. The digital survey showed that there are remains of auxiliary beacons in four types of terrain: mountains, plains, hills, and basins. According to the layout characteristics of the auxiliary beacons, they can be classified into 16 location types, covering all of the auxiliary beacon sites discovered so far (Figure 5).

3.2.2. Location Types of Independent Auxiliary Beacons

In instances where military expenditure is insufficient, soldiers may opt to construct independent auxiliary beacons without the need for accompanying watchtowers, yet still fulfilling the fundamental requirements of multi-beacon signal transmission [37]. This shows that, within the multi-beacon signal network, watchtowers primarily serve as structures for observation, guarding, and storage, while the auxiliary beacon emerges as the central facility for signal transmission. This distinction provides the rationale for referring to these structures as "watchtowers" in China. During the digital survey along the Great

Wall, numerous independent auxiliary beacon sites were identified, primarily categorized into two location types: “on the wall” and “on the mountains inside the wall” (Figure 6).

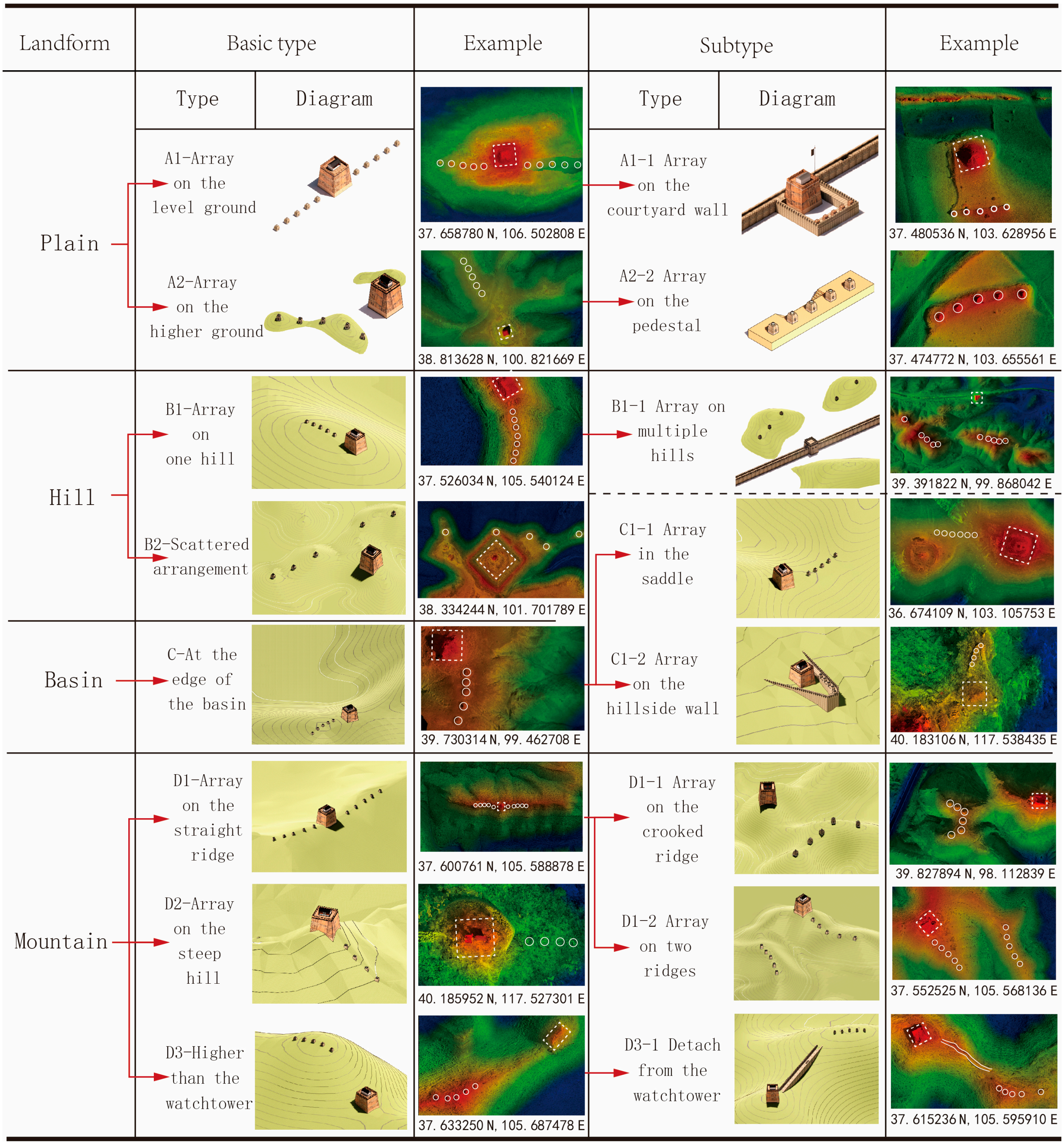


Figure 5. Location types of the combination of auxiliary beacons and watchtowers.

