Applications of remote sensing technique in archaeology: a review

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Abstract: Remote sensing technique is able to quickly detect the distribution of the sites above and below the ground, and plays a constructive role in the present archaeological work, so it becomes an important tool for archaeological investigations. This article presented the fundamental principles of the remote sensing technique in detection of sites, and then listed comprehensively the general methods used and some successful applications, and finally reviewed the its functions, constraints and future development.

Key words: remote sensing, archaeology, site, review

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1 INTRODUCTION

With dramatic increase of the world's population, rapid development of the society and powerful capacity of transforming the world, archeological work should acquire the information of cultural heritages with effective and low-cost means before the sites are destroyed and disappeared. Traditional methods and field investigation in archaeological work have lots of limitations in case of the grand sites and sites group, etc., however, remote sensing makes it possible to survey quickly cultural heritages in large areas at low cost: archaeological remote sensing is the method applied to detect the ancient sites, relics and to analyze and identify them, so that some features of ancient sites never observed by human eyes can be found. Additionally, sites mapping can be made and some reasonable explanations can be also made based on understanding of the situation, distribution and the surrounding environment of the sites.

In comparison with archeological field work, archaeological remote sensing provides much information which can hardly be acquired in field work, and its main advantages show in six aspects as follows: (1) Large coverage. Remote sensing provides overall image or the study area at different scales and resolutions from cultural relics census in large area to a specific site. (2) Large spectral range. Human eyes can only observe the visible part, but remote sensing is able to use the ultraviolet, visible, infrared, thermal infrared, microwave, etc., to detect the targets. (3) High spatial and temporal resolution. Field archeology can only survey the sites at a certain time in some limited ways, but remote sensing archeology could repeatedly observe the study area at the different time, and investigate the multi-temporal site landscape and relics condition. (4) High spectral resolution. Multi-spectral remote sensing images can provide the different spectral information in the same area, and the imaging spectrometer enhance the ability to recognize the archaeological objects. (5) Powerful Penetration capability. Synthetic aperture imaging radar can be used to detect ancient remains in arid desert areas because of its ability to penetrate ground surface, and ground-penetrating radar technology can obtain a certain depth archaeological information below the ground. (6) Non-destructive detection to archaeological objects. Remote sensing archeology has the advantage of non-destructive detection to underground archaeological targets (Zhao, 2004).

2 PRINCIPLES OF REMOTE SENSING DETECTION IN ARCHAEOLOGY

Ancient sites and relics were the places where the ancients had ever lived, therefore their natural condition must be changed then by human factors and the difference between the sites and natural environment emerged. Although these changes could not be detected easily because of the later human intervention, there was still much difference between the sites and their surrounding environment in terms of water content condi-

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tion, vegetation growth status, land use condition and different geomorphic structures. These differences can be recorded in remote sensing imagery, providing a decision basis for archaeological analysis. Archaeological remote sensing makes use of these differences to obtain data, and then makes sure that whether there are sites in some region (Zhang *et al.*, 2008).

Whether remote sensing can detect archaeological target depends on the following factors: (1) the match between physical characteristics of the archaeological target and detection capability of the sensor; (2) the difference in physical characteristics between the archaeological target and its surrounding environment; (3) the environmental conditions when the remote sensing data is acquired.

The size of the archaeological target that can be detected by remote sensing depends on the spatial resolution of the sensor. According to the experience, good detection results could be achieved when the spatial resolution is not larger than the geometric size of the smallest object in all of the targets. Generally speaking, the closer to ground the sensor is, the higher its spatial resolution is, so that much more detailed information can be observed and investigated, which explains the ground-based detection method can often achieve better results. At present airborne remote sensing can also provide sub-meter spatial resolution. Until the end of last century the spatial resolution of satellite remote sensing usually ranged from 10m to 30 m, which is too coarser to be used in archaeological detection, but the new type of remote sensing sensors developed in recent 10 years could provide meter-scale and even sub-meter spatial resolution. What is more, the detection accuracy, the degree of sensitivity and other physical properties of the sensors also influence the detection capability.

In comparison with the anomal targets without regular geometric characteristics, some anomal targets with regular geometric features (linear, circular or rectangular) can be more easily identified as archaeological targets, because those targets without regular geometric features may be caused by the biological activity (trunks collapse, animal bones, etc.); the formation of mounds often increases to some extent the magnetic conductivity of its surface soil, which causes the magnetic field to be increased in some region, while in other regions the magnetic field tends to decrease; the distribution pattern of vegetation suffers from the influence of near-surface structure; the growth of vegetation is hindered because of the near-surface stone base, but the ancient ditches with wet sediment accelerates the growth of vegetation, and both cases lead to changes of spectral properties of vegetation (Scollar *et al.*,1990; Wilson, 2000); sediment composition, density, moisture retention and other factors would affect its absorption rate of solar radiation, emissivity, which leads to changes in thermal characteristics (Dabas & Tabbagh, 2000).

When data is acquired, the environmental conditions would also greatly influence the results of detection: the radiation of sunlight is a necessary condition for visible/near infrared remote sensing, while not necessary for thermal remote sensing or microwave remote sensing; to obtain the topography shadow of sites, aerial photography often makes use of a lower sun incident angle; to get the "vegetation marks" of the sites, it is needed to image the sites in a particular period; resistivity/permeability method cannot be used in frozen soil; too much or too little soil moisture will cause failure for the method of resistivity/magnetic or thermal conductivity measurement; too much soil moisture also influences the penetration of the radar wave.

3 ARCHAEOLOGICAL REMOTE SENSING DETECTION TECHNOLOGY

According to the types of remote sensing platform, Archaeological remote sensing can be divided into ground-based archaeological remote sensing, airborne archaeological remote sensing and spaceborne archaeological remote sensing. Among them, the ground-based archaeological remote sensing mainly refers to electrical, magnetic, gravity field of geophysical exploration, etc., and it also the important detection means used in most archaeological applications, and the airborne or spaceborne archaeological remote sensing refers to use all kinds of sensors carried on the airborne or spaceborne platform to detect archaeological sites.

3.1 Ground-based remote sensing archaeology

Ground-based remote sensing refers to the method of deploying detection equipment within or above the ground. Most methods are based on geophysical prospecting to measure physical and chemical properties of the sites buried in shallow ground (usually 1—2m below the ground). There are mainly four methods: magnetometry, resistivity, magnetic permeability method, ground-penetrating radar method.

3.1.1 Magnetometry

Ancient relics, ancient sites, ancient tombs, ancient buildings and ancient human fossils, etc., located some stratum, in which the magnetism, magnetic susceptibility, anisotropy of magnetic susceptibility and residual magnetization are different from their surrounding environment, so the difference of magnetism form the basis of magnetism archaeology(Yan, 1996). As the method of the magnetometry has characteristics of quickly completing the measurement of magnetic force in large areas within a limited time, high sampling rate, and forming some abnormal magnetic force to some degree for archaeological detection, it is often considered as the most effective way in ground-based remote sensing detection. Magnetic density is measured in nanoteslas (nT; 10^{-9} Tesla). In the mid-latitude areas, the Earth's magnetic field ranges from 40,000 to 55,000nT. The magnetic anomaly of archaeological targets generally range between ±5nT, and usually smaller. As the magnetic density decreases with the cube of the distance, the detection of magnetic field is often limited within the 2m above the archaeological targets, unless the magnetic field source is greater (Clark, 2000).

The most successful application of magnetometry is the exploration of San Lorezo Tenooktlan, Mexico, which was well-known for the great stone statues wearing the helmet, and a number of statues were bared for natural erosion. In order to find more underground statues, archaeologists have analyzed the properties of granity of these statues, and found that these granity had a strong magnetism, so they decided to use the magnetometry method to detect these targets. Thus, a 1m×1m net within the scope of 0.5km^2 was distributed and the magnetometer with 0.1nT resolution was used to measure 80,000 points, and more than 100 magnetic anomaly points with better shapes were obtained after analysis and processing. And then archaeologists studied the 20 magnetic anomaly points, and unexpected results were achieved. They unearthed the Olmec statue, Holy Communion platform, plate carved symbols and other hundreds of cultural relics, causing great sensation in the archaeological field.

3.1.2 Resistivity/permeability

Resistivity and permeability methods quantify identical aspects of targets in different ways, so only resistivity method is discussed here. The resistance of electric current from soil depends on the type of soil substance, humidity, the ion's volume dissolved in soil, density, holes of soil and other factors. Soil conductivity is simply the inverse of resistivity: the high resistivity substance means the low conductivity at the same time. These methods are sensitive to the resistance difference of subsurface resulted from stone material or block with high resistance, and to small-scale resistance difference caused by sediment. The wet sediment filled in the ditch may present a low resistivity (high conductivity), but the unpressed accumulated soil with many holes may present a high resistivity (low conductivity).

According to the different problems, the method of resistivity can be divided to two types, electric profile and electric depth probe. The former aims to detect the change of the resistivity of underground medium in the horizontal direction, and the later is mainly focus on the change in vertical direction. Electric profile can be applied to detect the underground ancient tombs and other ancient structures (e.g. the wall below the soil, building's base, underground track, mine pits, ditch, pools) and ancient river channel, fluctuate bedrock, ect. In 1946, British scientist Atkinson used the resistivity method to study the Dorchester Neolithic underground sites, which was the first application of the geophysical exploration of the ancient ruins. The detection of the middle capital sites of Ming-dynasty, in Fengyang, Anhui Province was the first case of systematic exploration of a large-scale site with the combination of resistivity method and aerial photogrammetry in China (Zhong, 2004). Su (2007) applied the high density resistivity method to investigate the trench of the ancient ruins of Sanxingdui, and the result basically agreed with the actual situation. The Zhejiang workstation in affiliation to the Joint Laboratory of Remote Sensing in Archaeology took the resistivity method as main means, and combined the magnetic method, ground penetrating radar and other methods to approximately find the specific location and distribution Six Tombs of Song Dynasty, which was composed of tombs of eight emperors and empresses (Ge & Ji, 2007). The work has a great practical significance for a large number of sites in China where field excavation is unsuitable.

