The science behind archaeological signatures from space

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Archaeology has traditionally focused on studying historic or prehistoric people and their cultures by analysis of their artefacts, inscriptions, monuments and other such material remains, especially those that have been documented from excavations. This focus is somewhat narrow, because it excludes many new methods that have emerged in the last few decades (described in detail by Prabhakar and Korisettar in this special section (page 1873)). One such novel method is to study large imprints on the landscape caused by human activity. These tell-tale features include soil marks, crop marks, drainage patterns, field boundaries and a host of man-made structures, whose study can provide additional cultural insights. In some cases, these features are difficult to detect by the naked eye at ground level, but are detectable by remote sensing techniques from aerial/space-based platforms in a non-destructive manner. For these reasons, it is now well recognized that examining archaeological landscapes using remote sensing can complement traditional investigations. An analysis of remote sensing data can play an important role in (1) understanding spatial relationships between cultural materials and activities, (2) formulating archaeological sampling schemes, (3) measuring distances and spatial distributions of structures and monuments, and (4) evolving schemes for their conservation.

Keywords: Archaeology, image interpretation, remote sensing, signatures.

Introduction

REMOTE sensing (RS) data are obtained from a variety of platforms, at various altitudes and spatial resolutions, and in different spectral bands. An analysis of multiple types of remote sensing data may be necessary to obtain novel archaeological insights[1–3]. In addition, it is often useful to analyse remote sensing data using GIS (geographic information system) and GNSS (global navigation satellite system) techniques. This article explains the scientific basis of these tools and illustrates their usage in an archaeological context with case studies.

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Remote sensing

Remote sensing refers to the branch of science which deals with objects (surface or subsurface features, in the context of archaeology) through measurements made from a distance (i.e. without being in physical contact with these objects). An everyday example of remote sensing is when we perceive objects through our eyes. We see an object by the light reflected from it falling on the sensor (in this case, the retina of the human eye). Our nervous system carries the data to the brain, which interprets the information to identify the object. Modern remote sensing is an extension of this natural phenomenon. It uses electromagnetic radiation (light) as the medium of interaction. Apart from visible light, sensors to detect electromagnetic radiation extending from the ultraviolet to the range of infrared and microwave regions are also used for remote sensing.

Every object reflects a fraction of the light incident on it (this fraction differs from object to object, depending upon their physical properties). In addition, objects also emit radiation according to Planck's law. Thus, the total energy emitted from an object is different at varying wavelengths, and this pattern is called the 'spectral signature' of the object. Buried archaeological features render distinct spectral signatures, as discussed later in this article. Such a signature, together with its shape, size, pattern, texture and association with adjacent features helps in identifying and discriminating the object.

Platforms and orbits

A remote sensing system consists of the platform on which sensors are placed, the sensors, the data transmission and (ground-based) data acquisition systems, processing sub-systems, and an interface to interpret/analyse the processed data. The platform can be a spacecraft, aircraft, balloon, tower or even a tripod[4]. More recently, unattended aerial vehicles (UAVs) have also been added to this list. Each platform provides a unique perspective based on its altitude, area of coverage and information at different scales; each platform also has advantages and limitations for specific applications. We will focus on archaeological applications.

Table 1. Some of the earth observation systems and their characteristics

Satellite (year of launch)	Sensors	Spectral range	Spatial resolution (m)	Swath (km)
LANDSAT 1 and 2	MSS 4	VNIR	79	185
(1972, 75)	RBV	VNIR	30	
LANDSAT-3 (1978)	MSS 5	VNIR + Thermal	79	185
	RBV	PAN	30	
LANDSAT – 4 and 5	MSS 5	VNIR	30, 120 (T)	185
(1982, 84)	TM	VNIR, SWIR, Thermal		
LANDSAT-7 (1999)	ETM	VNIR, SWIR, Thermal, PAN	30, 60, 15	185
LANDSAT-8 (2013)	OLI	VNIR, SWIR, PAN, Thermal (2)	30, 15, 100	185
IRS-1A, 1B and P2	LISS 1	VNIR	72.5	148
(1988, 91, 93)	LISS 2	VNIR	36.25	74
IRS-1C, 1D	WiFS	VNIR (2)	188	770
(1995, 97)	LISS 3	VNIR, SWIR (4)	23	140
	PAN		5.8	70
RESOURCESAT-1,	AWiFS	VNIR, SWIR (4)	56	740
2 and 2A	LISS-3	VNIR, SWIR (4)	23	140
(2003, 11, 16)	LISS-4	VNIR (3)	5.8	70
SPOT 1, 2 and 3	PAN	PAN	10	117
(1986, 90, 93)	Multispectral	VNIR	20	117
SPOT 4 and 5	PAN	PAN	2.5	60
(1998, 2002)	Multispectral	VNIR	10–20	60
SPOT 6 and 7	PAN	PAN	1.5	60
(2012, 14)	Multispectral	VNIR	6	60
MOS-1A & 1B (1987, 90)	MESSR	VNIR, TIR		100
JERS-1 (1992)	Optical	VNIR, SWIR	18 × 24	75
SENTINEL-2 (2015)	Multispectral imager	VNIR, SWIR (0.443–2190 mm)	10, 20 (red edge) 60 (atm. corr.)	290
TERRA (1999)	ASTER	VNIR (3), SWIR (6), TIR (5)	15, 30, 90	60

VNIR, Visible and near infrared; SWIR, Shortwave infrared; TIR, thermal infrared.

Table 2. High spatial resolution satellites

Satellite	Sensors	Spatial resolution (m)	SWATH (km)
IKONOSS (1999)	PAN	0.82	11.3
	MS (multispectral)	3.2	
QUICKBIRD (2001)	PAN	0.61	16.8
	Multispectral	2.44	
WORLDVIEW-1 (2007)	PAN	0.50	17.2
WORLDVIEW-2 (2009)	PAN	0.46	16.4
	MS	1.85	
WORLDVIEW-3 and 4 (2014, 16)	PAN	0.31	13.1
	MS	1.24	
	SWIR	3.70	
CARTOSAT-1 (2005)	PAN (stereo)	2.5	30
CARTOSAT-2 (2007)	PAN	0.83	~10
GEOEYE-1 (2008)	PAN	0.46	
PLEIADES-1A/1B (2011, 12)	PAN	0.7	20
	MS	2.8	
KOMPSAT-3A (2015)	PAN	0.7	16.8
	MS	2.8	

Pioneering archaeological surveys used kites, balloons and aircraft[5]. Since the launch of Earth Resources Technology Satellite (ERTS-1, later renamed as LANDSAT-1) in 1972, satellite data are increasingly used for most remote sensing investigations. There are three kinds of orbits based on the plane in which satellites orbit the earth: near-polar, equatorial and inclined. Satellites in near-polar sun-synchronous orbits with altitudes ranging from 500 to 1000 km are generally best suited for archaeology and other applications that map surface features. Near-polar orbits provide global coverage. Satellites go around the earth from pole to pole at a certain inclination (±5°), which facilitates sun-synchronous orbiting: repetitive imaging of a location under near-similar illuminating conditions. In contrast, satellites in geosynchronous orbits (at about 36,000 km altitude) provide constant surveillance over a fixed region, but the spatial resolution of the ground surface (the instantaneous field of views; IFOV) of their sensors is usually too poor for archaeological applications. Such orbits are more suited for meteorological studies and satellite communication.

