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Beach topography mapping – a comparison of techniques

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Abstract. A comparison of current techniques for measuring elevations in the beach and near-shore zones is presented. Techniques considered include traditional methods such as ground survey along transects and airborne stereophotogrammetry, and also newer methods based on remote sensing such as airborne scanning laser altimetry (LiDAR). The approach taken was to identify a representative group of users of beach elevation data, elicit their requirements regarding these data, then assess how well the different methods met these requirements on both technical and financial grounds.

Potential users of beach height measurements include those concerned with coastal defence, coastal environmental management, economic exploitation of the intertidal zone, and coastal flood forecasting. Three test areas in the UK were identified covering a range of such users and also different beach types. A total of 17 basic user requirements were elicited. For each requirement each method was scored according to the degree to which it could meet the requirement. Total scores were calculated and each method ranked. This was undertaken for all the requirements together, for a subset relating to survey of narrow beaches, and for a subset relating to survey of wide beaches. Approximate costs were also established for the top six methods.

Airborne stereophotogrammetry proved to be the best method technically, but was also the most expensive. Ground survey provides very good technical performance on narrower beaches at moderate cost. Airborne LiDAR can achieve good technical performance on both narrow and wide beaches at lower cost than ground survey. The satellite-based waterline method was also inexpensive and gave good results on wide beaches. An overall conclusion is that, while the traditional methods of ground survey and airborne stereophotogrammetry remain the best for engineering-related surveys requiring high levels of accuracy, airborne LiDAR in particular looks set to have a significant impact on beach survey for applications for which a vertical accuracy of 20 cm is acceptable, provided that its technology evolves satisfactorily.

Keywords: Digital Elevation Model; Geomorphology; Interferometry; LiDAR; Profiling; Remote sensing; Stereophotogrammetry; Waterline.

Abbreviations: CC = City Council; DEM = Digital Elevation Model; EA = Environment Agency; EN = English Nature; LiDAR = Airborne scanning laser altimetry; SAR = Synthetic Aperture Radar; SPA = Special Protection Area; SSSI = Site of Special Scientific Interest.

Introduction

A variety of methods for measuring elevations in the beach and near-shore zones now exist. As well as traditional methods such as beach profiling using ground survey, bathymetric sounding and airborne stereophotogrammetry, a number of methods based on remote sensing have either recently emerged or are currently evolving, including airborne scanning laser altimetry, radar interferometry, the satellite-based waterline method, and bathymetry measurement by radar imaging of wave current interaction.

Given the recent rapid rate of technological change in this area, a comparison of current methods seems opportune. The impetus for this came from a user requirements study carried out under a British National Space Centre Earth Observation LINK project which developed and assessed the commercial potential of one particular remote sensing method (the waterline method) (Mason et al. 1998). The approach taken was to identify a representative group of users of beach elevation data, elicit their requirements regarding these data, then assess how well the different methods met these requirements on both technical and financial grounds. Although the study focused on UK beaches and users, the results should be applicable more generally.

Identifying users

Very broadly, the coastal users who have a requirement for beach height measurements can be divided into four groupings according to their areas of interest:

1. Coastal defence

The term ‘coastal defence’ applies both to protection against erosion and against flooding. In England and Wales, the construction, improvement and maintenance of defences against flooding is largely undertaken by the Environment Agency (EA), while protection against erosion is undertaken by Maritime District Councils (MDCs). Provided that the EA and MDCs discharge their responsibilities, there is no statutory requirement on them to undertake specific surveys of beach areas. However, in the implementation of any new defence scheme, it is highly likely that some form of shoreline survey would be required, followed by post-construction monitoring which included monitoring both at the site and along adjacent shorelines. Beach profiling coupled with profile analysis to estimate sediment volume changes has been identified as an essential component of the planning and evaluation procedures for such schemes as beach recharge, barrage construction, groyne construction, beach drainage and managed retreat (Anon. 1993). Sediment volume change measurement is also useful for validating computer models of sediment transport.

2. Environmental management

Coastal areas contain a number of different types of site of particular biological, geological, geomorphological, landscape or cultural heritage value, each with specific requirements for monitoring. Examples include Special Protection Areas (SPAs) and Sites of Special Scientific Interest (SSSIs). The status of many such areas can only be assessed if some sort of monitoring which includes beach survey is undertaken. For example, marine site conservation includes the identification of habitats on intertidal areas such as bird feeding areas, and must take account of such factors as fragility, size, diversity and recorded history. In order to achieve this beach areas must be mapped and monitored. Within England, English Nature (EN) is the government's statutory adviser on nature conservation.