3.1.3 Ground-penetrating radar

Ground-penetrating radar is one of the most frequently used geophysical survey methods. The method of ground-penetrating radar is to use antenna to directly send high-frequency (a few MHz to hundreds of MHz) electromagnetic waves into the ground, and the part of the electromagnetic energy after reflection from the boundaries was received by antenna and recorded. Through the measurement of time and speed of the received wave, the distance from the antenna to the detection targets can be calculated. By surveying several points located at different positions, the target's spatial position can be detected. Ground-penetrating radar can provide relatively accurate quantitative information, and this equipment is so convenient to operate that most archaeological workers would like to use it. However, this method is difficult to work in low resistance stratum, because high-frequency electromagnetic wave is strongly absorbed by the low resistance medium. Meanwhile, as the energy of high frequency electromagnetic wave would rapidly decrease with the depth of detection, the frequency of the electromagnetic wave have to be reduced to detect the targets located in much deeper place, but this way in turn lead to a lower spatial resolution, which is the deficiency. Zhu Weiping made use of ground-penetrating radar to detect the Liang zhuweng home sites and Leifeng Tower site, and found that ground-penetrating radar was successful in detecting the tomb with the brick, stone structure and the tomb sites with a large-scale soil structure, as well as small early ancient cultural sites (Zhao, 2004). In addition to non-destructive detection of buried objects, Ground-penetrating radar was also used in the maintenance and repair work of ancient buildings, caves, murals and other key heritages, and what is more ground-penetrating radar technology was often applied to detect the extent and depth of the surface erosion of these ancient architectural sites (Liu *et al.*, 2001).

3.1.4 Other geophysical methods

Magnetic susceptibility survey. Magnetic susceptibility survey is to quantitate the trend of magnetization of investigation objects positioned in magnetic field (such as earth magnetic field), and magnetic susceptibility can provide the buried archaeological information from a different perspective compared with the usual magnetometry. Most magnetic susceptibility survey is based on the experiment of soil samples. Several studies have utilized the in-phase component of electromagnetic induction instruments to measure magnetic susceptibility in the field, although only at very shallow depths, ranging from a few centimeters to perhaps 0.5 m (Challand, 1992).

Seismic detection technology. Frankly speaking, seismic detection technology is seldom applied in the archaeological work.

Conceptually, seismic detection technique is relevant to the ground-penetrating radar technology, but its record is sound waves rather than the microwave energy. In the measurement of refracted seismic wave, man-made shock waves were generated by hitting rubber mat with a long-handled sledgehammer or mushroom cloud explosion. The small-scale seismograph was set in the cross section and distributed in a certain interval to record the time (in milliseconds) and intensity of each received wave. Variations in timing and amplitude can indicate stratigraphic layering or large anomalous features such as ditches or architectural constructions (Goulty & Hudson, 1994; Tsokas *et al.*, 1995).

Metal detective. Metal detective is the method that the equipment of electromagnetic induction is optimized to detect all kinds metal targets in near-surface (usually the maximum depth is 0.5m). This method is especially useful to map and analyze the concentration of metal debris, and to isolate targets from archaeological site location.

Other methods. Other methods, including polarization, natural electric potential and gravity method, etc., which are little used in archaeological practice.

3.2 Aerial remote sensing archaeology

Remote sensing from the air or space utilizes electromagnetic radiation reflected or emitted from the Earth's surfaces, offering a cost-efficient means for archaeological reconnaissance over wide areas (Bewley, 2000). Aerial remote sensing often uses plane as its platform, but spaceborne remote sensing used the satellite platform(discussed in the next section). Both of them use similar sensors, but their main difference is the height of platform, which brings obvious influence to the spatial resolution and analysis of spatial details. Aerial photogrammetry is the oldest and most widely used means of remote sensing in archaeology, but in recent decades, aerial remote sensing truly become a multi-dimensional approach of remote sensing, with the application and development of all kinds of sensors applied to the airborne platform, including multi-spectral, thermal infrared sensors (passive mode) as well as radar, laser altimeter (active mode) and other sensors.

3.2.1 Aerial photography

Compared with other means of survey, aerial remote sensing played a more important role in discovering archaeological sites (Wilson, 2000). As early as the 19th century, aerial photography began to be deployed in hot air balloon, and the first archaeological application was the photo of Stonehenge taken in 1906, shown in Fig. 1. During the First World War, aircraft's control performance and pilot's skill made greatly progress, and since then some pilots had concerned about finding archaeological sites. An observer in the Rayal Flying Corps was primarily responsible for the development of aerial archaeology. While sites in arid areas and sites' features were primarily revealed from the projection of broken remains' shadow, Crawford identified the prehistoric building structure depending on the signs of vegetation in aerial photographs, and used the shadow of topography in arid areas without vegetation to identify sites. In this way, he documented more archaeological sites in a single year than had been located by pedestrian surveys in the previous century (Wilson, 2000; Bewley, 2000). This method had been further improved in the middle of 1920s, when a lot of classic air photos were posted in the Antiquity, a journal founded by Crawford in 1927. Bewley (2000) pointed out that the reason why archaeological aerial photography developed in the United Kingdom was determined by its archaeological resources and the characteristics of the landscape, the clear vegetation marks produced by soil, the availability of aircraft, relatively free airspace, and a military establishment and other factors contributed to a number of archaeological discoveries.

Fig. 1 UK Stonehenge photograph taken in 1906

Archaeological aerial photography started late in China, but some significant results were achieved. China's first large-scale aerial photo was taken in 1960, and these data was valuable for the archaeological research, because many archaeological sites suffered from damage during the Cultural Revolution especially in the period of "Emulating Da-Zhai agriculture", and the earlier the air photo was taken, the more archaeological value was (Liu & Wang, 2006). During the 1960s aerial photography was used to analyze the distribution of ancient sites, tombs in reservoir area before the Sanmenxia Reservoir was constructing. In 1996, a serial of aerial investigations was conducted by the Archaeological Aerial Photography Working Group, Cultural Relics Department of Chinese History Museum and Cultural Relics Bureau, Luoyang, to study the Yanshi Erlitou sites, Yanshi Shixiang ditch sites, the southern of Luoyang East capital of the Sui and Tang dynasty sites etc. in Gongyi City, Luoyang City, Henan Province. And another archaeological work was conducted by taking the aerial photography of late Warring States "ancient city of Shouchun" in Anhui. From 1997 to 2001, Center for Archaeological remote sensing and aerial photography, History Museum of China and Institute of Archaeology, Inner Mongolia jointly took the aerial photography in the south-east district, Inner Mongolia, and the first archaeological aerial photography report, aerial photography in the south-eastern Inner Mongolia, was published in April 2007. The role of aerial photography is also reflected in the long-time records of archaeological landscape, and thus the dynamic monitoring of archaeological landscape and environment becomes possible.

3.2.2 Aerial multi-spectral remote sensing

Airborne multi-spectral scanner can provide much more information than traditional aerial photographs, because the spectral range used in aerial photograph is much less than multi-spectral. Morain *et al.*(1981) made use of the 11-channel Bendix multi-spectral scanner with 1.25m spatial resolution to image the Bandelier National Monument in Mexico and validated the conclusion. By supervised classification of multi-spectral data, the separation of landuse between archaeological and non-archaeological zone was clear, validating that the noise from human activity could be detected through spectral analysis. The project of Heslerton Parish in East Yorkshire, Britain also used the Daedalus multi-spectral scanner to take the image of historical sites and found that multi-spectral scanner could reveal more archaeological features and more clearly shown the vegetation marks, in comparison with panchromatic image acquired at the same time (Donoghue, 2001; Powlesland, 2001). The Institute of Remote Sensing Applications, Chinese Academy of Sciences utilized color infrared remote sensing technology to detect the distribution of Laoshan Tombs of Han Dynasty in Beijing, and inferred several locations of greater mausoleums with help of some archaeological research (Yin & Wang, 2003).

3.2.3 Aerial thermal infrared remote sensing

The Stefan-Boltzmann law shows that the infrared radiation energy from objects on the ground is proportional to the fourth power of temperature, so the radiation energy would change greatly even if there was a small difference between the objects. Such characteristic constitutes the theoretical basis of infrared remote sensing. The changes of thermal radiation in archaeological sites include three reasons: (1) the changes in micro-topography cause the difference of the surface heat absorption in sunshine, because the slope facing the sun will absorb more heat, while the back slope decreases the heat absorption, and the process will last for a long time; (2) the vegetation marks can also cause different surface temperature, because different growth status of vegetation or health status lead to different evapotranspiration, while the different evapotranspiration further gives rise to the different cooling effect of vegetation; (3) the difference of thermal inertia results in dry porous objects can quickly reach the maximum temperature during the day, while at night the temperature will quickly reach the minimum value (low thermal inertia), and the temperature of compact objects (high thermal inertia), such as stones, changes relatively weakly in the day and night. And these three reasons may result from the buried archaeological sites: the underground ancient sites, the microtopography changes caused by buried relics under the shallow surface, vegetation mark, and the different thermal inertia between the surrounding soil and archaeological sites because of its shallow buried surface density, permeable materials. The high-brightness areas in the thermal infrared images represent thermal anomaly region, while the impact of solar radiation is relatively small in thermal infrared images taken at night. However, the border in thermal infrared images would be clearer in the daytime, so when we want to find geothermal anomaly regions in thermal infrared images taken in nighttime, panchromatic or multi-spectral images are needed for further analysis (Zhou *et al.*, 2007).