Sensors

Sensors are the heart of any remote sensing system. Passive sensors detect natural radiation, i.e. either reflected solar radiation or radiation emitted by the earth's surface. In contrast, active sensors generate electromagnetic radiation (at specific wavelengths, or across a band of wavelengths) to illuminate surface objects and then detect the scattered radiation reflected from them. As an illustration, the use of a flash-bulb can turn a passive photographic camera sensor into an active one. Sensors are characterized by their spatial resolution, the number of spectral bands in which they operate, their bandwidth, radiometric resolution and repetitivity/revisit (duration between two consecutive observations of the same location by the sensor).

Sensors that provide images for feature detection

Optical and thermal sensors

Electro-optical sensors/camera systems flown on satellites such as LANDSAT, SPOT and IRS have operated in the visible, near infrared and shortwave infrared bands. LANDSAT also obtained data in the thermal infrared region. The spatial resolution ranges from about 80 m to as detailed as 5 m. More recently, high-resolution satellites (including Indian cartographic satellites) provide multi spectral and panchromatic data at a resolution of 1 m or better, and ASTER operates in multiple bands of the thermal infrared region. Hyper-spectral sensors operating in very fine spectral bands (5–10 nm bandwidth) are also flown on some spacecraft missions, which provide spectroscopic information of targets. Tables 1 and 2 provide a list of some of the remote sensing satellites and their characteristics. A more extensive list can be found in the *CEOS Database Hand Book*[6].

Optical imagery and associated spectral signatures

Radiation (aggregate of reflected, emitted and scattered) detected by the sensors flown aboard satellites is transmitted to Earth stations set up for this purpose. These signals are preprocessed before the output (an image covering a portion of the earth's surface) is generated. The output is either in the form of a photographic product or digital image. Preprocessing includes geometric corrections (correcting for spatial shifts between consecutive pixel lines caused by the geometry of the earth as it rotates east–west while the satellite orbits north–south), and radiometric corrections (improving visibility in images with low contrast caused by varying light conditions and/or haze). The output is formatted into data products corresponding to certain geographical regions defined by their latitudes and longitudes. Products are geo-registered to existing topographical maps of different scales to facilitate better use. Data thus obtained from satellite sensors in different wavelengths are available both in hardcopy and digital format.

False colour composites (FCCs) are typically generated using data obtained in near-infrared (NIR), red and green spectral regions, with red, green and blue colours respectively, assigned to these regions in the output image. Natural colour composites (NCCs) are generated using data in the red, green and blue spectral regions, with the same colours assigned in the output image. NCCs usually lack subtle information carried by data in the NIR region.

Vegetation looks green because the chlorophyll present in leaves absorbs blue and red light and reflects green and infrared light (Figure 1). In the NIR region, this reflectance is particularly high (about 45%), transmittance has a similarly high magnitude, and absorption is low (only about 5%). As the leaves grow, their intercellular spaces increase and reflectance in the NIR region therefore increases. Conversely, if vegetation becomes stressed or senescent, its chlorophyll content decreases. Consequently, red reflectance increases, and the decrease in intercellular air spaces decreases reflectance in the NIR region. Soil reflectance generally increases with increasing wavelength in the visible and NIR regions. Soil reflectance is also influenced by moisture content, its surface roughness, the amount of organic matter and iron oxide present, and the relative percentage of clay, silt and sand.

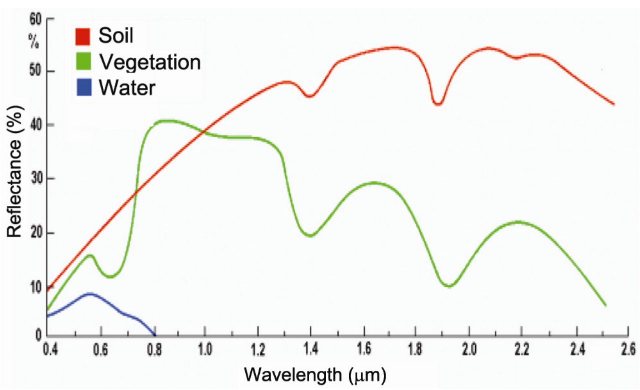

Figure 1. Reflectance curves for different earth surface features.

Table 3. Synthetic aperture radar missions

Mission	Frequency (GHz)	Nominal resolution (m)	SWATH (km)
SEASAT (1978)	L (1.275)	25	100
SIR-A (1981)	L (1.275)	40	50
SIR-B (1984)	L (1.275)	15–50	20–50
SIR-C (1994 and 95)	C, L, X 5.289 1.239 9.602	10–200	15–90
ERS-1/2 (1991)	C (5.3)	26 × 28	100
JERS-1 (1992)	L (1.275)	18 × 18	75
RADARSAT – 1 and 2 (1995, 2002)	C (5.3)	9 × 9 to 100 × 100	45/510
ENVISAT-ASAR (2002)	C (5.3)	30	56
ALOS-1 and 2 (2006, 14)	L (1.257)	3	25
RISAT-1 (2012)	C (5.3)	3 × 3 to 5 × 50	10–225
SENTINEL-1A and 1B (2014, 16)	C (5.405)	5 × 5 to 25 × 100	80–400

As the moisture content increases, soil reflectance decreases (most significantly in water absorption bands). In a thermal IR image, moist soils look darker than dry soils. The large difference in the dielectric constant of water and soil at microwave frequencies makes it possible to quantify soil moisture. Water absorbs most of the radiation in the near and middle infrared regions. In the visible region, water reflectance depends on the reflectance from the surface, the material at the bottom, and on other suspended materials present in the water column. Water reflectance generally increases with increasing turbidity, and the reflectance peak shifts towards longer wavelengths. Snow has very high reflectance for wavelengths up to 800 nm, but this reflectance decreases rapidly for higher wavelengths. Clouds have uniformly high reflectance.

High-resolution imagery (better than 1 m per pixel) provides the necessary level of detail for making archaeological site plans, which include marking the spatial distribution of buildings accurately (for example, monuments and forts together with infrastructure that forms the modern-day context such as roads, railways and settlements)[7]. Medium-resolution imagery (5–10 m per pixel, especially multispectral imagery) is useful in identifying contextual features in the larger landscape (for example, waterbodies, river and buried moats)[8]. Coarse-resolution imagery (20–30 m per pixel) facilitates viewing much larger regions and identifying large-scale patterns (for example, palaeochannels that can span tens of kilometres). Even coarser imagery is useful for archaeology only on rare occasions[9–11].