3. Economic exploitation

Environmental Impact Assessments are required on projects such as oil refineries, power stations, holiday villages and ports. Engineering surveys undertaken for such assessments might include measurement of beach elevations. Detailed surveys are required near commercial ports to supply information required for dredging operations. Economic fishing interests, particularly in relation to shellfish, are also of vital importance in many large intertidal areas. The requirements of the fishermen follow very closely the requirements for environmental monitoring, since they need to determine the precise areas in which shellfish might thrive. These areas are virtually the same as the bird habitats, since the birds feed on the shellfish.

4. Coastal flood forecasting

An accurate knowledge of bathymetry in the intertidal zone can lead to improved prediction of coastal flooding. Short-term changes in sea-level are predominantly due to the tides, and to the effects of storms. Winds associated with a storm can raise or lower sea level by several metres in a matter of hours, producing a storm surge. These are superimposed on the normal astronomical tides, and may cause flooding of coastal areas if the peak surge occurs at the time of high tide. Forecasts of sea levels are commonly made using numerical models, and an accurate knowledge of bathymetry is essential for the correct modelling of the tide and surge, particularly in shallow water (Flather & Hubbert 1989).

Assessing user requirements

Test areas

In order to assess the requirements of users for beach height data, three test areas in the UK were selected to cover as wide a range of geographical conditions as possible and to cover the primary type of user identified above. These were the Humber/Wash area on the east coast, the New Forest coastline on the south coast and Morecambe Bay on the northwest coast. Within the three areas, end users were contacted and asked to participate in the project by discussing their requirements and sharing their data. The test area characteristics and end-users are summarized in Table 1.

Below we describe the characteristics of each area, current monitoring practices, and the requirements of the users. Each requirement is given an identifier. These requirements are then summarized in tabular form.

The Humber/Wash area

The Wash is a macrotidal estuary covering an intertidal area of 29 770 ha and forming the second largest intertidal area in the UK. The tidal flats have an average slope of about 1 : 500. The spring tidal range is ca. 5 m. Maintenance of sea defences is critical to flood prevention, as the land behind the sea walls is several metres below current sea level. The whole of the Wash is a designated SPA and contains within it several SSSIs. North of the Wash along the Lincolnshire coast the beaches are narrow, extending only 250 m in the Skegness area, and of slope 1 : 30 to 1 : 100. The Humber estuary is a macrotidal estuary with more than 10 000 ha of intertidal area. The estuary is of significant economic importance for shipping as well as containing areas of environmental importance.

The EA carries out bi-annual beach surveys along this coast in January and August each year. Transects, consisting of a series of survey points extending seaward from the sea wall to the low-water mark, are surveyed at one kilometre intervals. Surveyors are expected to measure heights at 20-m intervals and at all breaks of slope. Airborne surveys are undertaken annually in July/August to coincide with beach monitoring and with the

Table 1. Test areas and end-users (see text for explanation of end-user acronyms).

Area	Primary User	Geographical criteria	User criteria
Humber/Wash	EA Anglian; CEFAS; POL	Range of beach slopes including large tidal flats area; East coast	Coastal defence requirements; shell fisheries research; flood forecasting
New Forest coast	NF District Council; ABP Research	Narrow, partly shingle beach; South coast	Local engineering requirements
Morecambe Bay	Lancaster District Council; Sea Fisheries Committee; English Nature; EA NW.	Large sand/mud area, environmentally important and largely unmonitored; West coast	Coastal defence, environmental and shellfisheries issues

lowest tides. Subtidal bathymetry is also measured by continuing the transects to 2 or 3 km offshore using a boat equipped with echo sounder, though a repeat survey is only undertaken every 5th summer. The Humber estuary is also routinely monitored by Associated British Ports in order to maintain shipping channels, by monitoring the effects of dredging and natural changes.

The ultimate goal of the surveying is to measure sediment movement and beach recharge, and to assess coastal flood defences. EA undertake intensive ground survey and require high levels of transect accuracy as a result. Vertical and planimetric accuracy of 1 cm in the beach zone [1.1] is required from surveyors. This level of accuracy is also required by the Humber Harbour Master (Myers, pers. comm.). Surveys are required in the winter and the summer periods [1.2] and repeated at annual intervals [1.3]. The ability to monitor the complete beach/near-shore zone [1.4] including the area above MHWS is required. Any alternative beach measurement method to ground survey must be simple to understand [1.5] by users accustomed to employing traditional ground survey techniques.