Perisset & Tabbagh (1981) made use of thermal radiometer ARIES and found many ancient roads, land borders, and the change of surface temperature caused by microtopography's transformation. Dabas & Tabbagh (2000) used the same thermal radiometer ARIES and found that the temperature of the soil marks in wheat field was 1.5 ℃ higher than the temperature of the prehistoric fence around border. Sever & Wagner (1991) utilized the thermal infrared multispectral scanner TIMS (Thermal Infrared Multispectral Scanner) with the spatial resolution of 5m and 6-channel, and found the surface or sub-surface site features, such as prehistoric roads, buildings, walls, and old farmland, in Chaco Canyon, New Mexico.

3.2.4 Airborne radar

Airborne radar includes AirSAR and GlobeSAR which are airborne radar platforms of America and Canada respectively for acquiring imaging radar data, and they also can be used as test platform of spaceborne radar. Adams *et al.* (1981) analyzed the AirSAR images of the region of Guatemala and Belize during the period of 1977 1980 and realized that a strong reflection (dihedral corner reflection) might be generated by a pyramid under a certain geometric condition of radar imaging, and also discovered a huge water system of an ancient canal drainage area covered 12,400km^2. Moore and Freeman (1998) used the AirSAR data system to analyze a series of typical characteristics of the ancient city of Angkor Wat in Cambodia, including the group of temples, the structures which had never been found previously, mounds, embankments, roads and reservoirs. Failmezger (2001) utilized the SAR data with 2.5m spatial resolution to map and position a group of historical sites and other features. In 1993, GlobeSAR conducted an airborne SAR experiment in Asia, and some radar data related to the ancient castle and ancient canal in Thailand were acquired. Supajanya *et al.* (1996) used the GlobeSAR data to study the ancient capital Sukhothai, Thailand, the moat, and the canal connecting three ancient cities, showing that SAR had strong capability of detecting archaeological sites.

3.2.5 Airborne laser altimeter

The surface's patterns in archaeology can also provide some important information. The surface's patterns can be obtained directly by ground-based measurements, and indirectly through the shadow of aerial photography or the temperature changes in thermal infrared imagery. The field survey of topographic has high accuracy, but it requires a great deal of investment including time, labor and cost etc.. A recently developed laser altimeter utilized the laser rangefinder to measure the height of surface, which could easily obtain the high-resolution surface elevation data. Laser altimeter often refers to Lidar (Light Detection and Ranging), which can quickly generate an accurate and dense digital terrain models, as well as other surface (the roof of buildings, tree canopy) in vertical profile. As a new rapidly developing technology, Lidar is able to map the topographic in large areas with 15cm of vertical precision (the relative accuracy of the homogeneous surface with the continuous observation is larger than the absolute accuracy) and less than 1m of horizontal sampling space (Flood, 2001). Lidar has also been put into several important applications in archaeology (Barnes, 2003; Holden. *et al.*, 2001). In the complicated terrain background, Lidar has become a powerful tool to map landscape of the archaeological sites and to interpret the interactions between terrain factors and the features of archaeological targets. It can exactly quantify the terrain factors, which helps the resistance method, ground-penetrating radar method and other detection methods suffered from terrain influence.

3.3 Spaceborne remote sensing archaeology

Spaceborne remote sensing widely refers to the remote sensing technology system carrying all kinds of spacecrafts as the platform. The main platform is the Earth's satellite, and the others include manned spacecraft, space shuttles and space stations, besides, sometimes a variety of planetary probes are also included. A number of space remote sensing programs played an important role in promoting remote sensing archaeology. These programs were shown in Table1.

Table 1 Satellite programs engaged in archaeological remote sensing

Satellite	Band	Wavelenght /μm	Pixel resolution/m	Swath width/km	Launch time	Function
Landsat1-3	Multi-spectral (G, R, NIR1, NIR2)	0.5—1.1	79	185	1972—1978	mapping the environment, land use, cover of the sites
Landsat 4-5	Multi-spectral (B, G, R, NIR, MIR1, MIR2, FIR)	0.45—12.5	30 FIR 120	185	1982, 1984	mapping sites, land use/cover, detection of ancient river channel and other large-scale targets
Landsat 7	Multi-spectral (B, G, R, NIR, MIR1, MIR2, FIR) Panchromatic	0.45—12.5 0.52—0.9	30 FIR 60 15	185	1999	the same as Landsat 4,5
Spot 1-3	Multi-spectral (G, R, NIR) Panchromatic	0.5—0.89 0.5—0.73	20 10	60	1986—1993	mapping sites, land use/cover, detection of abnormal vegetation in sites
Spot 4-5	Multi-spectral (G, R, NIR, MIR) Panchromatic	0.5—1.75 0.48—0.71	20,10 10,5	60	1998, 2002	the same as SPOT 1-3
Corona KH-4B	Panchromatic-film photography	0.5—0.7	2—10	14	1967	detection of medium or small-scale archaeological targets, detection and validation to the abnormal vegetation and other archaeological marks
KVR-1000	Panchromatic-film photograph	0.51—0.76	1—2	40	1987	the same as CORONA KH-4B
Ikonos	Multi-spectral (B, G, R, NIR) Panchromatic	0.45—0.9	4 1	13	1999	the same as KVR-1000
Quickbird	Multi-spectral (B, G, R, NIR) Panchromatic	0.45—0.9	2.44 0.61	16.5	2001	the same as KVR-1000
SIR-C/X-SAR	Microwave (X, C, L band)	3—24cm	10—50	30—60	1994	detection of abnormal soil humidity in sites and archaeological targets buried in arid regione (dihedral angel reflection)
RADARSAT	Microwave (C band)	5.7cm	8—100	50—500	1995	the same as SIR-C/X-SAR

B= Blue; G= Green; R= Red; NIR= Near Infrared; MIR= Middle Infrared; FIR=Far Infrared

3.3.1 Spaceborne multispectral remote sensing

The earliest spaceborne multispectral remote sensing is certainly Landsat MSS data with spatial resolution of 79m which is unsuitable to detect general targets and features in archaeology, so its application mainly focused on mapping the environment and land cover of the sites and identifying some known large archaeological targets. For example, Quann & Bevan (1977) identified the shadow of Great Pyramids of Giza; Ebert & Lyons (1980) identified nearly 80km long the Hohokam canal in the basin of Phoenix; Richards (1989) utilized the *Landsat-1* data to show the existing ancient structure for collecting rain water. TM multi-spectral data was greatly improved in both spatial resolution and spectral resolution in comparison with MSS, so that the trend of TM application in archaeology started to develop spectral analysis and detection of sites. Some scholars analyzed the statistical characteristic of the spectral properties and found that the spectral reflectivity in the surrounding of the sites was obviously different from the sites themselves (Custer *et al.*, 1986), which indicates that the range of spatial distribution of the sites would be generally detected according to the spectral difference between sites and surrounding environment. Johnson *et al.* (1998) made use of the TM data to divide the north Mississippi into several geographical areas, and then defined the environmental index depending on the appearance frequency. Showalter conducted a more accurate detection of the canal in Phoenix basin with TM data.

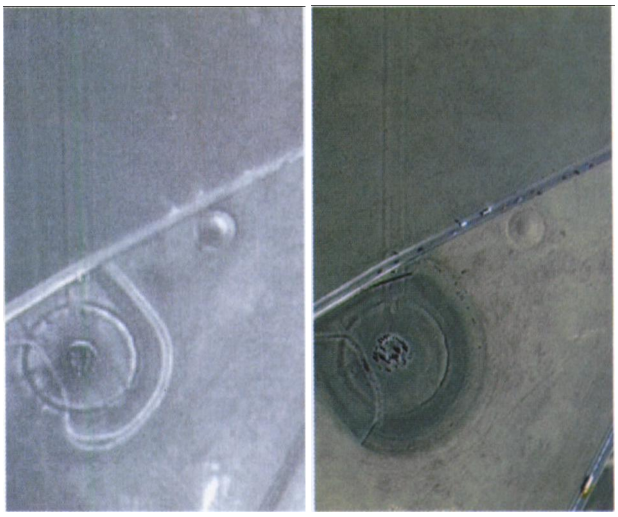
Through data processing, interpreting and mutual comparison of TM and aerial photos, Hong *et al.* (2006) fully investigated the ancient river channels and ancient city of Sanxingdui, and found many ancient river channels and some ever undiscovered sites of ancient city along the Mamu river from south to north, and then he concluded that ancient city of Sanxingdui included the inner and outer parts (center city and outer city). Compared to TM, ASTER's spatial resolution was further improved to 15m, so that its capability of detection was enhanced. Altaweel (2005) applied ASTER data to identify the ancient site, ancient canal and other archaeological targets located at Mesopotamia Iraq, and he found that through the comparison with CORONA data, ASTER's near infrared multispectral data was not only able to identify the archaeological targets discovered by CORONA panchromatic imagery with 2m of spatial resolution, but also could detect the features of the site unidentified by CORONA. It can be seen that multispectral image has more advantages over panchromatic image in archaeological work.