The digital survey found three independent auxiliary beacon sites “on the mountains inside the wall”. In these cases, the closest distance from the Great Wall exceeded 272 m, well beyond the effective range of bows and arrows. Furthermore, it should be noted that the minimum height in relation to the Great Wall was 27 m, exceeding the typical stature of Ming Dynasty watchtowers, which stood at approximately 16 m [38] (Table 2). These sites were strategically situated at a distance from the border, horizontally and vertically, enhancing the safety of stationed soldiers. The selection of sites for independent auxiliary beacons demonstrated optimal visibility, with soldiers able to discern their surroundings clearly from ground level without relying on watchtowers. Notably, the locations of these auxiliary beacons were meticulously chosen, considering terrain features to meet the dual requirements of soldier safety and visibility.

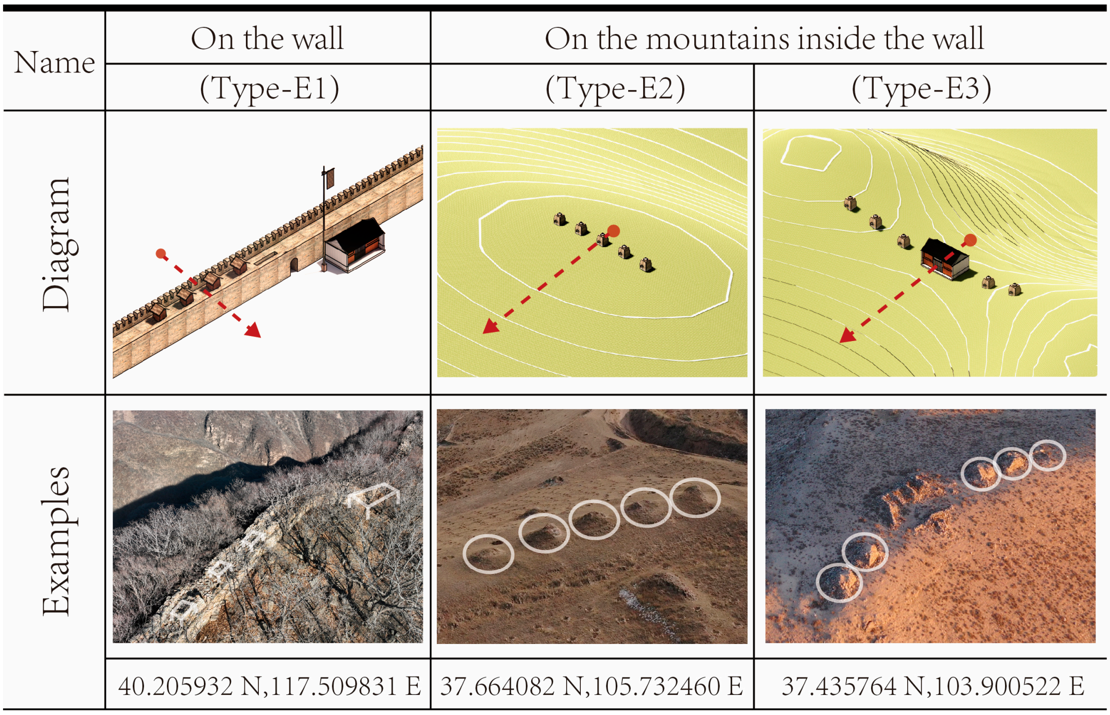


Figure 6. Location types of independent auxiliary beacons.

Table 2. Site information statistics of independent auxiliary beacons.