Thermal imagery and associated signatures

All objects on the earth's surface emit radiation. The amount of radiation emitted depends on the physical temperature (the average temperature is about 300 K) and the emissivity of individual objects at thermal wavelengths (roughly 8–14 μm). The rate at which surfaces heat up and cool down also varies, depending on the thermal inertia of the materials/rocks. The amount of thermal infrared radiation emitted by an object at various times of the day is called its thermal signature.

Archaeological sites may have material different from the adjoining areas, which may be agricultural or scrub/waste land. Even if the archaeological debris is thin, such areas may have thermal signatures sufficiently different from their surroundings to facilitate identification. Generally, satellite thermal data are at coarser resolution compared to VNIR (very near infrared) range, and so only large-scale features are distinguishable. Aerial thermal measurements typically have higher resolution and have therefore been successfully used for planning excavations[12].

Microwave sensors, images and associated signatures

While sensors operating in the VNIR and thermal regions provide a host of information on surface features, microwave sensors (particularly those operating in C and L bands – about 5 cm and 21 cm wavelengths respectively) such as the active sensor synthetic aperture radar (SAR) provide subsurface details. SAR essentially sends a microwave pulse and receives the back-scattered signal which depends upon the dielectric constant of the target, its roughness, moisture content, angle of incidence and wavelength. Table 3 lists some of the SAR missions.

The response of surface objects in the microwave region is influenced by their dielectric properties, surface roughness and shape/structure/orientation. In addition, the response is also influenced by sensor parameters such as its operating frequency, polarization and incidence angle. In the microwave region, most natural materials have their dielectric constant between 3 and 8 in dry conditions. Water has a very high dielectric constant of

80. Hence, a change in moisture content causes a significant change in the overall dielectric constant of the soil, resulting in a change in radar backscatter. Penetration of microwaves is higher in barren and dry surfaces, and also at longer wavelengths. This permits the detection of subsurface (buried) features and palaeochannels. Dykes buried as much as 2 m beneath alluvium, unknown fluvial landscapes beneath the Aeolian cover, and the existence of limestone beneath the aeolian cover have been identified in radar images. In cases where vegetation cover is present, microwave back-scatter depends on the density and geometric structure of the vegetation. At smaller wavelengths (i.e. in the X-band), backscatter is primarily from vegetation. At longer wavelength (i.e. in the L band), it is primarily from the surface. (At intermediate frequencies, it is a mix of both depending on the angle of incidence.)

One of the early uses of radar for geoarchaeological applications was in detecting drainage patterns under the thick layer of sand in the Sahara[13,14]. Since the dielectric constant in the medium of dry sand is less than that in the soil, the radar pulse can penetrate deeper and reveal the topography of the underlying layer. SAR is also used in interferometric mode to obtain topographical information, as discussed in the next section.

Sensors for measuring heights

Optical

Photographs of an area taken from two locations by optical sensor scan determine heights using the principles of binocular vision. Traditionally, aerial photographs taken along a flight path with a 60% overlap have been used to obtain height information of each point within the overlapping region, using parallax measurements through a stereoscope. To determine height with sufficient accuracy, the base to height (B/H) ratio should be greater than 0.5 (the base is the distance between the two points from where the photographs are taken).

In case of space-based imaging, there are two ways in which stereoscopic imaging is realized: across-track and along-track. In across-track stereo imaging, images are acquired from two different orbits, sometimes even from two different sensors/satellites. It is also possible to acquire the two images by tilting the mirror in front of the optics of the sensor, as in the case of SPOT and IRS-1C and 1D satellites. Generally, it is found that such stereoscopic views are not ideal because of varied illumination and surface conditions due to the time lapse between the two observations. Also, the spatial resolution from the two orbits can vary, and the B/H ratio is usually lower than 0.5. Along-track stereo imaging comprises of two or three camera systems at different viewing angles with respect to the nadir. Images are acquired at near-simultaneous times, and are designed to have a B/H ratio greater than 0.5. Cartosat-1 had two cameras at +26° and –5°, allowing a B/H ratio of about 0.65, with a spatial resolution of 2.5 m and 30 km swath. These methods have been compared using stereo images of archaeological landscape of Badami[15], and along-track is generally preferred. Using Cartosat-1 stereo and photogrammetric techniques, a digital elevation model (DEM) for the entire Indian landmass has been generated at 10 m posting. Efforts are on to extend the generation of a DEM for many areas across the globe. (The ASTER satellite system freely provides a 30 m posting.)

Microwave

Microwave radar (i.e. SAR in interferometric mode) has been extensively used to generate digital elevation models of the earth's surface. Return pulses over a region obtained by SAR from two different locations in space (e.g. from adjacent orbits) or from two well-separated antennae on a single spacecraft differ in phase. Measuring and processing this phase difference provides very high-resolution digital elevation information. Shuttle radar terrain mission (SRTM) has provided global 90 and 30 m DEMs using interferometric principles. The ASTER and SRTM DEMs are regularly used for archaeological and other applications, as they are freely available on-line.

LiDAR

Terrain height can also be measured by LiDAR sensors aboard aircraft, UAVs and space-borne platforms (e.g. GLAS on-board ICEsat). LiDAR is an active sensor. A laser beam transmits several pulses per second to the earth's surface and measures the time taken by the reflected signal to return to the sensor. The position in terms of the x, y and z coordinates of each measurement is obtained using in-built GPS or any other GNSS. This dataset consists of millions of measurements, called a point cloud. Analysing this point cloud using photogrammetric techniques provides the three-dimensional surface of the terrain, called a digital terrain model (DTM). Since laser pulses have sub-micrometre wavelengths, the DTM obtained is of very high resolution. Such models have been used to reveal ancient cities buried under thick forests around Angkor Wat, Cambodia[16] and Caracol, Mexico[17]. Terrestrial laser scanning is also gaining importance in many archaeological studies, where one can create a point-cloud dataset for any monument or group of structures. If this is performed from multiple directions, high-fidelity three-dimensional models can be obtained for documentation and reconstruction[18].

Other dimensions of signatures and their interpretation

The previous section has discussed spectral signatures of objects in remotely sensed data. However, there are other dimensions to signatures that can lead to the identification of features. Spatial variations are the spatial arrangements of terrain features and their association with other surrounding objects. Temporal variations are the changes of reflectivity or emissivity with time (diurnal and/or seasonal). Polarization variations (particularly useful in microwave data) relate to the changes in the polarization of the radiation reflected or emitted by objects. The degree of polarization is a characteristic of an object which can help in identification. Signatures are, however, not completely deterministic. They are statistical in nature, with a certain mean value and some dispersion around it. The effects of polarization in analysing archaeological landscapes have been studied by Holcomb and Shingiray[19] and Rajani *et al.*[20].