3.3.2 Spaceborne Hyperspectral remote sensing

Hyperspectral remote sensing usually has more powerful capability of identifying the land cover with small differences and different composite sites, when it compared with multi-spectral data, so it plays an important role in detecting the types of sites at different time and with different components. Compared with traditional remote sensing technology, Hyperspectral remote sensing with integrated image and spectrum from visible light to thermal infrared band, is a comprehensive means of remote sensing technology. Heritage information on the ground is relatively weak, and hyperspectral remote sensing has the advantage of identifying weak information and quantitative detection (Belvedere *et al.*, 2001; Tan *et al.*, 2005). However, due to the scarcity and cost of the hyperspectral data and the large volume of data, hyperspectral remote sensing is not frequently applied in archaeology because of the difficulties in processing and analysis (Yuan & Lin, 2007). Tian (2008) analyzed the spectral signatures and surveying the spectral reflectivity of surface, and then finely processed the Hyperion data of canal located in Wuxi and Yangzhou with de-noise smoothing, endmember extraction, data fusion etc. He studied the spatial information extraction and interpretation in the large sites with Hyperion data, and discussed the fine classification detection technology based on hyperspectral remote sensing.

3.3.3 Spaceborne high spatial resolution

Recently developed high spatial resolution sensors can detect a certain specific feature of the archaeological targets. Now we are moving into a new era in which the satellite-based platform will be used to map the objects on the ground and their features (Fowler, 2002). High spatial resolution satellite data was opened to civil use in 1990s, and the Russian spy satellite KVR and American spy satellite CORONA could obtain the panchromatic image (the latter could obtain images during the time of 1960—1970, which was recently retired), with resolution of as high as 2m. Fowler (1996) found that KVR-1000 images could clearly show vegetation marks of the Stonehenge, United Kingdom (Fig. 2 (a)). Kennedy (1998) identified the prehistoric settlements in Turkey with the help of CORONA data. IKONOS satellite was launched in 1999 and Quickbird satellite was launched in 2001, and their spatial resolution were 4m and 2.44m respectively (multispectral), 1m and 0.61m (panchromatic), which have been proved quite effective in archaeological work. Fig. 2 (b) is a 4m-resolution image of the British Stonehenge, and it could reveal more details about the site compared with the panchromatic image of KVR-1000. De & Waelkens (2007) obtained the IKONOS-2 data of the Hisar site never detected in southern Turkey, through the methods based respectively on GIS, image pixel and objectives in extracting archaeological features, and took the reference of the visual interpretation to assess each of the three methods. Lasaponara & Masini (2006) applied the Quickbird multi-spectral data of two sites in southern Italy to make data fusion and edge detection, and to successfully extract the archaeological crop marks. The study found that the fusion of multi-spectral and panchromatic of Quickbird image was quite helpful in the feature extraction before archaeological excavation. At present, archaeologists have begun to explore the potential of these high-rsolution data in the archaeological work (Fowler, 2000; Wheatley & Gillings, 2002).



(a) (b)

Fig. 2 KVR-1000 imagery(a) and IKONOS imagery(b) show clearly the crop marks around the stonehenge

3.3.4 Spaceborne Radar

In 1981, U.S. space shuttle SIR-A onboard the synthetic aperture radar had revealed the ancient river channels buried below the Sahara desert and attracted great attention of archaeologists throughout the world. As the dielectric constant of the sand was quite small in these dry sand area, radar waves could easily penetrate the sub-surface in those regions (El-Baz, 1997; McCauley *et al.*, 1982), and thus it might discover some targets which were not found with visible/near-infrared remote sensing methods. Guo (1997) and Lu *et al.*, (1997) used SIR-C multi-band and multi-polarization imaging radar, to identify the

Great Wall buit in Sui and Ming dynasty buried under the dry sand, which was located at the junction region of Ningxia and Shaanxi, and this discovery gave rise to great sensation in the international archaeological remote sensing community. Radar waves have the capability of penetrating the dry sand and then reached the Great Wall buried under the sand, because the imaging geometric relationship among the wall of Great Wall, basement of Great Wall, and the space shuttle met the conditions of dihedral angle reflection, so that most of radar waves were backscattered from the Great Wall and a bright "strip" in radar image revealed the direction of the Great Wall was formed as shown in Fig. 3. In 1994, SIR-C/X SAR and AIRSAR conducted a research on the ancient city of Angkor Wat surrounded by dense forests in Cambodia, and reconstructed the distribution of the ancient city of Angkor Wat, which was enlarged to $1000 km^2$ from the original areas 200—400 km^2. And a new map of water system of ancient canal was redrawn, so that we could understand the original spectacular appearance of the ancient city of Angkor (Freeman *et al.*, 1999), shown in Fig. 4. Sever and Sheet (Sheets & Sever, 1998; Sever 2001a; Sever 2001b) utilized the SAR images to analyze the ancient roads in Costa Rica. Scarre (1999) used the penetration of radar wave to detect the Maya farmland system located in Guatemala, and to position and survey the ancient site near the ancient capital of Angkor in Cambodia, providing a strong evidence for the history of the Khmer country's development. Holcomb (1998) summarized the radar archaeological theory, methods and archaeological applications, one of which is the discovery of ancient city of Ouman Ubar under the desert with SIR-A and SIR-B. In 2000, the U.S. Shuttle Radar Topography Mapping Scheme (SRTM) obtained the elevation data with accuracy of 30m that covered 80% of the global land surface through the InSAR technology. In 2003, the European Space Agency launched Envisat-1 satellite onboard the ASAR sensor with the same polarization and cross-polarization imaging capability. In December 2006, June 2007 and December 2007 ALOS, TerraSAR-X, Radarsat-2 satellite, were launched

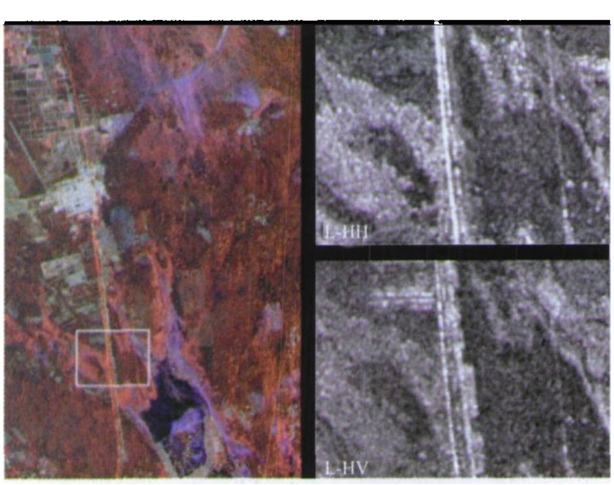


Fig. 3 SIR-C radar detected two segments of Great Wall buried by sand, built in Sui and Ming Dynasty

Fig. 4 SIR-C/X-SAR radar detected the ancient city of Angkor Wat in Cambodia in 1994

respectively, with the L, X, C-band synthetic aperture radar, all of which have capacity of imaging with the full polarization. The emergence of these new sensors would certainly promote the applications of archaeological remote sensing to a large extent.

4 CONCLUSION AND VISION

Archaeological remote sensing provides a quick method to acquire data and information of large-scale archaeological region with much lower cost in comparison with field excavation. Remote sensing provides a new perspective for the archaeological landscape. This broad perspective can bring us a new point about how the ancients utilized the space and how the ancients interacted with landscape. Only through remote sensing technology, archaeologists can map, analyze and interpret the targets interested in the global archaeological and cultural landscape region. In this sense, remote sensing not only is a tool for finding or mapping archaeological sites, but also supply a strong support for regional archaeological landscape research.

Archaeological remote sensing gives a guide that bring the archaeological field excavation with high cost to focus on the potential targets interested. Archaeological remote sensing can reveal the depth of the buried archaeological target, spatial distribution, types of soil and other information about sub-surface condition. With the help of remote sensing archaeology, the work of field excavation may be substantially decreased, and more archaeological targets may be discovered. Archaeological targets are usually suffered from damage and even destruction with traditional method of archaeological survey, however, archaeological remote sensing is a non-destructive method for archaeological detection, so the maintenance cost of archaeological sites and relics can be greatly decreased with its help.

The information acquired by remote sensing archaeology needs an analysis process during which archaeological features detected by remote sensing were interpreted and turned into the thematic map. It is needed to consider and study the features formed in different imaging conditions and different background environment to transform the information obtained by remote sensing into archaeological features and useful target information. On the one hand, the archaeological feature itself is a complicated concept, and it has no fixed mode in remote sensing imagery because it changes with time and place. On the other hand, remote sensing itself is influenced by many factors such as imaging time, imaging place, types of soil, humidity of surface, land cover, etc., which may make it difficult to effectively investigate the archaeological features.

Although remote sensing archaeology can reduce the workload of field investigation to a great extent, absolutely it cannot replace field archaeology. It cannot solve the basic problem like the estimation of the sites' time and the study of cultural relic. Thus, archaeological remote sensing must be combined with field archaeology in practical archaeological work, and we should fully consider the merits of spaceborne, airborne and ground-based remote sensing technology and field archaeology technology to utilize the 3D information acquired from space to surface and underground detection, and then to conduct archaeological research, including target detection, thematic mapping, and clustering analysis, etc.. Only in this way, archaeological work can be much more effective.