Number	Type	Horizontal Distance from the Nearest Great Wall (m)	Vertical Height Relative to the Nearest Great Wall Foundation (m)	Latitude	Longitude
1	On the Great Wall	0	7.6	40.221780	117.502866
2		0	8.2	40.210075	117.489292
3		0	6.3	40.244103	117.407106
4	On the mountains inside the wall	272	27	40.243251	117.456214
5		709	69	37.435763	103.900522
6		10,122	288	36.694775	103.163347

3.3. Structure Types of Auxiliary Beacons in Different Periods

The digital survey uncovered variations in the structure, appearance, and combinations of auxiliary beacon sites across different historical periods. By combining ancient records, site information, maps, and historical photographs, the distinct forms of individual auxiliary beacons from each historical period were reconstructed. Simultaneously, the historical imagery of the combined structures of auxiliary beacons and watchtowers was also restored.

3.3.1. Auxiliary Beacons of the Han Dynasty

Auxiliary beacons of the Han Dynasty (202 BC~AD 220), also known as "Jixin", represented the initial stage of the auxiliary beacon. The "Jixin" consists of bundled firewood placed on a stone/rammed earth platform, forming a 1.9 m × 2.5 m × 1.3 m cubic structure covered with sand on the top [39]. These "Jixin" structures were arranged in groups of four and positioned in proximity to the watchtowers. The management system was documented in ancient records from the Han Dynasty(Figure 7) [40].

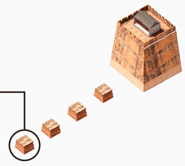
Name	Type-Jixin				
	Location and photos of the remains		Restoration		Combined with Watchtower
	 40.765286N, 106.498544E				
Han Dynasty	Management system	The number of enemy troops detected	Corresponding beacon signal		
		A reconnaissance team of about 10 people outside the wall.	Day	raise a flag	No need to ignite any Jixin.
			Night	raise a torch	
		Infiltration of fewer than 500 troops into the wall.	Day	raise two flags	Ignite a Jixin.
			Night	raise two torches	
		Infiltration of 500 to 1000 troops into the wall or attacking the watchtower.	Day	raise three flags	Ignite two Jixins.
			Night	raise three torches	
		Attack the watchtower or walls by over 1000 troops.	Day	raise four flags	Ignite three Jixins.
			Night	raise four torches	
		The watchtower is completely surrounded.	Day	Wave the flag	Ignite four Jixins.
			Night	Wave the torch	

Figure 7. Types of auxiliary beacon in different periods (Han Dynasty).

3.3.2. Auxiliary Beacons of the Ming Dynasty (Yanzao)

The auxiliary beacons of the Ming Dynasty (AD 1368~AD 1644), referred to as "Yanzao", were structures approximately 3 m in height with a horizontal length of about 1.8 m. The lower half resembled a cube, while the upper half took the form of a trapezoid. The top of the "Yanzao" had a smoke outlet, which was usually covered with a tile basin. In the middle of the structure, there was an opening (1 m high from the ground) for placing fuel, with a width and height of 50 cm [41]. These "Yanzao" structures were arranged in groups of five, and the combination of beacon signals with the sound of cannons was employed to convey pre-arranged information. The management system was documented in ancient records from the Ming Dynasty (Figure 8) [42].

In the Tianjin area, the Great Wall features a distinctive form of auxiliary beacon known as the "fire pool". These structures are predominantly dustpan-shaped in plane, measuring about 0.8 m^2. Low stones were built on three sides, leaving an opening on one side for ventilation and fire. Fire pools had stone tiling, the upper frame held two cubic meters of firewood, and the top would have a straw mat to form a sloping roof-like cover [43]. These fire pools were arranged in groups of four. At night, the number of flames emitted by the fire pools would be combined with the number of cannon sounds to convey pre-arranged information, such as a fire pool burning combined with a cannon sound, which would have meant that there was an enemy force of over a thousand troops attacking in the "Shanhai" region, whereas two fire pools burning combined with two cannon sounds would mean that there were over a thousand troops attacking in the "Xifeng" area, which should be supported immediately [44].

3.3.3. Auxiliary Beacons of the Qing Dynasty (Yandun)

The auxiliary beacons of the Qing Dynasty (AD 1636~AD 1912), also referred to as "Yandun", exhibit a trapezoidal structure with a bottom width of approximately 3 m, a top width of about 1.8 m, and a height of around 2 m [45]. The top of the "Yandun" is equipped with battlements and smoke outlets. In the Qing Dynasty, a watchtower was set up every ten miles, with three or five auxiliary beacons nearby [46]. Similar to the practices in the Han and Ming Dynasties, the varying numbers of beacon signals lit by these auxiliary beacons served as indicators of the scale of invading enemies in the Qing Dynasty [47].