Visual interpretation

Visual interpretation of RS data for studying terrains requires an understanding of the spectral signatures of different earth surface features, a priori knowledge of the ground, and some domain knowledge. Interpretation also makes use of shape, size, pattern, texture, site/location and association characteristics of the objects present in the image for identification. These are called interpretation keys or elements. In a typical FCC image (Figure 2), standing crops appear in red tone (in view of their high infrared reflectance). Different shades within this tone may indicate different growth stages, vigour, crop density, variety, cultural practices, stress conditions, etc. Densely forested areas that are evergreen appear in dark red tones throughout the year. Fallow lands bereft of vegetation have a cyan tone. Moist soils have a darker tone compared to dry soils, whereas sandy soils appear in bright tones because of their high reflectivity. Gullied/ravenous lands are identified by their pattern and association with river/stream systems. Surface waterbodies are easily distinguishable on such images through their dark blue tone resulting from absorption of infrared radiation by water. Turbidity in water provides higher reflectance compared to pure water, and the presence of aquatic vegetation provides pink tones within water bodies. Geological features such as lineaments, faults, dykes, valley fills, flood plains, drainage pattern, palaeochannels and areas of anomalous vegetation growth can also be identified with careful image interpretation.

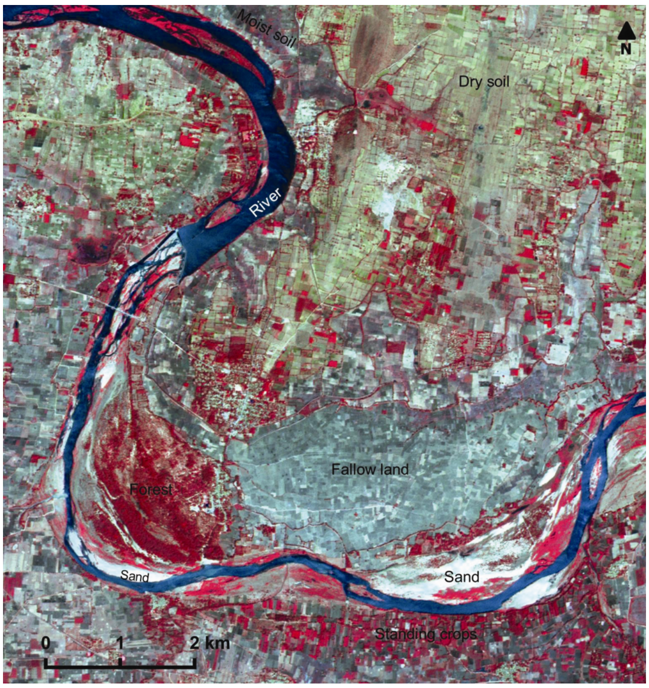

Figure 2. A typical FCC image.

Digital image processing and interpretation

Digital image processing comprises of image restoration, image enhancement, image transformation as well as classification of data. These steps help in improving the contrast and visibility of certain features. Transformation of data from the original set of spectral bands is employed to reduce dimensionality, using principal component analysis (PCA). For example, the LANDSAT series provided 7–8 bands, but the transformed data have higher information content in one or two bands. Pixel values in the new dimensions are a linear combination of values in the earlier bands, and the process is reversible (no information is lost during the transformation process). PCA has been used to analyse many RS images of archaeological sites; it yields effective results on geophysical[21] and LiDAR images[22].

Classification is another method which aims to allocate each pixel to a thematic class. There are many kinds of classification (supervised, unsupervised, hierarchical, etc.). Multispectral classification is an information extraction process by which all pixels having similar spectral signatures are assigned to a single class (vegetation, urban, etc.). In addition, there are non-parametric classifiers. Efforts have also been made to include context, texture, shape, etc. in the classification of data. Neural network algorithms and fuzzy classification have been employed for image processing. For more details one may refer to Navalgund[23,24] and Joseph[25]. In archaeological investigations, classification has yielded better results when applied on high-resolution images[26,27].

Archaeological signatures

FCCs of medium to high (20 m–1 m per pixel) spatial resolution satellite images covering hundreds of square

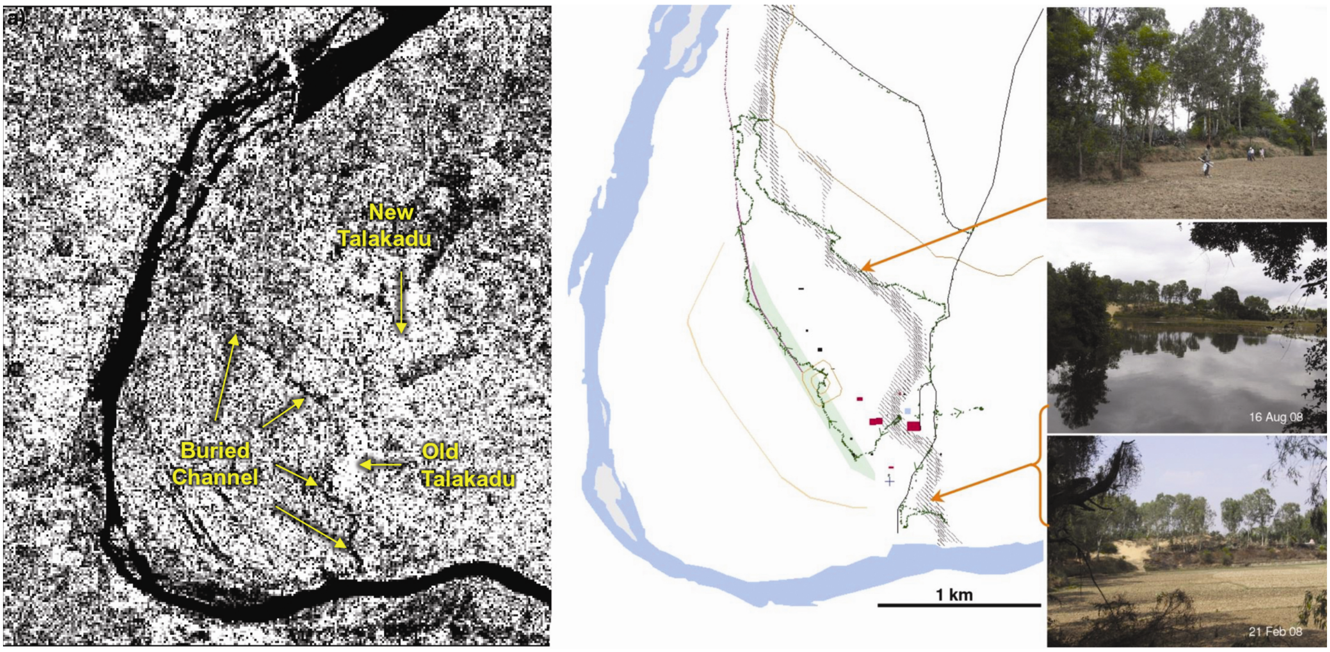

Figure 3. (Left) Buried channel seen distinctly on RADARSAT SAR imagery of 22 April 2008; (Middle) GPS tracks of field survey conducted for ground truth of features and of palaeochannel; (Right) Field photographs of palaeochannel.