The Fish Stock Management Group of the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) needs to estimate the proportion of cockle stocks in the Wash above the 4 m drying contour, which approximates the upper limit of commercial exploitation by suction dredger. Annual beach height monitoring of the Wash would also give them an accurate up-to-date value for this contour.

Hydrodynamic tide-surge modellers at the Proudman Oceanographic Laboratory (POL) require a 10-cm vertical accuracy [1.6] in the beach and near-shore zones in this and other areas.

The New Forest coastline

The New Forest coastline covers the mainland coast of the western Solent. Beaches in this area range from narrow shingle to coastal mud flats and salt marshes, and beach slopes show a corresponding range from 1:8 to 1:100. The area includes several SSSIs. Along this coast there is a double tide, with a spring tidal range of ca. 2 m.

Conventional ground survey is undertaken by the New Forest District Council (NFDC) on a quarterly basis, using transect surveying coupled with differential GPS to obtain high locational accuracy. These methods give 0.1 m vertical and 0.1 - 0.5 m planimetric accuracy (possibly higher when GPS is used (Morton et al. 1993)). EA Southern also undertake ground survey in the area. The winter surveys are the most problematic because of the short daylight time and adverse weather conditions. However, winter survey is considered important because this is the time of the most severe storms and hence the greatest potential sediment movement and damage to coastal defences. Extensive airborne surveys are also undertaken. The entire coastline is flown at low water every summer at 1:2500. Stereo photography to produce height maps – or Digital Elevation Models (DEMs) – of the beach are produced every 5 yr at 1:8000.

As with EA Anglian, the ultimate goal of the Council is to be able to estimate beach recharge volumes and rates. Their stated requirement of 10 cm vertical accuracy [2.1] and 10-50 cm horizontal accuracy [2.2] is made with the knowledge that it is possible to measure vertically to centimetric levels of accuracy, but not strictly necessary because the shingle sediments themselves are larger than this. The Council requires at least annual repeats [2.3] of any survey. The ability to monitor storm damage [2.4], especially in winter, is an important requirement. The narrow beach and relatively small tidal range means that it is essential for any survey to cover the full tidal range [2.6], as without this too large a proportion of the beach would remain unsurveyed. The Council is also interested in the ability to monitor changes in salt marshes [2.7].

Morecambe Bay

Morecambe Bay is a macrotidal estuary situated in northwest England. The Bay contains the largest area of tidal flats in Britain, covering 34 339 ha, and provides a habitat for large numbers of both nationally and internationally important wildfowl. Intertidal sand and mud banks represent 68% of the total area, and salt marsh 7.7% (Comber & Hansom 1994). The Bay experiences a spring tidal range of ca. 8.2 m.

The sheer size of Morecambe Bay, coupled with the division of responsibility between various groups in the area, has meant that surveys have tended to be uncoordinated. The South Cumbria Consortium, consisting of Lancaster CC, Cumbria CC, Barrow BC, S. Lakeland

DC, the EA, Rail Track and EN, has recently been established in order to coordinate strategy, and is currently developing a Shoreline Management Plan for the whole coastline. The area is very difficult to survey using conventional ground-based methods because of the extent of the intertidal area and the difficulties of surveying where the tide advances rapidly. Accordingly, beach transects exist only for some of the more exposed portions of the Bay, and do not extend far into its interior. Airborne surveys are similarly limited. Survey of the whole area at the same state of (low) tide is logistically difficult to achieve. Various surveys exist for selected portions of the Bay, but focus on the nearshore region and do not extend across the whole Bay. A problem with airborne survey with stereo pairs is to establish reference points far out from the shore. Accurate DEMs of extensive intertidal areas are difficult and expensive to produce by stereophotogrammetry. Bathymetric survey in sub- and intertidal regions is carried out by the North Wales and North West Sea Fisheries Committee using an echo sounder linked to GPS.

The overriding issue is to measure change within the Bay as a result of natural or anthropogenic activity, and to identify the causes where possible. Since the Bay is not routinely surveyed as a whole, the accuracy requirements of users are considerably less stringent than in those areas where conventional survey is straightforward.