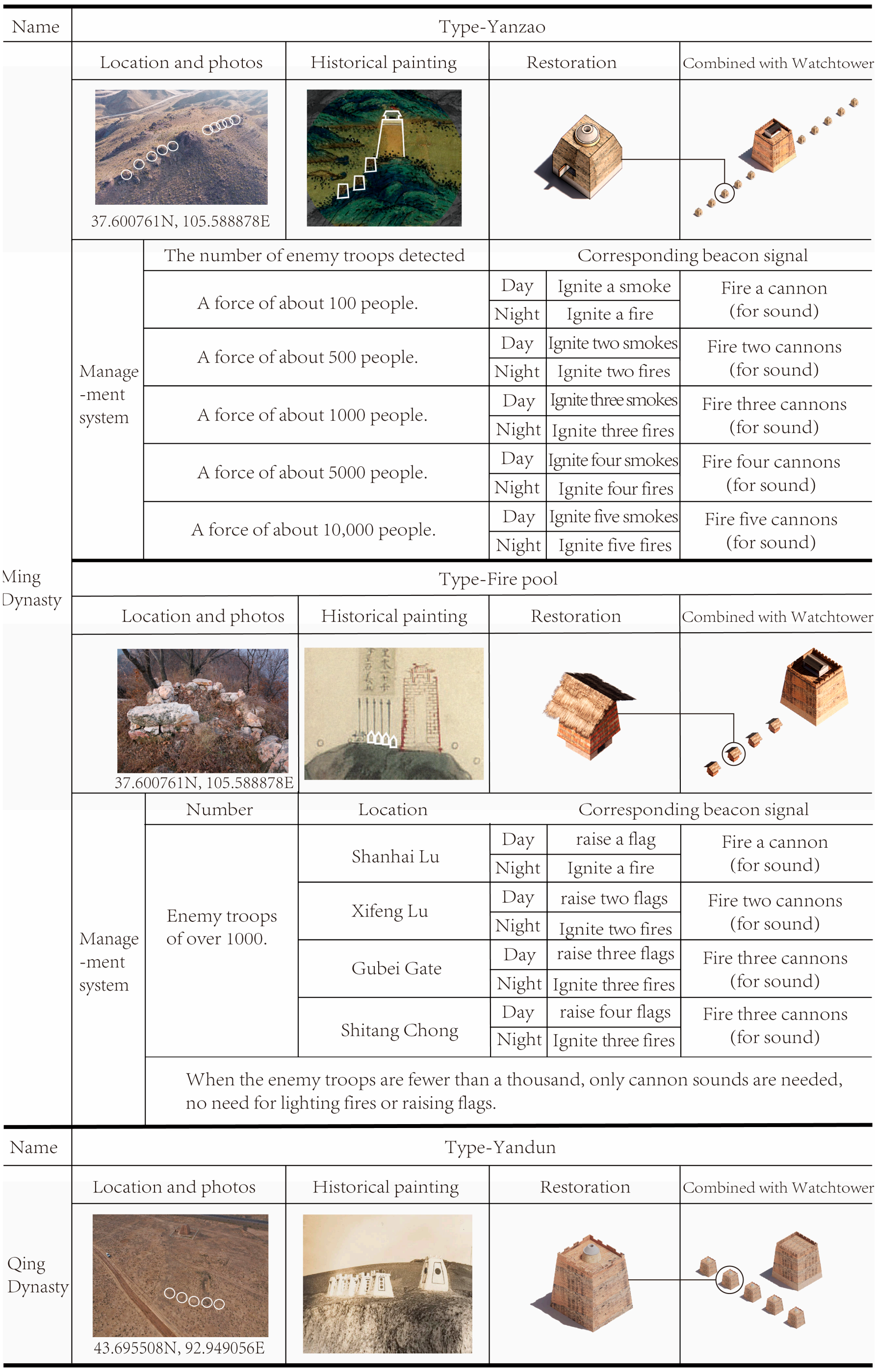


Figure 8. Types of auxiliary beacon in different periods (Ming and Qing Dynasties).