China is an old civilization in the world which has a continuous development history, and the civilization is both extensive and profound, with much cultural heritage distributed throughout the country. There are abundant in archaeological resources, including the unique large-scale archaeological sites in the world, such as the Great Wall, the Grand Canal, the Silk Road, the Mausoleum of First Emperor of Qin, etc. Thus, there are greatly broad prospects for the application of archaeological remote sensing in China. At present, China has lunched projects, such as the third national survey of cultural relics and Seeking Source of the Chinese civilization, which urgently requires the participation of archaeological remote sensing. Besides, remote sensing archaeology should also develop some thematic research through this kind of strongly intensive archaeological work, including archaeological quantitative research, improvement of detection method, promotion of information extraction. At last, it is needed to develop some comprehensive projects step by step under certain conditions, and to realize the full development of fundamental principles, technical methods and applications.

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遥感技术在考古中的应用综述

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摘　要: 遥感技术能够快速有效地探明地上和地下古遗址的分布信息, 在现代考古中发挥着重要的作用, 逐渐成为考古研究的重要手段。阐述了遥感考古探测的基本原理, 以遥感考古探测平台为序系统介绍了遥感考古探测方法与进展情况, 对遥感考古探测的作用、局限性及发展前景进行了评述。

关键词: 遥感, 考古, 进展, 遗址

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1 引　言

当世界人口在急剧膨胀、社会快速发展、人类改造世界的能力越来越强大的时候, 考古迫切需要在文化遗产被破坏、消失之前以积极有效廉价的方式获取文化遗产目标的信息。传统的考古挖掘和野外调查方法在大型遗址、遗址群等文化遗产目标的调查上越来越难以满足现代考古的需求, 遥感考古可以使大区域的文化遗产目标的快速廉价调查成为现实: 遥感考古是利用遥感技术对古代遗迹、遗址进行感测、分析和辨认的一种勘探方法, 能够探测地表人类肉眼观察不到的遗迹特征, 对这些遗迹进行成图, 在分析其形态、分布和周边环境的基础上进行合理的解释。

遥感考古与田野考古相比, 在许多方面弥补地面观测无法得到的大量信息, 其优势主要表现在 6 个方面: (1)覆盖范围广。可获取研究区的全局信息, 从大范围的文物普查到具体一个遗址, 可获得不同空间分辨率的遥感数据; (2)光谱范围大。人的肉眼只能观测到可见光部分, 而遥感能从紫外线、可见光、红外线、热红外、微波等全波段探测地物; (3)时空分辨率高。田野考古只能在特定的时间对考古对象进行有限的勘查, 而遥感考古可利用卫星在不同时间重复获得的数据识别考古目标, 研究考古遗址区多时相的地形景观及古遗址状况; (4)光谱分辨率高。多光谱遥感图像能提供同一研究区域不同谱段的遥感信息, 成像光谱仪技术增强了对考古对象的识别能力; (5)穿透能力强。合成孔径成像雷达的穿透特性可用于干旱沙漠区古遗址的探测, 探地雷达技术能获取地表以下一定深度的考古信息; (6)对考古对象的无损探测。遥感考古具有对地下考古对象无损探测的优点(赵生才, 2004)。

2 遥感考古的探测原理

古代的遗址和遗迹是先人们生活过的地方, 在当时导致其自然形态发生变化, 使其与周围纯自然的环境有所区别。虽然这些变化经过后来的人工扰动不易察觉, 但是毕竟与原来的周围环境存在差异, 并通过地表水分条件、植被生长状况、土地利用状况、地貌结构的不同得以保存下来。这些异常表现被遥感影像记录下来, 为考古提供判读分析的依据。遥感考古是利用这些差异获得最初的数据, 进而确定某一地区是否存在考古遗址(张文若等, 2008)。

遥感能否探测到考古目标取决于以下因素的相

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互作用: (1)考古目标物理特性与传感器探测能力的匹配; (2)考古目标与其周边环境要素的物理特性的差异; (3)遥感数据获取时的环境条件。

传感器的空间分辨率决定了可发现考古目标的大小。根据经验, 空间分辨率不大于探测对象最小个体几何尺寸的一半才可能取得良好的探测效果。一般来说, 传感器越是靠近地面, 其空间分辨率越高, 从而可以探测到更多的细节信息, 正因如此, 地基的探测方法往往能取得较好的探测效果。现在航空遥感的方法能提供亚米级的空间分辨率。直到20世纪末, 卫星遥感通常其分辨率在10—30m, 这一分辨率对于探测考古目标太粗, 但最近10年发展起来的新型遥感器能提供米级甚至亚米的空间分辨率。同时, 传感器的探测精度、敏感程度等物理特性也影响到探测能力。

与无规则几何形体特征的异常点比较, 有规则几何形体特征(线状, 圆形或矩形)的异常点更容易被确定为考古目标, 因为无规则几何形体特征的异常点可能是由于生物活动(树干倒伏、动物骨骼等)引起; 土堆的产生往往使用具有更大磁化率的表层土, 土堆局部磁场增大, 而在表层土被剥离的区域倾向于形成磁场收缩; 近地表建造物能影响地表植被的格局: 近地表的石质基址阻碍植被生长, 被潮湿沉积物填充的古沟渠加速植被生长, 两种情况会改变植被光谱特性(Scollar 等, 1990; Wilson, 2000); 沉积物的物质组成、致密程度、水分保持能力及其他因素的变化将影响其对太阳辐射的吸收率、发射率, 从而引起热特性的改变(Dabas & Tabbagh, 2000)。

数据获取时的环境条件极大的影响探测结果: 日光照射对于可见光/近红外遥感是必要条件, 对于热红外与微波遥感却未必; 为获取遗址的地形阴影, 航空摄影往往借助于较低的太阳入射角; 为获取遗址的"植被标志", 遥感成像需选择遗址区植被在某一特定生长阶段; 电阻率/磁导率方法在冰冻土壤上无法展开; 过大或过小的土壤湿度能够让电阻率/磁导率或热测量失效; 过大的土壤湿度也影响雷达波的穿透能力。

3 遥感考古探测技术

遥感考古探测根据遥感平台可分为地基遥感考古、航空遥感考古和航天遥感考古等3种方式。其中, 地基遥感考古主要是指电法、磁法、重力场等地球物理探测等方式, 航空或航天遥感考古是指将各种类型的传感器搭载在航空或航天飞行平台的遥感探测方式。

3.1 地基遥感考古

地基遥感是指在地表或者靠近地表部署探测仪器的方法。多数方法是基于地球物理探测测量近地表埋藏(通常在地表以下1—2m范围)物理与化学性质。主要方法有4种: 磁力测定法、电阻率法、磁导率法和探地雷达法。

3.1.1 磁力测定

古遗存、古遗址、古墓葬、古建筑与古人类化石等所处地层的磁性、磁化率、磁化率各向异性, 剩余磁化强度等, 与周围环境存在差异, 这种磁性差异就构成磁学考古的基础(阎桂林, 1996)。由于磁力测定方法快捷、能在有限时间内完成大区域的磁力测定、采样率高、对考古埋藏形成一定程度的磁力异常等特点, 磁力测定通常被认为是地基遥感探测方法中最有效的方法。磁场强度测量单位为纳特(nT; 10^{-9} Tesla)。在中纬度地区, 地球磁场介于40000与55000 nT之间。考古目标的地磁异常范围一般在±5 nT, 通常更小。由于磁场强度随着距离三次方快速衰减, 磁场探测通常被限定在考古埋藏上方2m范围内, 除非磁场场源较大(CLARK, 2000)。

磁力测定成功的例子是墨西哥圣校茨特洛克蒂兰(San Lorezo Tenooktlan)的勘探, 该地以戴头盔巨大石雕像闻名, 一些雕像因自然侵蚀露出地表, 为了寻找更多的地下雕像, 考古学家分析了雕像由花岗岩岩石制, 具有强烈的磁性, 利用磁法勘探。在$0.5km^2$的范围分布1m×1m的测网, 测点80000个, 使用分辨率0.1nT的磁力仪, 经过分析处理得到100多个形态较好的磁异常。对其中20个异常点发掘, 取得了很好的收获, 出土了奥尔麦克主神雕像、圣餐台、雕有符号图案的盘子及其他数百件文物, 引起考古界的轰动。

3.1.2 电阻率/磁导率

电阻率/电磁传导率方法从不同的角度量化完全相同的考古埋藏参数, 这里只讨论电阻率方法。土壤对电流的电阻取决于土壤物质类型、湿度、溶解的离子含量、密度、土壤孔隙等因素。土壤传导率是土壤电阻率的倒数: 高电阻物质是传导率低的导体。这些方法对有高电阻的石料或砖块引起的次表面电阻差异以及土壤和沉积物微小的电阻差异很敏感。填充沟渠潮湿的沉积物可能呈现低的电阻率(高的传导率), 但是未压实的多孔隙的堆积土可能呈现高的电阻率(低的传导率)。