kilometres of area provide regional perspectives of archaeological sites, and an understanding of the relationships that may have existed between cultural materials and the activities of their inhabitants. These indicators can be at various scales, and can be categorized as direct or indirect indicators. Signatures such as palaeodrainages or dried channels span across tens or hundreds of kilometres, whereas palaeo mudflats and coastal strandlines span at most tens of kilometres. These features are indirect signatures of archaeological remains – they merely indicate that the landscape might possess past settlements. Direct indicators include traces of buried structures and (whole or partial) settlements. These traces can be in the form of crop marks, soil marks, field boundaries or urban land-use. Some of the typical signatures which help in archaeological investigations are discussed here with a few illustrations.

Indirect signatures

Palaeochannel: A palaeochannel (i.e. a dried riverbed) is the remnant of an inactive river or stream channel that has been subsequently filled or buried by younger sediments. It is well known that early settlements flourished near rivers and streams. Hence, identifying paleochannels can assist archaeological investigations. Synoptic views provided by satellite images are extremely useful in the identification of such channels, which may not be identifiable while traversing the area on foot. Palaeochannels often have more subsurface moisture than their immediate surroundings, which results in a distinct signature (channel with a red tinge) in an FCC. (In some cases, anomalous vegetation growth can produce a similar signature.) Palaeochannels buried under dry sand for a long time may not be readily visible in FCCs. However, microwave SAR (particularly SAR operating at longer wavelengths like the L-band) can show such palaeochannels clearly.

In the context of the Harappan Civilization, Rajani and Rajawat[28] have clearly shown that satellite data in both VNIR and microwave bands not only help in identifying palaeochannels, but also in understanding their relationship with settlements. The study showed a large spread of Mature Harappan sites (2200–1700 BC) along the palaeochannel of the Saraswati and its tributaries in northwest India. In contrast, Late Harappan sites (1700–1500 BCE) are located further west, in the adjoining regions of Pakistan, indicating that the migration of settlements followed the river as it shifted westwards. In addition to the use of FCCs and SAR data, this study was also supported by the digital elevation models generated using SRTM DEM. SAR imagery also revealed a palaeochannel adjacent to the site Talakadu near Mysuru[20]. Field observations showed agricultural land along this channel, which gets flooded during heavy rains (Figure 3). The paper by Kumar and Rajawat in this special section (page 1899) demonstrates the potential of microwaves more elaborately.

Paleo mudflats/coastal strand lines: Mudflats, also known as tidal flats, are coastal wetlands. They are formed when mud is deposited along the shores by tides

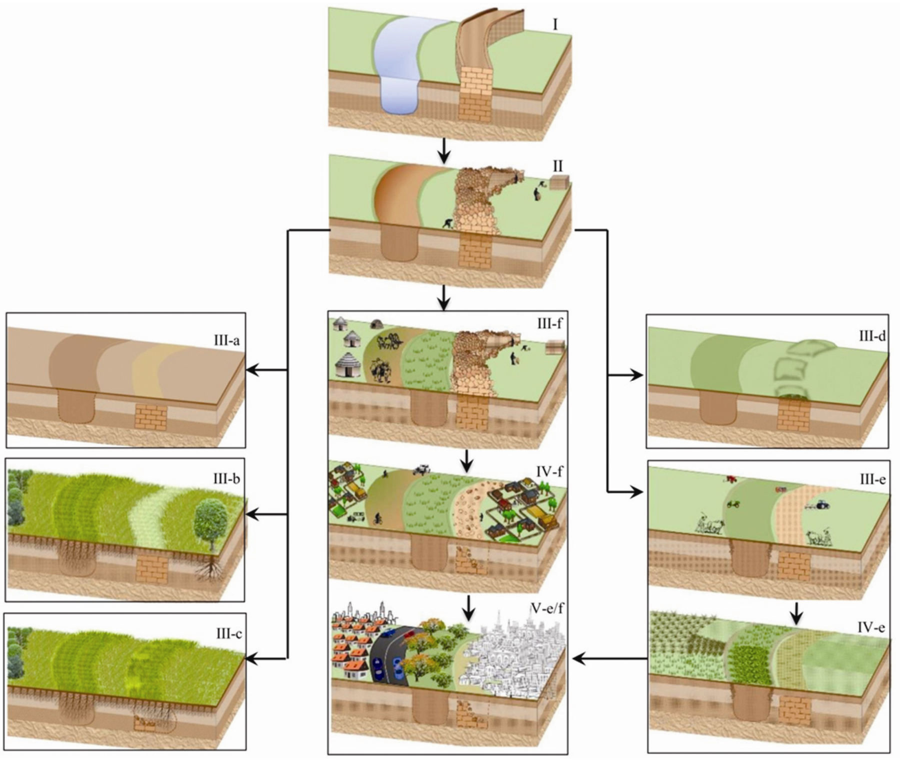

Figure 4. Diagram illustrating various possible transformations of a landscape possessing typical archaeological features.

or rivers. These shores may host port towns/cities. If the water recedes over time, such settlements may no longer function as ports, and may fall into ruin. Identifying palaeo mudflats away from present-day shorelines, or the occurrence of larger river mouths serves as clues to potential archaeological settlements nearby. Coastal strandlines (seen distinctly on FCCs) show sea levels at different periods of time. Many civilizations flourished on shores, for obvious reasons of sea-going trade. Several archaeological investigations have been performed using multi-date, multi-spectral data. The discovery of Vallabhi town, an ancient port on the bank of the present Ghelo river near Bhavnagar, Saurashtra, Gujarat was facilitated by such signatures[29]. The detection of palaeo-strandlines has also helped in understanding old coastline shapes in Mahabalipuram[30].

Direct signatures

To interpret direct signatures, it is important to understand the various kinds of archaeological remains and types of morphology that a typical landscape with such remains can go through. Most built features are of two types: those created by scarring the earth's surface (i.e. removal of surface/subsurface soil for making ditches, pits, canals, moats, tanks, ponds, etc.), and those where foundations are laid to support larger structures above. In both cases, these have shapes that are typical to specific locations, and are linked to the rest of the settlement and the main water sources. Once these structures fall into disuse, they are affected by decay (natural decay and deterioration from exposure to the elements, and anthropogenic decay caused by the removal of building material for reuse or clearance). This decay can reduce structures to ruins, thereby transforming their surface appearance. Such scattered vestiges can sometimes only be identified synoptically.