In addition, there are ancient books recording the historical scenes of "multi-beacon signal" from other periods, such as the Spring and Autumn Period (770 BC~476 BC) [6], Sui Dynasty (AD 581~AD 618) [48], Tang Dynasty (AD 618~AD 907) [49], and Song Dynasty (AD 960~AD 1279) [50], which can preliminarily prove that the system of "multi-beacon signal" had been inherited and used from the Spring and Autumn Period to the Qing Dynasty, with a history of more than 2000 years.

While auxiliary beacons across different periods and regions may exhibit variations, their commonality lies in transmitting pre-arranged information through the illumination of varying numbers of beacon signals. This shows that the auxiliary beacons are influenced by climate, geography, systems, technology, and other factors, showing the regional characteristics of the construction of wisdom.

4. Discussion

By combining the aforementioned visual and written sources and site data, we found that the combination of auxiliary beacons and watchtowers formed the signal network along the Great Wall. Taking the Ming Great Wall as an example, the information transmission in the signal network had three modes under different scales of warfare: "Along the Great Wall", "From the Great Wall to military settlements", and "Around military settlements and camps". Auxiliary beacons played a crucial role in all three modes.

4.1. Modes of Transmitting Beacon Signals "Along the Great Wall"

Two types of auxiliary beacons, vertical (Type-B in Figure 9) and parallel (Type-A in Figure 9) to the wall, were strategically positioned along the Great Wall. In response to the detection of enemy gatherings outside the border, soldiers lit the corresponding number of beacon signals according to the number of enemy troops. The "multi-beacon" signal was relayed along the Great Wall by Type-B auxiliary beacons. As the signal reached Type-A auxiliary beacons, they would redirect the communication towards the interior of the wall, rapidly transmitting it to the nearest military settlement.

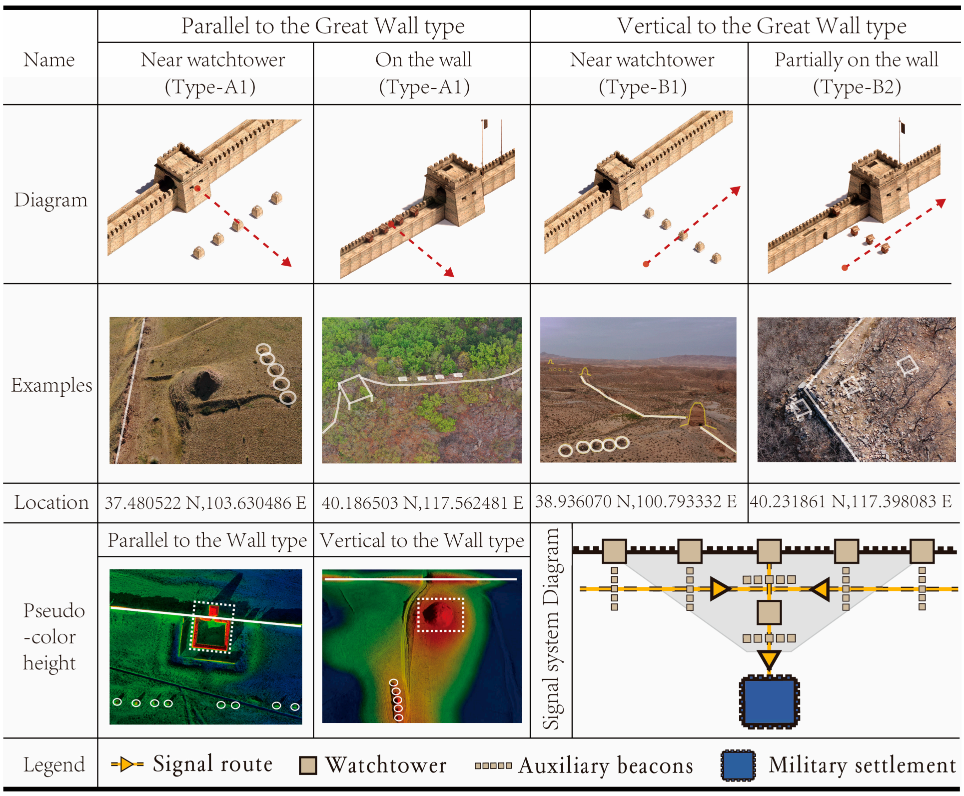


Figure 9. Different types of the auxiliary beacons along the wall, and their modes of signal transmission.