根据需要解决问题的不同, 电阻率法分为电剖面法和电测深法 2 类。前者的目的是探测地下介质电阻率在水平方向的变化, 后者的目的主要是探测地下介质电阻率在垂直方向的变化。电剖面法可用来探测埋藏在地下的古墓及其他古建筑(如覆土之下的城墙、房屋基址、地道、矿坑、沟渠、池沼)以及古河道、基岩起伏等。1946 年, 英国的 Atkinson 用电阻率勘探法研究 Dorchester 新石器时期地下遗址, 这是地球物理勘探法在古遗址探测中的首次应用。安徽凤阳明中都遗址的探查, 是中国用电阻率勘探技术和航测相结合, 对一个大型遗址进行系统探查的首例(钟世航, 2004)。苏永军等用高密度电阻率法对三星堆古遗址壕沟进行勘探, 其勘探结果与实际情况基本吻合(苏永军 等, 2007)。遥感考古联合实验室浙江工作站以电阻率法为主, 结合磁法、探地雷达等方法, 经过近 3 年的努力, 基本确定了江南最大皇家陵园——宋六陵内 8 位皇帝、皇后陵墓的具体位置和布局(葛熔金&季银燕, 2007), 该考古实践对于研究与保护中国为数众多的暂不适宜发掘的遗址具有重大的现实意义。

3.1.3　探地雷达

探地雷达是考古地球物理勘查中用得比较多的一种地球物理方法。探地雷达方法是用天线将高频(数兆赫到上千兆赫)电磁波定向送入地下, 电磁波在向下传播过程中遇到不同电性介质的分界面(如覆盖层与古墓等地下建筑物的分界面)时, 一部分电磁波能量从分界面上反射后返回地面, 由设在地面的接收天线接收并记录下来。获知电磁波在地下传播的时间和速度, 可以求得探测目标距天线的距离。通过地面上一系列不同位置的测点上的观测, 即可确定探测目标在地下的空间位置。探地雷达可以提供比较准确的定量信息, 而且设备使用轻便, 因而深受考古工作者的欢迎。但是, 由于低阻介质对高频电磁波的强烈吸收, 这个方法在有低阻地层埋藏的地方难以起到作用。同时, 由于高频电磁波的能量随探测深度衰减较快, 为了探测埋藏深度较大的目标, 不得不降低频率, 从而又导致其分辨率降低, 这也是该方法的不足之处。祝炜平利用探地雷达对良渚闻家遗址和雷锋塔遗址进行地下探测发现: 探地雷达能够成功的探测出砖、石结构的墓葬及大型夯土结构的墓葬遗址, 对于小型的早期古文化遗址也能取得很好的探测效果(赵生才, 2004)。探地雷达除了对地下埋藏进行无损探测以外, 地表的古建筑、石窟、壁画等重点保护文物的维护和修缮工作中, 也常常用到探地雷达技术探测这些古建筑遗迹表面风化侵蚀深度和程度(刘敦文等, 2001)。

3.1.4　其他的地球物理方法

磁化率勘测。磁化率勘测是量化置于磁场(如地球磁场)中的勘测对象被磁化的趋势, 相比于通常的磁力测量, 磁化率能从不同的角度提供考古埋藏的信息。多数的磁化率勘测是基于土壤样本的实验测量基础上。已有一些研究利用电磁感应的同相分量测量磁感化率, 但其勘测深度一般不超出 50cm (Challand, 1992)。

地震技术。地震技术是地质地球物理相当重要的一项技术, 很少在考古中用到。从概念上讲, 地震技术与探地雷达技术相关, 但其记录的是声波而不是微波的能量。在地震波折射勘测中, 人造的冲击波由一长柄大锤敲击橡胶垫或者爆炸的蘑菇云中产生。在横切面上按照一定间隔安置的小型地震仪记录冲击波到达每一个地震仪的时间(以毫秒计)和强度。时间和强度的变化能预示地层结构或大的异常特征, 如沟渠或其他建筑结构(Goulty & Hudson, 1994; Tsokas 等, 1995)。

金属探测。金属探测是电磁感应装置经优化探测近地表(通常最大深度 0.5m)各种类型金属目标的方法。该方法对金属碎片集中度制图分析和定位考古遗址中孤立目标非常有用。

其他方法。其他方法包括极化法、自然电位法和重力法等, 这些在考古实践中应用甚少。

3.2　航空遥感考古

航空或航天遥感记录从地表反射或发射的电磁辐射, 为大区域考古勘察提供了一种经济的手段(Bewley, 2000), 航空遥感利用飞机平台, 航天遥感利用的是轨道卫星平台(将在下一节讲述)。航空遥感和航天遥感采用相似的传感器, 其主要的差别在于平台离地高度, 平台离地高度显著影响能够解析的空间细节。航空摄影测量是遥感考古中最古老、应用最多也是受到关注最多的遥感方式, 但在最近几十年包括多光谱、热红外传感器(被动方式)以及雷达、激光高度计(主动方式)等传感器在机载平台也得到应用与发展, 使得航空遥感真正成为多模式的遥感方式。

3.2.1　航空摄影

航空摄影较之其他勘查手段, 对考古遗址的发现具有更大的作用(Wilson, 2000)。早在 19 世纪, 航空摄影开始在气球上应用, 最早应用于考古遗址的是 1906 年拍摄的巨石阵, 如图 1。第一次世界大战期间飞机操控性能及飞行员技术取得长足进步, 其

图 1 拍摄于 1906 年的英国巨石阵

中就有一些飞行员关注于战争时期的考古遗址。英国皇家飞行军团观察员 Crawford 就是当时主要负责航空考古的发展。在干旱区的遗址及遗址特征主要从破碎遗迹的阴影投影中揭示出来, Crawford 依据植被标志从航空相片上辨认出史前的建筑结构, 在无植被标志的干旱区依据遗址的地形阴影识别遗址。用这种方法, Crawford 在 1a 的时间里发现的遗址比此前 100a 的时间里依靠徒步调查发现的遗址还要多(Wilson, 2000; Bewley, 2000)。这种方法在 19 世纪 20 年代中期得到进一步完善, 其间很多经典的航空相片登载在由 Crawford 1927 年创刊的 Antiquity 杂志上。Bewley (2000)指出, 航空摄影考古之所以在英国率先发展起来, 是因为其考古资源和景观本身的特点、其土壤能产生明显的植被标志、航空平台的可用性、相对自由的空域和军事基础设施建设促成了一些考古发现等因素。

中国的航空摄影考古起步较晚, 但也取得了重大成果。中国首次大规模拍摄的航片在 1960 年前后, 这些资料对考古研究是很有价值的, 因为很多考古遗迹是在文革期间特别是“农业学大寨”的时候被毁坏的, 更早的航空影像就更有考古价值了(刘建国&王清山, 2006)。从 20 世纪 60 年代修建三门峡水库时就利用航空照片分析库区古代遗址、墓葬的分布。1996 年, 由中国历史博物馆航空摄影考古工作小组与洛阳市文物局合作进行的河南省洛阳市和巩义市一带的飞行勘察, 主要对象是偃师二里头遗址、偃师尸乡沟商城遗址、洛阳隋唐东都城遗址南部等, 在安徽开展了对战国晚期“寿春古城”的航空摄影考古工作。1997—2001 年, 由中国历史博物馆遥感与航空摄影考古中心同内蒙古自治区文物考古研究所联合进行了内蒙古自治区东南部专区航空摄影考古工作, 并于 2007 年 4 月由科学出版社出版中国第一部航空摄影考古报告——《内蒙古东南部航空摄影考古报告》。航空摄影的作用体现在对考古景观系统的长时序的成像记录, 考古景观与环境的动态监测成为可能。

3.2.2 航空多光谱

航空多光谱扫描仪能够比传统的航空相片提供更多的信息, 因为航空相片用到的光谱区间长度比多光谱扫描仪工作的光谱区间长度小得多。Morain 等(1981)利用 1.25m 分辨率的 11 通道的 Bendix 多光谱扫描仪对新墨西哥班德利尔国家保护区(Bandelier National Monument)进行成像验证了这一结论, 对多光谱影像进行监督分类发现考古区和非考古区土地利用类型之间的可分离度较高, 证实了人类活动的干扰是可以通过光谱分析探测到的。英国东约克郡的 Heslerton Parish 工程曾用到 Daedalus 多光谱扫描仪对一古遗址进行成像, 经与同一时间获取的全色航空相片比较发现, 多光谱扫描仪的红外波段能揭示更多的考古特征, 能更清楚的显示植被标志(Donoghue, 2001; PowlesLand, 2001)。2001 年中国科学院遥感应用研究所利用彩色红外遥感飞行探测技术, 对北京老山汉墓遗址墓葬区陵墓的分布进行了探测, 并结合考古研究成果推测出周围几个地点可能有较大陵墓或陪葬墓(尹宁 & 王长林, 2003)。

3.2.3 航空热红外

斯蒂芬-玻尔兹曼定律表明地物红外辐射能量与温度四次方成正比, 所以只要有地物微小的温度差异, 就会引起红外辐射能量较显著变化。这种特征构成红外遥感的理论根据。考古遗址热辐射变化来自 3 方面的原因: (1)微地貌的变化引起日照时地表吸收热量的差异, 这是因为面向太阳的坡面吸收更多的热量, 而背向太阳的坡面吸收的热量减少, 而且这一过程持续时间较长; (2)植被标志也能引起地表温度差异, 这是因为植被生长状况或健康状况不同导致蒸散作用不同, 而蒸散作用不同进而引起植被自身的冷却作用的差异; (3)热惯量的差异导致干燥的多孔性物体在白天能很快的达到温度最大值, 在晚上也能很快达到温度最小值(热惯量低), 致密的物体, 如石块, 在白天和夜间温度变化相对较小(热惯量高)。这 3 个方面的原因可能与遗址区的考古埋藏引起: 地下古遗址、浅地表埋藏可能引起遗址区微地貌的变化, 可能引起遗址区地表植被生长状况有别(植被标志), 地下古遗址、浅地表埋藏由于其致密度、透水性、材质等与周围土壤的差异引起热惯量与周围土壤存在差异。热红外图像高亮度代表