The outer defences of a settlement (moats and fort walls) can often be identified in this manner. When fort walls collapse, their material is often deposited into their surrounding moats. Source of water to moats may also dry up for various reasons, and the remains may be difficult to recognize at ground level. However, in synoptic views from satellite images, excess water/moisture is usually present in areas where the moat existed. This is either detectable directly, or indirectly when it is covered by comparatively healthy vegetation, in tell-tale patterns (circular, oval, rectangular, etc.). Figure 4 illustrates six different ways in which a pair of typical archaeological features (a fort with a surrounding moat) could decay. Moats are usually located adjacent to forts as drawn in the e and f series in Figure 4, but in the rest of the diagram a gap between the moat and the fort is introduced for the sake of clarity. The Roman numbers (I–V) denote different stages of landscape evolution (in some cases there are only three stages), and these are explained in detail next.

(I) A typical fort and adjacent moat as they would have existed during use. Note the cross-section indicating the subsurface – the moat has a channel filled with water, and the fort has a tightly packed foundation.

(II) A disused moat filled with silt and a dilapidated fort, parts of which have collapsed (due to natural decay, human destruction during conflicts, or as material removed by subsequent inhabitants for reuse/clearance).

Beyond this stage the landscape can take different kinds of transformation depending on subsequent activities in it. Six possibilities (labelled a–f) are explained here:

(IIIa) Soil marks: Arid lands with little or no plant cover normally show bare soil with uniform colour. However, sometimes the soil does show different colour marks in an otherwise homogeneous land parcel. Such variations are caused by differences in mineral and organic content of the soil. In addition, buried ditch fillings can sometimes show distinct marks because of differences in moisture content. Such signatures can indicate the existence of ancient ruined dwellings. Thakker[31] has demonstrated the existence of archaeological sites connected with such findings in parts of Kachhch, Gujarat.

(IIIb) Crop marks: Crop marks on an FCC identify areas where the vegetation cover differs from its immediate surroundings. Negative crop marks indicate that the local vegetation is stressed, in contrast to surrounding growth that is healthier. At such places, there is a possibility of buried structures that prevent roots of surface vegetation from reaching water and nutrients adequately. These clearly manifests as lighter tones of red in FCCs, or with a lower NDVI value in digital data. Positive crop marks correspond to areas with richer soils and/or enhanced moisture content, which allows vegetation to prosper. Such features in an FCC can also identify areas associated with ancient settlements.

Positive and negative crop marks may be difficult to identify in certain weather conditions (e.g. shortly after heavy rainfall, when the variability in soil moisture content may be reduced). It is therefore advisable to examine FCCs corresponding to different seasons, since patterns can be more pronounced in certain seasons. Several interesting studies have relied on such archaeological signatures. FCCs available from IRS satellites have been used to identify the oval fort that was part of Bengaluru in the 18th century[32] (Figure 5). Similarly, Rajani and Kasturirangan[33] have identified moats around the Channakesava temple of Belur (Figure 6) and the Hoysaleshvara temple at Halebidu.

(IIIc) An area that originally had a fort and foundations can sometimes show positive cropmarks (rather than negative cropmarks as indicated earlier). Such anomalies have been noticed under three circumstances: (i) When certain plants/trees thrive on construction material (Figure 7), (ii) When cavities in subsurface structures hold moisture, (iii) When the subsurface building materials have been mined, creating cavities that hold moisture. However, positive crop marks created in such cases are usually irregular in shape (compare illustration IIIc with IIIb). Figure 7 shows an FCC image of Sisupalgarh, a fortified city on the southeastern edge of the modern city of Bhubaneswar, Odisha. The site was formally surrounded by a rampart and moat enclosing over 1 sq. km. Since this is one of the few well-preserved urban sites in the Indian subcontinent, excavations have been conducted here to study layers and materials to assess the economic and social conditions of early urbanism[34].

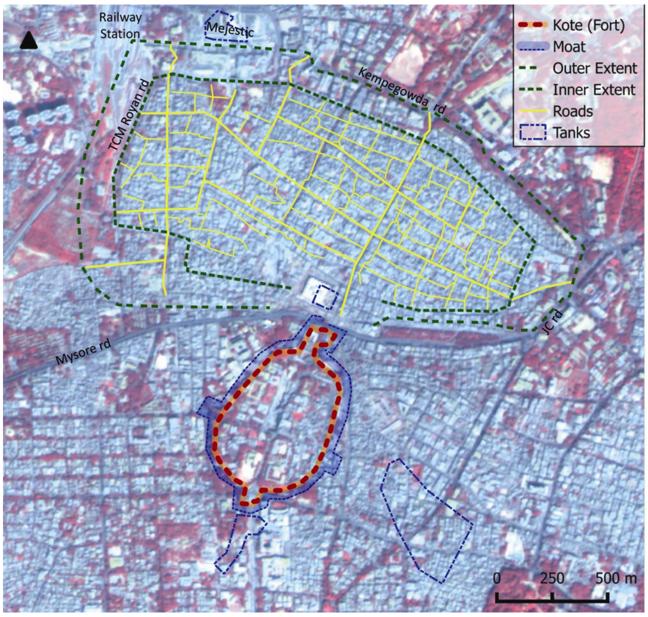

Figure 5. IRS-R2 LISS-4 (9.01.2014) image of Bengaluru on which the 1791 map has been overlaid. The road/landmark names annotated in black give current context.

Figure 6. Multispectral image (IRSP6 LISS-IV; 31.12.2006) clearly showing the circular positive vegetation mark indicating location of past moat surrounding Belur, with Chennakesava temple at the centre of settlement.

(IIId) Building material can get covered over time by silting and undergrowth, and could result in a ridge. Figure 8 shows such a ridge in the shape of a fort at Saravasti, and Figure 9 shows intermittent mounds corresponding to fragmented remains of a fort in Koshambi. Figure 8 clearly shows the crescent-shaped plan of the site Saravasti, abutting a palaeochannel on its northwest (identified as the ancient river Achiravati). Excavations were conducted here jointly by the Archaeological Survey of India (ASI) and Kansai University, Osaka, Japan, in the 1990s[35]. Rai[36] has surveyed the fortified area of Koshambi using GPS to geo-tag locations of archaeological remains, and has also used RS and GIS techniques to document the site.

(IIIe) Subsurface materials can make it difficult to alter land-use boundaries, and may dictate the future division of land into parcels. Continuous adjoining field boundaries in agricultural land can reveal shapes of forts/moats as shown in IVe (e.g. the fortifications in Ahichchhatra shown in Figure 10).