Shellfish modellers want to know where the shellfish beds are and whether they are economically viable. To do this they need to know the extent of exposed area [4.1], the exposure time above water [4.2], and crude sediment typing [4.3] (coarse/medium/fine). The stability of any exposed area [4.4] and the positioning of minor channels [4.5] is also important because sand/mud banks must persist for several years before shellfish become sufficiently established to form an economically viable bed. The mussel beds, which are located on coarse cobbles, are only exposed at very low tides so there is a clear requirement to monitor close to minimum tide [4.6]. In contrast the cockle beds are on finer sand/mud deposits and are located on higher ground. Knowledge of the shellfish habitats also gives important information for wildfowl habitats, since the shellfish form a major food source for birds. These requirements therefore apply to both EN and the Seafisheries Committee.

The requirements of the EA and Council engineers relate to their interest in the maintenance of coastal defences. They require vertical accuracies of 10 cm [4.7] from any survey. While the main focus is on the inshore area, there is increasing acceptance that changes over the whole Bay may also have inshore engineering implications. Hence there is a requirement to monitor changes over a long time period [4.8] and over as large an area [4.9] as feasible, with changes identifiable on the order of 50 cm [4.10] to be of value. The ability to see all the Bay at one time [4.11] is of fundamental importance to this type of monitoring. The EA is also interested in monitoring storm damage [4.12]. Monitoring of salt marshes [4.13] and changes in areas of marsh are also of interest to both EA and EN.

Requirements summary

Table 2 summarizes the main requirements identified by the users. The ‘source’ column indicates the users who specified the requirement, together with its identifiers. Little attempt has been made to prioritize requirements, though the ‘need’ column indicates the degree of importance attached to a requirement (1 = essential, 2 = desirable). Where the same requirement has been identified by more than one user this is indicated in the table. Conflicting requirements (e.g. varia-

Table 2. Summary of requirements.

No.	Requirement	Source with ID between []	Need	Comment
1	Vertical and planimetric accuracy 1 cm	EA Anglian[1.1]; ABP Research [3.1]	1	see also requirements 4 & 5
2	Winter and summer surveys	EA Anglian [1.2]; NFDC [2.5]	1	
3	Annual repeat survey	EA Anglian [1.3]; NFDC [2.3]	1	
4	10 cm vertical accuracy	NFDC [2.1]; M Bay [4.7]; POL [1.6]	1	
5	10-50 cm planimetric accuracy	NFDC [2.2]	1	
6	Cover complete beach/nearshore zone	EA Anglian [2.6]; NFDC [2.6]; M Bay [4.6]	1	
7	Synoptic view (ability to see all the area at one time)	M Bay [4.11]	1	
8	Map extent of exposed area	M Bay [4.1]	1	
9	Monitoring over a long time period (to study stability of exposed area)	M Bay [4.8, 4.4]	1	
10	Monitor changes over as large an area as possible	M Bay [4.9]	1	to cover whole coastal cell
11	Height changes identifiable ~50cm	M Bay [4.10]	1	
12	Ability to monitor storm damage	NFDC [2.4]; EA NW [4.12]	1	especially rapid response in winter
13	Exposure time of any part of intertidal zone above water (for shellfishing)	M Bay [4.2]; CEFAS	2	
14	Sediment type (for shellfishing)	M Bay [4.3]	2	only crude division required
15	Monitor changes in salt marsh extent	NFDC [2.7]; M Bay [4.13]; ABP Res. [3.2]	2	1m planimetric accuracy required by ABP; other accuracy levels unspecified
16	Map positions of minor channels	M Bay [4.5]	2	
17	Methods must be easy to understand	EA Anglian [1.5]	2	

tions in accuracy requirements) are listed as separate requirements.

Meeting user requirements

Technical evaluation

In this section the possible methods for meeting users requirements are described and their relative advantages and disadvantages summarized. The ability of each method to meet requirements is then scored and a percentage score calculated. At this stage the focus is on whether requirements can be met technically. A comparison of the costs of the methods is given later.

The beach height measurement methods considered include ground survey along transects, stereophotogrammetry from both aircraft and satellite platforms, airborne scanning laser altimetry (LiDAR), Synthetic Aperture Radar (SAR) interferometry from both aircraft and satellites, the satellite-based waterline method, and bathymetry measurement by SAR imaging of wave current interaction. Even the so-called 'traditional' methods are still evolving, and recent relevant developments in these are brought out where necessary.