热异常区域，夜航热红外遥感受太阳辐射的影响小，但地物边界不如日航热红外或可见光图像清晰，所以，在夜航热红外图像上寻找热异常区域时，需结合全色或多光谱图像进行分析(周小虎等, 2007)。

Perisset 和 Tabbagh(1981)利用 ARIES 热辐射计发现了诸多古道路以及田地边界，系微地貌变化引起地表温度变化。Dabas 和 Tabbagh(2000)同样利用 ARIES 热辐射计发现麦田土壤标志的温度比周围史前围栏边界的温度高出 1.5℃。Sever 和 Wagner(1991)利用分辨率为 5m 的 6 通道热红外多光谱扫描仪 TIMS(Thermal Infrared Multispectral Scanner)在新墨西哥 Chaco 大峡谷发现位于地表或次地表的遗址特征，如史前道路、建筑物、城墙以及古老的农田。

3.2.4 航空雷达

航空雷达有 AirSAR 与 GlobeSAR，分别是美国和加拿大的机载雷达数据获取平台，也兼用作星载雷达的测试平台。Adams 等(1981)分析了 1977—1980 年危地马拉和伯利兹地区的 AirSAR 影像发现在满足一定的成像几何条件下金字塔对雷达波产生强反射(即二面角反射)，还发现流域面积达 12400km^2 的庞大的古运河水系。Moore 和 Freeman(1998)利用 AirSAR 数据系统分析了柬埔寨吴哥窟古城的一系列典型特征，包括庙宇群、以前没有发现的结构、土墩、堤防、道路和蓄水池。Failmezger(2001)应用 2.5m 分辨率的航空 SAR 数据对一历史遗迹群的遗迹和其他特征进行了地图定位。1993 年, GlobeSAR 在亚洲地区开展了机载雷达试验飞行，获取了泰国一些有关古城堡与古运河的雷达数据。Supajanya 等(1996)利用 GlobeSAR 数据对泰国古都 Sukhothai 及环绕的护城河、连接 3 个古城的运河进行研究，显示出 SAR 探测考古遗迹的能力。

3.2.5 航空激光高度计

地表形态在考古中也能提供重要信息。地表形态可以直接通过地面测量获取，也可以间接通过航空影像的阴影或者航空热红外影像的温度变化等获取。地形的野外测绘精度很高，但是其要求在时间、劳动力及成本等方面有很大的投入。最近发展起来的激光高度计利用激光测距仪测量地表高度，可以很容易的获取高分辨率地面高程数据。激光高度计常称作 Lidar(Light Detection and Ranging)，它能够快速生成准确而密集的地形数字模型，以及其他表面(建筑物楼顶、林木冠层)的垂直结构。Lidar 是一项正在飞速发展的新技术，它能够在大区域对地表细节以 15cm 的绝对垂直精度(对同一均质表面的连续观测能达到的相对精度比绝对精度大)和小于 1m 的水平采样间隔进行地形制图等常规任务(Flood, 2001)。Lidar 在考古中也取得了重要应用成果(Barnes, 2003; Holden 等, 2001)。在全球考古遗址区复杂地形的背景下，Lidar 已成为对考古遗址景观进行地形制图和解释地形因素与考古目标特征相互作用的强大工具，其对地形因素的准确量化，有助于电阻法、探地雷达等受地形影响的探测方法的成功实践。

3.3 航天遥感考古

航天遥感泛指利用各种空间飞行器为平台的遥感技术系统。它以地球人造卫星为主体，包括载人飞船、航天飞机和空间站，有时也把各种行星探测器包括在内。诸多的航天遥感计划在推动遥感考古的过程中发挥了重要作用。航天遥感计划如表 1。

3.3.1 星载多光谱

最早的星载多光谱是分辨率为 79m 的 Landsat MSS 数据，不适合进行遥感考古典型目标与特征的探测，在考古中的应用研究集中在遗址区环境与土地覆盖制图以及识别一些已知的较大的考古目标，如 Quann 和 Bevan(1977)识别出吉萨的大金字塔的阴影，Ebert 和 Lyons(1980)识别出 Phoenix 盆地近 80km 长的 Hohokam 运河，Richards(1989)利用 Landsat-1 数据展示了埃及现存的古代雨水收集结构。TM 多光谱数据较 MSS 无论是空间分辨率还是光谱分辨率有了显著提高，TM 的考古应用开始走向光谱分析与遗址的探测。Custer 等(1986)对考古目标光谱特性的统计分析，发现在遗址的周边区域的光谱反射率与正常情况有着明显的差别，这意味着根据遗址区与周边环境光谱特性的差异可初步确定遗址区空间分布范围。Johnson 等(1988)利用 TM 数据分类将北密西西比地区划分成几个自然地理省，在这些省之间比较考古目标出现的频率，依此定义考古目标出现概率比较大的位置的环境标志。Showalter 利用 TM 数据对 Phoenix 盆地的运河进行了更准确的探测。洪友堂等(2006)通过对 TM 和航空图像的处理、解译及相互映证，对三星堆的古河道、古城池进行了全面调查，发现了马牧河由南往北的多期古河道及一些未曾被发现的古城遗址，得出三星堆古城池分为内外二层(中心城池和外城池)的结论。与 TM 相比，ASTER 多光谱空间分辨率提高到 15m，其探测能力得到进一步加强。Mark Altaweel 应用 ASTER 数据识别伊拉克两河流域的古遗址、

表 1 开展过遥感考古应用研究的航天遥感计划

卫星计划	波段	波长/μm	像元大小/m	幅宽/km	发射时间/年	作用描述
Landsat 1—3	多光谱 (G, R, NIR1, NIR2)	0.5—1.1	79	16.5	1972—1978	遗址区环境、土地利用/覆盖制图
Landsat 4,5	多光谱(B, G, R, NIR, MIR1, MIR2, FIR)	0.45—12.5	30, FIR 120	185	1982, 1984	遗址区环境、土地利用/覆盖制图, 古河道等较大考古目标的探测, 遗址区建模
Landsat 7	多光谱 (B, G, R, NIR, MIR1, MIR2, FIR) Panchromatic	0.45—12.5, 0.52—0.9	30, FIR 60, 15	185	1999	同 Landsat 4,5
SPOT 1—3	多光谱 (G, R, NIR) 全色	0.5—0.89, 0.5—0.73	20, 10	60	1986—1993	遗址区环境、土地利用/覆盖制图, 探测遗址区植被异常
SPOT 4—5	多光谱 (G, R, NIR, MIR) 全色	0.5—1.75, 0.48—0.71	20, 10; 10, 5	60	1998, 2002	同 SPOT 1-3
Corona KH-4B	全色-胶片摄像	0.5—0.7	2—10	14	1967	探测中小尺度考古目标, 探测并验证植被异常等考古标志
KVR-1000	全色-胶片摄像	0.51—0.76	1—2	40	1987	探测小尺度考古目标, 探测并验证植被异常等考古标志
Ikonos	多光谱(B,G, R, NIR) 全色	0.45—0.9	4, 1	13	1999	同 KVR-1000
Quickbird	多光谱 Multispectral (B, G, R, NIR) 全色	0.45—0.9	2.44, 0.61	16.5	2001	同 KVR-1000
SIR-C / X-SAR	微波(X, C, L)	3—24cm	10—50	30—60	1994	探测遗址区土壤水分异常、探测干旱区被掩埋考古目标(构成角反射)
Radarsat	微波(C)	5.7cm	8—100	50—500	1995	同 SIR-C / X-SAR

B=蓝; G=绿; R=红; NIR=近红外; MIR=中红外; FIR=远红外(热红外); X, C, L=微波波段

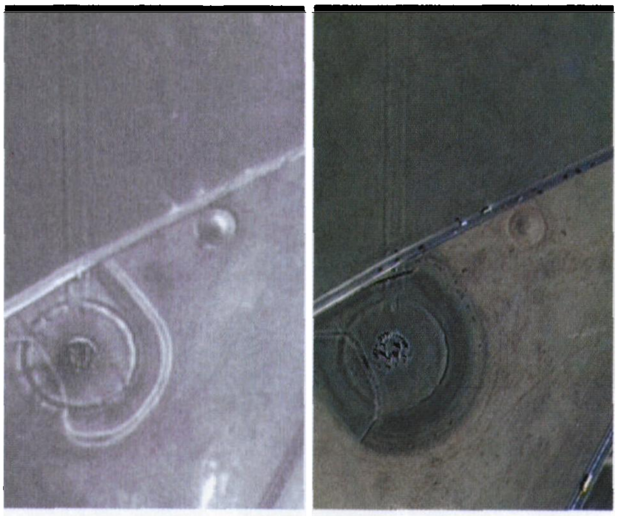
古运河等考古对象, 通过与 Corona 数据的对比发现, 空间分辨率为 15m 的 ASTER 近红外多光谱数据不仅可识别出空间分辨率为 2m 的 Corona 全色数据发现的考古目标, 还可识别 Corona 无法识别的遗址特征(Altaweel, 2005), 由此可见遥感考古实践中多光谱较之全色数据的优越性。