For smaller numbers of enemies, the Great Wall Defense System would initiate a localized military response. Auxiliary beacons along the walls would function as "skin-surface neurons" in the "multi-beacon" signal network, issuing warnings to the nearest military settlement. This would prompt generals to deploy troops in accordance with pre-arranged plans. The application of the auxiliary beacons could enable the Great Wall Defense System to dispatch the appropriate troops for support at the first time, avoiding the deployment of insufficient or excessive forces.

4.2. Modes of Transmitting Beacon Signals "From the Great Wall to Military Settlements"

Between the Great Wall and the different levels of military settlements, there were various types of watchtowers and auxiliary beacons, forming a multi-beacon signal network. In the event of a large number of invading enemy troops, the Great Wall Defense System would trigger a comprehensive military response. Surrounding military settlements would dispatch troops to support the Great Wall, which required coordination among the various settlements. Therefore, in addition to messenger communication, some positions in the signal network needed to transmit signals in multiple directions simultaneously. In these cases, a watchtower was installed at the corresponding position, and multiple sets of auxiliary beacons were arranged around it, each transmitting beacon signals in different directions (Type-D in Figure 10).

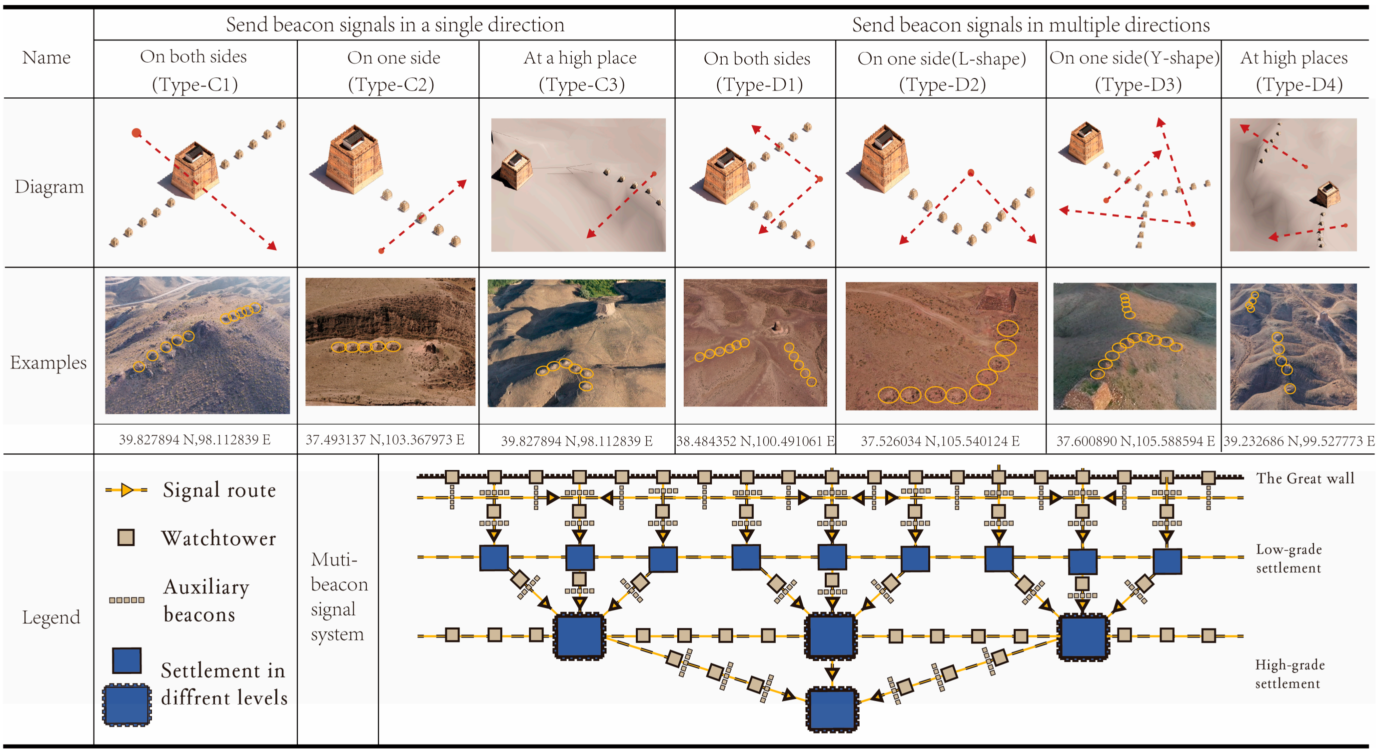


Figure 10. Different types of auxiliary beacons inland, and their modes of signal transmission.