1. Ground survey

Ground surveys usually consist of measurements along shore-normal transects spaced at roughly regular intervals along the beach, using traditional surveying techniques employing theodolites or total stations as described in the previous section. Shore-parallel transects may also be surveyed to obtain a longitudinal view of a beach. Accretion and erosion are measured by repeating surveys at periodic time intervals. Profiles usually extend above mean high water into the area which may be inundated by storms. They may also extend below mean low water into the near-shore zone as far as beach closure depth, using a boat-mounted echo sounder or a sled towed by boat. An excellent review of the many practical aspects of beach transect measurement is given in (Gorman et al. 1998).

The major advantages of ground survey are:

- Very high accuracy along the transect (Req. 1, 4, 5, 11). Vertical heights and position accuracies of 1cm can be obtained at surveyed points on the beach, though in practice even under ideal conditions the estimated vertical accuracy of a typical transect across the beach extending offshore to closure depth is 5 cm (Gorman et al. 1998). Brampton (1990) has argued that the high accuracies given by the method may be unnecessary because of fundamental uncertainties in beach surveying due to the rapid spatial and temporal fluctations which can occur in beach levels (e.g. it is meaningless to survey to 1 cm height accuracy on a shingle beach). The advent of GPS technology has led to increased precision, in particular the ability to re-survey along exactly the same transect;
- Repeatability (Req. 2, 3). Separate summer and winter surveys repeated annually are possible, as well as supplemental surveys after big storms to determine their effects;
- Complete beach and nearshore zones can be monitored (Req. 6);
- Items other than height can be monitored, e.g. beach material type (Req. 13, 14);
- Simplicity (Req. 17).

The major disadvantages are:

- Difficulties in covering a large area (Req. 7, 15). This is a highly labour intensive method requiring two people to survey a profile. Large areas can be sampled only sparsely and relatively infrequently. On large intertidal areas such as Morecambe Bay, ground survey may be logistically difficult and even dangerous. The advent of GPS will lead to increased efficiency. Morton et al. (1993) compared kinematic GPS with conventional surveying techniques using a GPS antenna attached to an off-road vehicle driven in a pattern which included both shore-normal and shore-parallel profiles. Height measurements accurate to 1 cm could be obtained on a much denser sampling pattern than by conventional surveying;
- For large areas the method only gives a 1-D view – it does not give a contour map, making it difficult to map spatial data (Req. 8, 9, 10, 16). There may also be difficulties in choosing a transect which is sufficiently representative of the beach in its local vicinity;
- Difficulties in poor weather, short daylight and certain tide conditions (Req. 2, 6, 12).

2. Airborne stereophotogrammetry

Aircraft can cover large areas in a short time and survey beaches inaccessible from the ground. Stereoscopic imaging using two perspective views of a three-dimensional object can be achieved by acquiring overlapping images at two aircraft positions. The image coordinates of a point in the scene, observed through one camera position, provide an infinite number of possible object locations along the ray from the camera focal point through the image coordinate. An image coordinate from the second camera position corresponding to the same object defines a second ray that locates the object position to a single point in space (Slama 1980). Airborne photography followed by photogrammetric interpretation of stereo-pairs to produce a DEM can give results at a variety of scales depending on the user's requirements and budget (Neill 1994). An example of the use of airborne stereophotogrammetry to produce a DEM of a narrow beach is given by Balson et al. (1996).

The major advantages are:

- High accuracy, provided reference points are available (Req. 4, 5, 11);
- Spatial data can be mapped (Req. 8, 9, 10, 14, 16);
- Large areas can be mapped synoptically (Req. 7, 15);
- Other items can be mapped as well as height (Req. 13, 14).

The major disadvantages are:

- It can be difficult to obtain reference points on flat featureless areas (Req. 1, 4);
- It can only fly in good weather and good light (Req. 2, 12);
- Near-shore zone cannot be mapped, and it is hard to obtain full tidal range over large areas (Req. 6);
- Although image matching operations may be performed automatically, considerable manual intervention is required (e.g. to identify breaklines).