(IIIf) The shapes of past fort/moats in urban areas are often preserved by roads. IIIf depicts the situation where a dilapidated fort wall is initially a hindrance to mobility, but is subsequently converted into a path, which then becomes a road (IVf). The ruins of the fort get fully cleared and land use on either side of the road keeps changing over time, but the roads usually gain importance and remain as permanent markers, as shown in Vf. Bengaluru provides a concrete example of this process (Figure 5), where the remains of the fort have gradually succumbed to urbanization. As another example, a map of Machilipatnam (an ancient port town in Andhra Pradesh) dating from AD 1759 shows a fortified area[37]. This shape can still be identified and the landscape morphology can also be seen when a recent satellite image is compared with one from more than a decade earlier (Figure 11). The area has fragmented into several parcels along the lines of the old fort. The land use of each fragment has changed gradually – one parcel on the northwest portion of the fort was agricultural land in 2001, but it is now a settlement (Figure 11).

Geographic information system

GIS is a computer-assisted information system that captures, integrates, stores, edits, manipulates and analyses geographical information, and displays it in a spatial format. GIS uses spatial location as the key index variable to relate different pieces of information/data. Location is given by x, y and z coordinates representing longitude, latitude and elevation respectively. The first step in creating a GIS database is the generation of

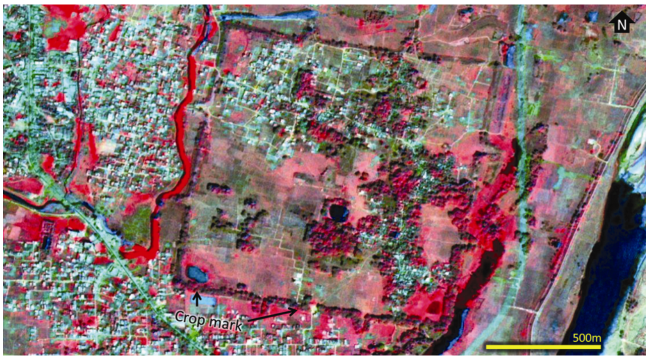

Figure 7. Positive crop mark indicating fortification at Sisupalgarh, Bhubaneswar, Odisha, India.

Figure 8. Intermittent ridges/mounds indicating buried remains of a fort at Sravasti, UP, India.

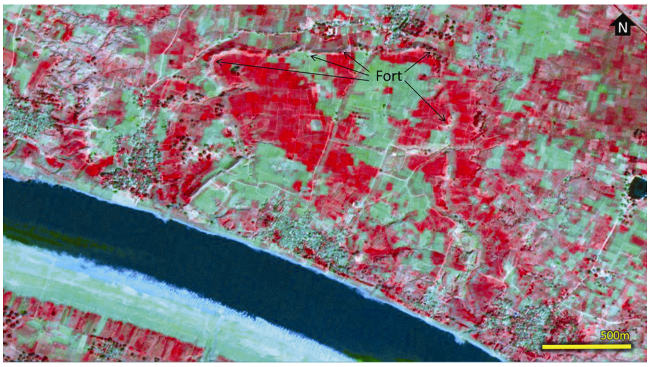

Figure 9. Intermittent ridges/mounds indicating buried remains of a fort at Koshambi, UP.

Figure 10. Continuous adjoining field boundaries in agricultural land revealing shapes of forts/moats in Ahichchhatra, UP.

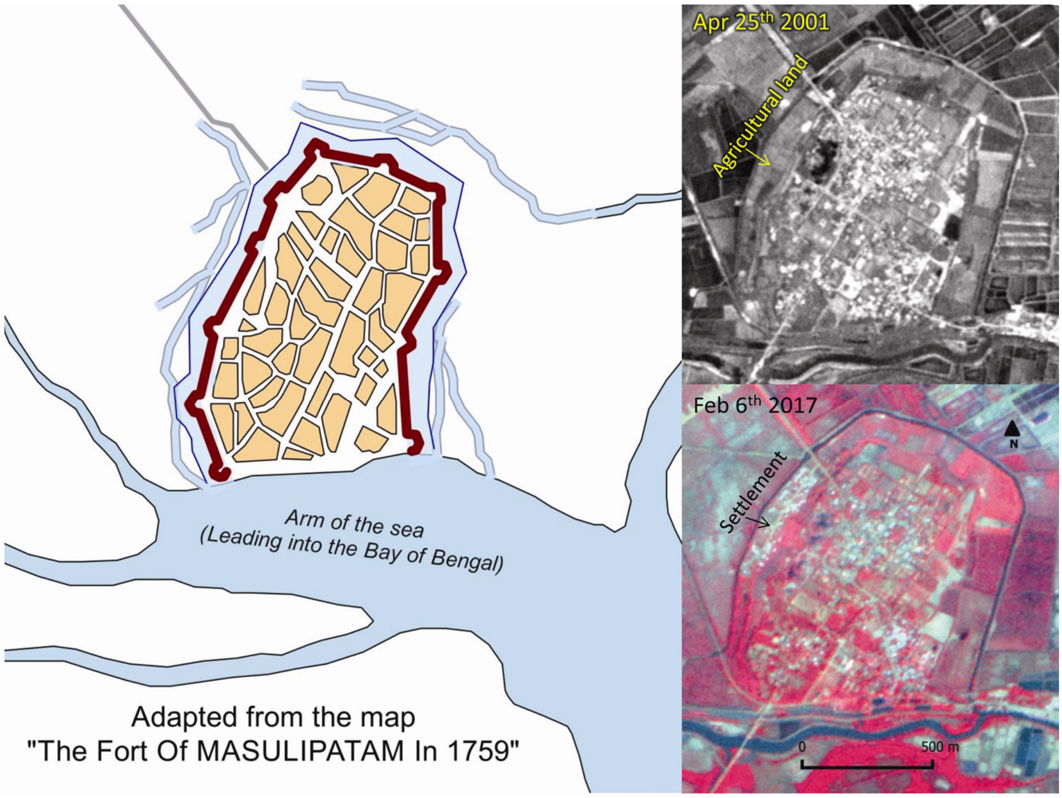

Figure 11. Landscape fragments transforming into settlements, still maintaining earlier boundary shapes.

digitized data. Typically, a base map (e.g. a topographic map) is created using software with geo-referencing capabilities. Other information in a GIS database is organized in layers, where each layer contains information from a different source (e.g. textual sources, various kinds of satellite images, archaeological excavation reports, ground survey and exploration, GPS surveys, etc.). These layers can then be collectively or selectively retrieved and superimposed using GIS software and analysed to see interrelations between them. In the context of archaeological studies, interpreted satellite data in the form of a thematic map showing different land-cover categories are an important layer in the GIS database. The database can also store attribute information related to specific points or regions. The GIS environment can incorporate DEMs, or these can be derived by the software using contours available in topographic maps.