Signals were transmitted from the Great Wall to the military settlements at different levels. In plain terrain, Type-C1, Type-D1, and Type-D2 were regularly arranged. In mountainous terrain, Type-C3 and Type-D4 auxiliary beacons were distributed along the ridge line. The combination of auxiliary beacons and watchtowers in different terrains formed the signal network, which enabled military settlements at all levels to act synchronously and carry out large-scale coordinated operations.

4.3. Modes of Transmitting Beacon Signals "Around Military Settlements and Camps"

If the Great Wall was breached, the nature of warfare would transition from defending the wall to large-scale field operations in the interior. The Northern Yuan cavalry's high mobility and unpredictable warfare demanded early warnings. Auxiliary beacons played a crucial role in signal networks for military settlements and marching camps (Figure 11 Type-F).

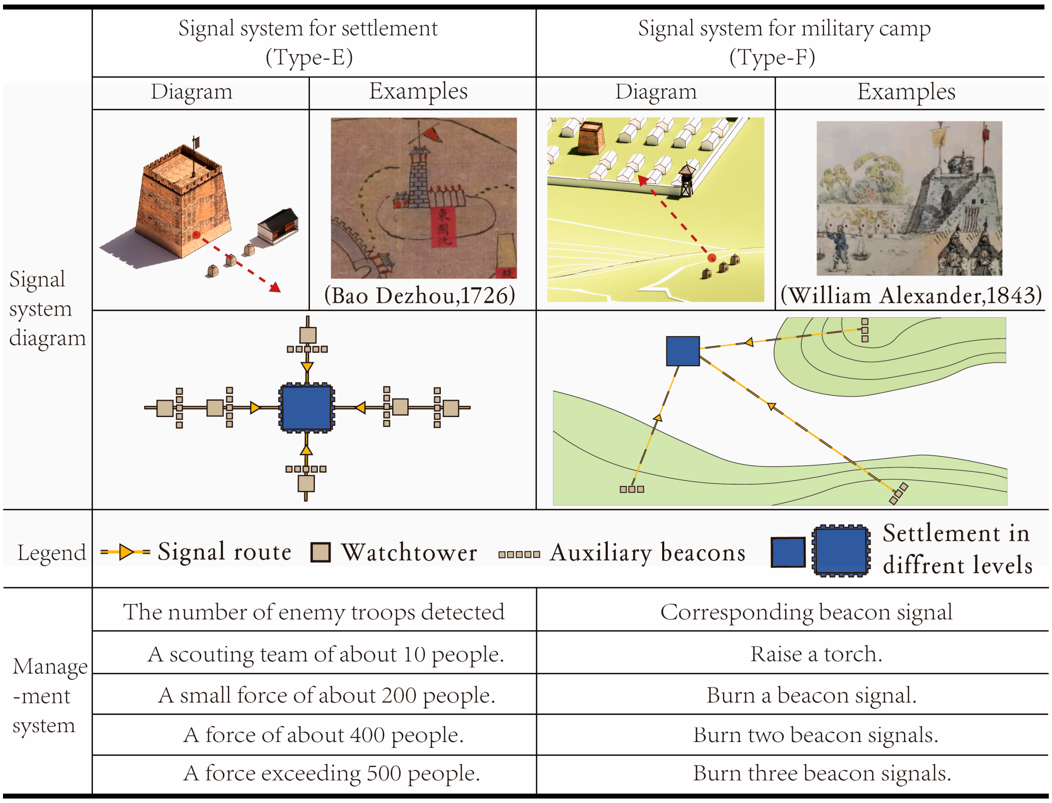


Figure 11. The different types of auxiliary beacons around military settlements and camps.

With the military settlement as the center, a watchtower and groups of auxiliary beacons were built every few miles around [51]. When the enemy was found, the soldiers on the watchtower would light beacon signals through the auxiliary beacons, providing the military settlements ample time to prepare for battle (Figure 11 Type-E).