Holland & Holman (1997) present an interesting experimental variation of this technique which uses trinocular stereophotogrammetry to recover foreshore topography from a set of synchronous overlapping video images. The method detects the position of the shoreline in each image (as in the waterline method below), and uses this as a feature in the stereo matching process. This overcomes the difficulty of obtaining reference points in featureless areas. A vertical accuracy of 1-3 cm has been achieved under field test conditions. The method gives a dense beach height map at low cost.

3. Airborne scanning laser altimetry

Airborne scanning laser altimetry (LiDAR) makes possible extremely rapid, dense and accurate elevation mapping (Flood & Gutelius 1997; Gutelius 1998). While there are still only a handful of LiDAR operators worldwide, the use of these systems is growing rapidly. LiDAR works by measuring the direction and time of flight of laser pulses from the aircraft to the ground and back, estimating the position of the aircraft using kinematic GPS, and measuring its roll, pitch and heading values using an inertial navigation system. A dense height map is built up by scanning the laser (with a footprint of 15-20 cm) orthogonal to the flight direction over a swath 250-700 m wide, and sampling heights every few metres. The position and height of the ground patch illuminated by the laser may be calculated to a vertical height accuracy of ca. 15 cm and a planimetric accuracy of ca. 1 m on relatively flat unvegetated surfaces such as beaches (Huising & Gomes Pereira 1998). A direct trade-off exists between sampling density and coverage. LiDAR can provide high rates of area coverage, with up to about 90 km^2/h being achievable over land. Depending on water clarity, LiDAR may also be used to map bottom topography in the Near-shore zone (Estep et al. 1994). A strongly reflected light return is recorded from the water surface followed by a weaker return from the seabed. Measurement of the time of first and last return may also be used to determine vegetation height, for example in salt-marsh areas.

The major advantages are:

- High vertical and planimetric accuracy (Req. 4, 5, 11). However, Huising & Gomes Pereira (1998) point out that, although the technology shows great promise, it is still evolving, and practical results often do not match theoretical expectations;
- Spatial data can be mapped (Req. 8, 9, 16);
- Large areas can be mapped with a high coverage rate (Req. 7, 15);
- Because a DEM can be produced within hours of the overflight, damage after a storm may be assessed rapidly (Req. 12);
- Simple to understand (Req. 17).

The major disadvantages are:

- Reasonably good weather is needed, with no cloud below the LiDAR, though night-time flying is possible (Req. 2, 12);
- Only heights are given and not associated information, although some systems fly accompanying video sensors (Req. 13, 14);
- May be difficult to obtain full tidal range over large areas and map Near-shore zone (if water turbid, as it often is in the UK.) (Req. 6).

4. Airborne interferometry

Airborne interferometry is based upon simultaneous imaging using two synthetic aperture radar (SAR) antennae mounted on the same aircraft, so that many of the coherence problems which exist for satellite based methods (see technique 7 below) can be overcome. Airborne systems such as that supplied by the Environmental Research Institute of Michigan are mounted on jet aircraft and so can survey an area very rapidly and are thus better able to monitor across the full tidal range and fly in adverse weather than the other airborne methods (Adams et al. 1996; Madsen et al. 1995). The Michigan system has been declassified and downgraded to 1-m height accuracy for commercial use by Intermap Technologies Ltd.

The major advantages are:

- Changes can be measured to a fairly high level of accuracy (Req. 11);
- Synoptic view can be obtained a over a large area (Req. 7, 15);
- Full tidal range can be covered (Req. 6);
- Spatial data can be obtained (Req. 8, 9, 16);
- Data other than heights can be obtain (Req. 13, 14).

The major disadvantages are:

- Low vertical and planimetric accuracy (Req. 4, 5);
- Mapping of near-shore zone is not possible (Req. 6).

These systems are still under development; as an example, Currie (1997) describes a high performance ESR system with a predicted vertical height accuracy of 20 cm and spatial resolution of 2 m which is currently being tested.

5. Waterline method

This method only works in the intertidal zone and effectively uses the sea as an altimeter (Collins & Madge 1981; Koopmans & Wang 1995; Mason et al. 1995; Ramsey 1995). From a remotely sensed image (usually a satellite SAR image) the position of the geo-coded waterline is determined using image processing techniques. Heights relative to mean sea level are superimposed on this waterline using the total tide plus surge water elevations predicted at the waterline by a hydrodynamic tide-surge model run for this area for the time of image acquisition with the meteorological conditions pertaining at that time. From multiple images obtained over a range of tide and surge elevations it is possible to build up a set of heighted waterlines within the intertidal zone, and from this a raster DEM may be interpolated.