When studying an archaeological site, there is tremendous value in geo-tagging the known information (i.e. attaching geographical references to every known archaeological object). This information can be pulled into a GIS database of known facts about the site, rich enough to incorporate information from literature, epigraphy, accounts/records of travellers and archaeological reports. With a geospatial context, one can analyse an important archaeological object in relation to adjacent objects (at various scales). Such an integrated information system can shed new light on well-studied problems, and create opportunities to ask new questions such as: Why is the object located here? What is up-/down-hill from it? How far is it from related objects?

As an example, multi-sensor imagery was interpreted and integrated with ground-truth data in Talakadu[38], making it possible to derive unique information about the study area, and to pose and answer novel research questions. Another example is the identification of the historical boundaries of Lalbagh Botanical Gardens in Bengaluru[39].

GIS has greatly assisted the process of documenting cultural heritage sites, such as in drawing up conservation plans and monitoring their implementation (for more details, please see the article by Rajangam and Rajani in this special section). While according heritage status, UNESCO insists on having an authenticated GIS databases of the site and its surroundings, with information related to topography, cadastral, roads, waterbodies, etc. as layers. This information is used to define core and buffer zones, and prepare site management plans. GIS has the potential greater usage in this context, which is an active research area.

Global navigation satellite systems

GNSS uses a constellation of satellites to provide geo-spatial positioning. A GNSS system allows small receivers on the earth's surface to determine its location in terms of latitude, longitude and elevation accurately (within a few metres) using timing signals sent by the satellites. A receiver must acquire signals from at least four satellites to determine its location unambiguously. The system can be used for navigation, as well as for tracking the vehicles carrying such receivers. The navigation payloads carry atomic clocks with very high stability (better than 10^{-13} sec), which facilitates time synchronization. With advances in technology, receiver chips have been miniaturized to fit in wrist watches and other mobile devices. The pioneering and most utilized GNSS is the United States' global positioning system (GPS). This system currently comprises of more than 32 satellites orbiting at an altitude of 20,180 km in six orbital planes. Galileo, a GNSS operated by the European Union, is expected to comprise of 30 satellites at an altitude of 23,222 km, and to be fully ready by 2020. The Russian Federation operates GLONASS, a constellation of 24/28 satellites orbiting at 19,130 km and is fully operational. China's Bei Dou GNSS comprises of five geostationary orbit satellites and 30 medium Earth orbit satellites, and is expected to be operational by 2020. India has a regional navigation satellite system named NAVIC consisting of seven satellites, which services the Indian landmass and approximately 1500 km beyond in all directions. Efforts are being made to create receivers that can acquire signals from more than one GNSS.

GNSS receivers have an important role in ground-truth investigations and geo-tagging of archaeological sites. The exact locations of monuments, excavation sites and other features of interest can be determined using these receivers, which can then be transferred to GIS databases. This technique was used to mark the location of sites that are under a tree canopy at Talakadu[38]. In some cases, these measurements may help identify sites with potential for further exploration. As an example, the potential for investigating the archaeological mound under Begumpur (north of Nalanda) was confirmed by navigating to the precise location using a handheld device[40]. Data (in the form of exact tracks and points) recorded from such ground surveys can help in documenting, organizing and analysing field information, reducing the labour and time involved while increasing accuracy compared to traditional methods, which involved making detailed notes with approximate directions, distances and reference points.

Geophysical investigations

Non-destructive geophysical methods have also been successfully used in archaeological investigations. Measurements from a sensitive magnetometer provide a magnetic map of the site. Variations/anomalies in the magnetic field can indicate the presence of buried materials such as iron artefacts. This technique has also identified the presence of bricks, rooftiles, kilns and furnaces[41]. Resistivity measurements have facilitated mapping the distribution, vertical dimensions and characteristics of features within a site. Ground penetrating radar (GPR) is another geophysical instrument which is becoming popular with archaeologists. It generates microwave pulses, sends these to subsurface objects, and detects the return signals. Analysis of these return signals provides information on the presence of buried materials. Today, portable GPRs are available, operating in a wide range of frequencies along with the necessary software for analysis. Geophysical surveys have identified different archaeological levels of occupation in Lumbini, the site of birth of Buddha[42].

Integrated use of geospatial techniques in monitoring, documentation and conservation of archaeological sites

The techniques discussed above have found numerous applications in the context of archaeology. A summary of the major application areas is presented below:

1. Statistical sampling for excavation: Excavation is a laborious and costly process. Having delineated the entire area of archaeological significance, the next step is to decide on where to excavate. Satellite images are found useful in drawing up a sampling plan based on identified features.
2. Monitoring and mapping excavations: Very high-resolution images are used to identify potential sites for exploration (based on signatures), and monitor the extent of excavations using multi-date images. For instance, very high-resolution DEMs generated using such data can quantify the total volume of earth removed.
3. Documentation of monuments: The exact locations and shapes of monuments can be documented. Maps can be prepared keeping the landscape and adjacent activities in mind, which help in planning future activities in the vicinity.
4. Conservation and planning management: Natural or man-made changes near sites can be monitored. Today, sites are increasingly under threat from development activities. A careful analysis of the surrounding landscape can generate authentic data to help policy makers. Remote sensing data are also a permanent record of the condition of a site at the time when the image was taken. Past images can be used in law courts as evidence for illegal encroachment and occupation. Sites close to coastlines, rivers and on hills are susceptible to natural disasters. Geospatial analysis and monitoring can also help in planning conservation of such sites.

5. Reconstruction: Remote sensing and GIS can be helpful in virtual reconstruction of sites. This has applications in education, assessing the effects of planned constructions (these can be added virtually), determining the impact of natural phenomenon such as floods and sea-level rise (these can be simulated to understand their effects and formulate preventive measures), and to create effective displays and presentations in museums and kiosks.

Summary

- Space-borne remotely sensed data provide synoptic coverage of archaeological sites and facilitate the understanding of relationships between different components of sites.
- Interpretation of false colour composite images provides characteristic signatures associated with potential archaeological sites, helping further exploration and identifying newer sites. The availability of very high spatial resolution multi-spectral images has enhanced usage in archaeology.
- Satellite products facilitate drawing up sampling plans for excavations.
- Microwave radar images are particularly helpful in delineating palaeo/buried channels, some of which may be associated with archaeological sites.
- Digital elevation models and SAR interferometry can be layered over data products/images to identify landforms with archaeological significance.
- Digital photogrammetry provides architectural measurements of monuments.
- High-resolution DEMs derived using LiDAR are particularly useful in areas covered by forests to identify different landforms beneath vegetation.
- Terrestrial laser scanning helps in creating three-dimensional models of monuments, which can be used to monitor their status over time, and aid in their reconstruction.
- Geophysical tools such as the ground penetrating radar provide non-destructive ways of understanding what is beneath the surface.
- Geographic information system helps integrate spatial and attribute data related to archaeological sites, and carry out spatial analysis and modelling to further facilitate in documentation and conservation.
- GNSS provides precise coordinates of each point, which assist in geo-tagging archaeological sites to simplify mapping and navigation.

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