3.3.2 星载高光谱

高光谱遥感在识别地表覆盖细小类别差异、遗址构成物质成分差别等方面通常比多光谱数据更强大, 因此对于识别不同年代不同成分的遗址类型有重要作用。高光谱遥感与以往遥感技术相比, 具有图谱合一的特征和从可见光到热红外的一系列波段, 是一种综合性的遥感技术手段。文物遗存在地面的信息一般比较微弱, 高光谱遥感具有识别微弱信息和定量探测的优势(Belvedere 等, 2001; 谭克龙 等, 2005), 但由于一方面高光谱数据相比其他数据稀少而且成本昂贵, 另一方面高光谱数据波段数众多, 致使其数据量也呈指数增加, 海量的数据给研究人员的分析和应用带来一定的难度(袁迎辉&林子瑜, 2007), 故高光谱遥感在考古中的应用偏少。田庆久等(2008)从 EO-1 卫星高光谱遥感 Hyperion 谱段响应特性、地面光谱测量等入手, 通过图谱去噪平滑处理、地物端元递进提取、融合处理等技术对无锡段运河与扬州段运河 Hyperion 数据进行精处理, 研究了应用 Hyperion 高光谱数据进行大遗址空间信息的提取与解译, 探讨了基于高光谱遥感的大遗址内部组成精细分类探测技术。

3.3.3 星载高空间分辨率

近些年发展的高空间分辨率传感器能够探测某一具体的考古特征并进行制图; 真正迈向从星基平台对地面目标及其特征进行制图的新时代(Fowler, 2002)。高空间分辨率卫星数据最早于 1990 年代中期向民用开放。俄罗斯 KVR 间谍卫星和美国 Corona 间谍卫星获取的全色影像(后者获取影像的时间为 20 世纪六七十年代, 于最近退役), 其分辨率高达 2m。Fowler(1996)研究表明 KVR-1000 影像能清晰显示英国巨石阵区域的植被标志(图 2(a))。Kennedy (1998)利用 Corona 数据发现了土耳其史前居民点。1999 年 Ikonos 卫星发射升空, 2001 年 Quickbird 卫星发射升空, 其分辨率分别是 4m 和 2.44m(多光谱),



(a)　(b)

图2　KVR-1000影像(a)与Ikonos影像(b)清晰显示英国巨石阵区域的植被标志

1m 和 0.61m(全色), 这一空间分辨率的遥感数据在考古调查中十分有效。图 2(b)是 4m 分辨率的英国巨石阵图像, 与 KVR-1000 全色图像相比, 能揭示遗址区更多的细节信息。De Laet 和 Waelkens(2007)获取土耳其南部还未发掘的 Hisar 遗址的 Ikonos-2 数据, 分别应用基于 GIS、像元和目标的方法进行考古特征的提取, 参照目视解译的成果逐一对前 3 个方法进行了评估。Lasaponara 和 Masini(2006)应用 Quickbird 多光谱数据在意大利南部两遗址点应用数据融合与边缘检测方法成功探测到考古农作物标志, 研究发现 Quickbird 全色与多光谱融合图像对遗址发掘前考古特征提取非常有用。目前, 考古学家已开始挖掘这些高分辨率数据在考古应用中的潜力(Fowler 2000; Wheatley & Gillings, 2002)。

3.3.4　星载雷达

1981 年美国航天飞机 SIR-A 搭载的合成孔径雷达揭示了埋藏在撒哈拉大沙漠地下的古峡谷和古河道吸引了全世界考古学家的目光。由于这些干沙区域其介电常数很小, 雷达波很容易穿透这些区域的次表面(ElBaz, 1997; Mccauley 等, 1982), 因而可以发现可见光/近红外等遥感方式所探测不到的目标。郭华东(1997)、卢新巧等(1997)利用 SIR-C 多波段多极化成像雷达, 识别出位于宁夏—陕西交界处的明隋两代被干沙掩埋的长城, 引起国际遥感考古界的关注。在干沙覆盖长城区段, 雷达波穿透干沙入射到干沙下的长城城墙, 由于长城城墙、长城基底与航天飞机三者之间成像几何关系满足二面角反射条件, 入射到长城城墙的雷达波大部分被反射, 在图像上形成揭示地下长城走向的明亮“条带”(图 3)。1994 年航天飞机成像雷达 SIR-C/X SAR 和 AIRSAR 对处于茂密森林的柬埔寨吴哥古城的研究, 重建了吴哥古城的分布范围, 使其由原来的 200—400km^2 扩大到 1000km^2, 重新勾绘出古运河水系, 使我们了解到已消亡的吴哥古城的壮观原貌(Freeman 等, 1999)(图 4)。Sever 与 Sheet(1998)利用合成孔径雷达图像分析了哥斯达黎加的古道路。Scarre(1999)利用雷达的穿透性探测到位于危地马拉的玛雅农田系统, 对柬埔寨古都吴哥附近的古遗址进行了定位和测绘, 对高棉国的发展历史提供了有力证据。Holcomb (1998)对雷达考古的理论、方法及其考古应用进行了综述, 其中列举的考古应用包括 SIR-A 和 SIR-B 发现被沙漠吞噬的欧曼古城 Ubar。2000 年, 美国航天飞机雷达地形测图计划(SRTM)通过 InSAR 技术获

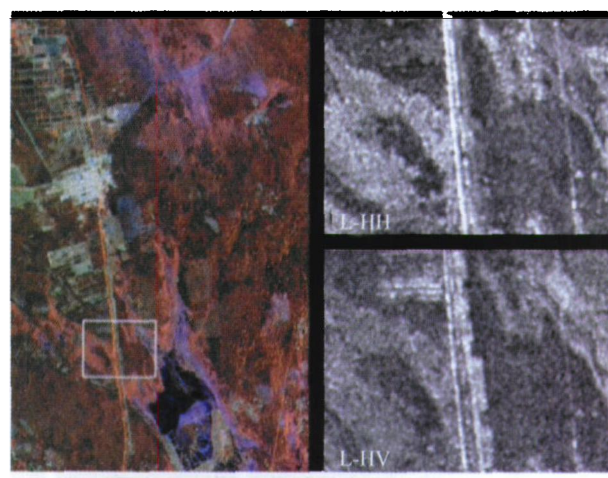


图 3　1994 年 SIR-C 雷达探测到宁夏—陕西交界处的明隋两代被干沙掩埋的古长城

图 4　1994 年 SIR-C/X-SAR 雷达探测到柬埔寨吴哥窟古城

取了全球80%陆地表面的精度为30m的高程数据。2003年，欧洲航天局发射的Envisat-1卫星上装载的ASAR传感器具有同极化和交叉极化成像能力。分别于2006年12月、2007年6月、2007年12月发射升空的ALOS、TerraSAR-X、Radarsat-2卫星分别搭载了L、X、C波段合成孔径雷达，均具有全极化成像能力。这些传感器的出现推动遥感考古应用向纵深发展。

4 结论与展望

遥感考古提供了一种快速的数据获取方式，能以比田野挖掘低廉的成本提供大型考古区域的信息，遥感提供了区域景观考古的新视角(通常考古挖掘的单位为 m^2)，对古人类空间的利用及过去人和景观的相互作用产生全新的观点。通过遥感，考古学家能够对全球大的考古区域与文化景观区域的感兴趣目标进行制图、分析与解译。遥感为区域景观考古提供强大支持，而不仅限于发现或制图的工具。

遥感考古引导成本高昂的田野挖掘和试验计划聚焦于潜在的考古感兴趣目标。遥感考古能揭示考古目标的埋藏深度、空间分布、土壤类型和其他次表面状况等信息。在遥感考古的帮助下，田野挖掘的工作量大幅减少，发现更多的考古目标。传统的考古探查通常损坏甚至毁坏考古目标，而遥感方法是一种无损的方法，能使考古目标毫发无损，在遥感考古的帮助下，遗址、遗迹的修复成本大大降低。

遥感考古获取的信息需要一个分析的过程即将遥感探测到的考古特征进行解译并转化到考古专题地图上才能真正发挥作用。将遥感考古所获取的信息转化成考古特征、考古目标的信息，需要对遗址、遗迹在成像条件、背景环境下的考古特征有一定的研究。一方面，考古特征本身就是一个复杂的概念，在遥感影像上没有固定的模式，因地因时而异；另一方面遥感本身也受到诸如成像时间、成像地点、土壤类型、地表湿度、地表覆盖等因素影响，这些因素可能导致无法探测到有效的考古特征。

遥感考古虽然可以很大程度地减少田野考古的工作量，但是不可以代替田野考古。它解决不了遗址的年代，出土器物的研究等考古学的基本问题。在实际考古工作中，遥感考古必须与田野考古紧密结合，综合利用星载、机载与地基的遥感探测技术地面田野考古技术形成从高空—地表—地下的三位一体的历史文化遗产全方位探测与信息获取，在此基础上进行考古目标探测、考古专题制图、聚落分析等研究工作。只有这样，考古工作才可以取得事半功倍的效果。

中国是世界上具有连续发展历史的文明古国，中华文明博大精深，古遗址遍布全国各地，具有极为丰富的考古资源，其中不乏具有世界独一无二的大型考古遗址，如长城、京杭运河、丝绸之路、秦始皇陵等，遥感考古在中国的应用前景广阔。目前，国家已启动第3次文物普查、中华文明探源等工程，迫切需要遥感考古的参与，遥感考古通过这类高强度的考古实践的开展，有针对性的开展遥感考古定量化研究，改进与完善探测方法，深化考古信息的分析提取与挖掘，有条件的开展遥感考的综合示范工程并逐步推广，实现在基本原理、技术方法、应用水平等3个层次的全面发展。

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