The method allows the construction of an intertidal DEM over a large area of coastline (that contained in a complete satellite scene). Its height accuracy falls with increasing beach slope (Mason et al. 2000). On wide flat beaches (~ 1 : 500 slope) accuracies are about 20 cm (using about 10 images distributed uniformly through the tidal cycle), whilst on narrower steeper beaches (~ 1 : 30 slope) these rise to about 30 cm. Spatial resolution is typically 10 - 50 m.

The major advantages are:

- A synoptic view can be obtained over a very large area (Req. 7, 15). The method is particularly suitable for wide flat beaches where vertical accuracy is reasonably high and correlation lengths are long compared with its spatial resolution;
- Spatial data can be mapped (Req. 8, 9, 16);
- Can be used day or night in all weather conditions (by employing SAR images), allowing a sufficient image acquisition rate for winter and summer surveys and possibly also rapid monitoring for storm damage (Req. 2, 3, 12);
- Can be used for beaches inaccessible to aircraft;
- Can be used with the historical image archive to generate DEMs of beaches from the recent past, for change detection studies (Req. 9);
- can measure exposure time above water easily as it uses an implicit tide-surge model (Req. 13).

The major disadvantages are:

- low planimetric accuracy (Req. 5);
- only covers the intertidal area (Req. 6).

6. Bathymetry measurement by SAR imaging of wave current interaction

Traditionally, bathymetric data is obtained by means of ship-based echo sounders, which can be very time consuming and expensive. This new method uses satellite remote sensing to complement bathymetric survey in shallow coastal waters. Under favourable conditions (moderate winds and strong tidal currents) SAR imagery shows features of the bottom topography of shallow seas (Alpers & Hennings 1984; Hesselmans et al. 1996). Microwaves can penetrate water to only a few mm, so that SAR data can reflect properties of the sea surface only. Bottom topography is measurable due to the interaction between bottom, current and sea surface roughness. Computer models describing the currents, waves and electromagnetic scattering can be used to interpret the SAR images. A first guess of the topography is corrected iteratively in a hydrodynamic model until the difference between predicted and measured radar back scatter is minimal. Accuracy is improved by combining estimated heights with ship-mounted echo sounder values. A vertical height accuracy of 20 - 30 cm and a spatial position accuracy of 30 m are claimed (Anon. 1997a). Whilst the method is primarily aimed at subtidal bathymetry, an image acquired near high water (yet with sufficient tidal current as required) could enable heights in the intertidal and near-shore zones to be mapped.

The main advantages are:

- High vertical accuracy (Req. 4, 11);
- A synoptic view can be obtained over a very large area (Req. 7, 15);
- can map spatial data (Req. 8, 9, 16);
- allows winter and summer surveys and rapid monitoring for storm damage (Req. 2, 3, 12).

The main disadvantages are:

- Low planimetric accuracy (Req. 5);
- Mapping above high water not possible (Req. 6).

7. Satellite interferometry

Interferometry from current satellites depends on obtaining two SAR images close together in time, and with small difference between antenna positions during SAR image acquisition (Massonnet 1997; Henderson & Lewis 1998). The phase information is then analysed to measure heights. To obtain the full tidal range, both images would be required at the lowest tidal state. Research using interferometry for intertidal monitoring has highlighted the difficulty of obtaining coherence over sand/mud regions, as there is often loss of coherence between corresponding pixels in the two images due to different beach drying conditions and to the low radiometric response of wet sand in SAR images, implying that its use may be restricted to shingle areas (Mason et al. 1995). Assuming an interferogram can be constructed, absolute height accuracy is likely to be limited to a few metres. However, changes in height can in theory be obtained to centrimetric accuracy using differential interferometry, which requires a third image taken at a later time.

The major advantages are:

- A synoptic view can be obtained over a very large area (Req. 7, 15);
- Spatial data can be mapped (Req. 8, 9, 16);
- Changes can be monitored accurately (in theory) (Req. 11);
- Data other than heights can be obtained (Req. 13, 14).

The major disadvantages are:

- Low absolute vertical and planimetric accuracy (Req. 5);
- May be impossible to obtain heights over sand/mud (all requirements);
- Hard to cover full tidal range, cannot map Near-shore zone (Req. 6).