When the army was stationed in the field, the auxiliary beacons were built in each camp and the surrounding elevated positions, establishing a temporary multi-beacon signal network around the camp (Figure 11 Type-F). Ancient Chinese records emphasize the indispensability of beacon fire warnings, equating them to the eyes of the army [38]. The management system for temporary signal networks around military camps is shown in Figure 11 [37].

4.4. The Implications and Value of Auxiliary Beacon Research

In summary, it is evident that beacon sites are distributed from the wall to military settlements, and their distribution pattern is scattered (Figure 4). The digital heritage preservation and exploration of other large-scale sites worldwide often have predefined scopes, focusing on subjects with known fixed locations, such as the Dolomite Mountains (Italy) [17], Hampi (India) [52], or Olduvai Gorge (Tanzania) [53]. In comparison, the positions of auxiliary beacon sites are unknown and scattered, making the exploration of these sites more challenging, thereby emphasizing the innovativeness and feasibility of the proposed method. The systematic study of the distribution, types, locations, and signaling modes of auxiliary beacon sites lays an important foundation for future research.

The auxiliary beacons would transmit the signals quickly and accurately through multiple beacons, which are the core structures in the Great Wall signal network. They should not be regarded solely as a subsidiary facility of the beacon tower to the extent of being overlooked. The study of the auxiliary beacons holds significant historical and cultural importance.

(1) Updating the perception of ancient Chinese “Signal Fires”:

The historical scenes involving multiple signal fires lack public awareness. Neglecting the auxiliary beacons makes it challenging to reasonably interpret the historical background of signal fires, including their warning mechanisms, planning, and design at the sites. The Great Wall Defense System achieved rapid communication through a signal network, ensuring the security of vast border regions with limited manpower. The auxiliary beacons were a crucial element in the operation of the expansive signal network, providing a new perspective for in-depth research into the historical engineering of ancient Chinese communication systems.

(2) Guiding site preservation and avoiding “Destructive Restoration”:

According to the conservation principles of the Venice Charter, the protection of architectural heritage aims to achieve integrity and authenticity. Due to a lack of awareness regarding auxiliary beacons, many sites have not been included in the scope of cultural heritage protection. Some auxiliary beacon sites have even suffered damage during Great Wall restoration projects. For instance, after the environmental refurbishment around the Jiayuguan city wall, the traces of auxiliary beacons completely disappeared [54]. This study contributes to the preservation of the integrity of Chinese Great Wall signal construction sites.

(3) Profound exploration of the cultural landscape resources of the Great Wall:

The well-preserved and showcased auxiliary beacon sites contribute to the restoration of authentic historical scenes, enabling a profound exploration of the cultural resources of the Great Wall. This effort can provide rich cultural content for the national-level project the “Great Wall National Cultural Park”, showcasing more attractive archaeological and historical landscape resources.

5. Conclusions

Based on digital technology, a field survey of the auxiliary beacon sites along the entire length of the Great Wall of China was conducted. The survey results confirm that the auxiliary beacon sites are widely and continuously distributed along the Great Wall, giving rise to various facility types influenced by factors such as climate and geography. The results of this study reveal that ancient China employed a “multi-beacon” signaling system. Auxiliary beacons served as the architectural carrier of this system and were key structures within the signal network of the Great Wall.

The application of the new digital survey methods solves the problem that the spatial scale of linear sites is wide and difficult to observe as a whole, and it can improve the efficiency of heritage information processing and the accuracy of site observation. Through practical digital surveys, this approach has proven to be feasible.

Through an examination of the often-overlooked structures within the Great Wall’s resources, specifically the beacon sites, this study endeavored to uncover the latent potential embedded in the cultural resources of the Great Wall. Simultaneously, it sought to enhance the preservation of crucial details of sites along the Great Wall, thereby preventing their gradual disappearance due to damage.

Implications for future research: Employing technologies such as low-altitude remote sensing and satellite remote sensing to establish a digitized archive for large-scale cultural heritage holds significant promise. This approach enables a comprehensive understanding of extensive heritage clusters, facilitating the exploration and presentation of cultural heritage values. Additionally, through computer vision using artificial intelligence, it is possible to achieve database information retrieval, statistics, and analysis. For instance, automatic identification of the volume of auxiliary beacon sites in database images can be implemented, enabling the systematic assessment of the current status of sites along the entire Great Wall. By integrating preservation principles and environmental factors, a comprehensive assessment of the value of each beacon site can be conducted, leading to the formulation of tailored protection strategies.

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