8. Optical satellite data

Optical satellite data (e.g. from Landsat TM or SPOT) can be used to produce a DEM by interpreting stereo-pairs (e.g. Tateishi & Akutsu 1992), and also by using the waterline method (Koopmans & Wang 1995). Alternatively, in clear conditions and using a simple transmission model it is possible to estimate Near-shore water depths from a high tide image (e.g. Bierwirth et al. 1993), though this is often unlikely to be possible in the turbid waters around the UK.

The major advantages are:

- A very large area can be covered (Req. 7,15);
- Spatial data can be mapped (Req. 8, 9, 16);
- Underwater depths can be obtained under certain conditions (Req. 6);
- Attributes other than height can be mapped (Req. 13, 14).

The major disadvantages are:

- Low vertical and planimetric accuracy (Req. 1, 4, 5, 11);
- Cloud cover limits coverage (e.g. for many UK. areas only one or two cloud-free Landsat TM scenes are available per year) (Req. 2, 3, 12);
- Orbit times make it hard to obtain full tidal range (Req. 6).

Summary evaluations

In this section the survey methods are scored against the user requirements in accordance with the discussions above. The assessments are concerned solely with technical ability, and costs are addressed in the following section. Score categories for each requirement are:
1 = not possible;
2 = improbable;
3 = possible;
4 = usually possible;
5 = easily possible.

For each method, the scores for each requirement have simply been added together. Users requirements 13-17 marked as 'desirable' rather than 'essential' have been assigned only half the weight of the other requirements in the scoring. Table 3 gives a broad indication of the suitability of each method with respect to all the requirements.

Airborne stereo emerges as the superior method because of its ability to cover relatively large areas with high accuracy and precision. Airborne LiDAR also gives good results for similar reasons. Ground survey also performs well, however the scores given relate to accuracy at measurement points rather than to the beach as a whole. When the profiles are used to interpolate a DEM for an entire beach (Mason et al. 1997) the total score drops to 66% (figures in brackets) and the ranking becomes lower than those of LiDAR and the waterline method.

It recognized that different applications will favour different requirements. A different picture emerges when user requirements for two different types of survey over two contrasting areas are considered. These are presented in Table 4. Table 4A shows those requirements that are most important for an engineering-related survey on a narrow beach such as at the New Forest coast. Requirements (7- 11) concerned with large area/long time-scale monitoring have been omitted, as have requirements (13-16). It is assumed that large scale airborne survey is flown in order to obtain the required levels of accuracy.

The advantages of ground survey in this case are clear since the requirements can be met by surveying narrow stretches of foreshore easily reachable by teams on the ground (however, its score again reduces if a DEM is interpolated from the profiles). The airborne stereo method still performs well, with its only disadvantages being the difficulty of winter survey and covering the full tidal range. LiDAR also performs strongly, partly because of its ability to monitor storm damage rapidly.

In contrast, Table 4B extracts those requirements which are most applicable to an environmental user on a large area such as Morecambe Bay. The planimetric accuracy (5) and repeat requirements (2) are omitted. It is also assumed that small scale airborne survey is used for all the airborne systems. The score for airborne stereo vertical accuracy (4) is reduced because of the difficulties of photo-interpretation over featureless areas with few reference points. For ground survey, the scores for covering the complete beach/near-shore range (6), monitoring changes over large areas (10), obtaining a synoptic view (7), mapping exposed area extent (8), monitoring over long time period (9) and mapping of minor channels (14) are reduced from those in Table 3, the general table, because of the limitations of ground survey over extended tidal flats.

Airborne stereo and LiDAR now achieve the highest scores, while the disadvantages of ground survey for

Table 3. Assessment of ability of different methods to meet user requirements.

No.	Requirement	Ground survey	Airborne stereo	Airborne LiDAR	Airborne InSAR	Water-line	Wave-current	Satellite InSAR	Optical satellite
1	Vertical and planimetric accuracy 1 cm	5 (2)	2	1	1	1	1	1	1
2	Winter & summer survey	4	3	4	4	4	4	5	2
3	Annual repeat survey	5	5	5	5	5	5	5	3
4	10 cm vertical accuracy	5 (3)	4	3	1	2	2	1	1
5	10-50 cm planimetric accuracy	5 (2)	5	3	1	1	1	1	1
6	Cover complete beach/nearshore zone	5	3	3	3	2	3	1	3
7	Synoptic view	2	4	4	4	5	3	5	5
8	Map exposed area extent	2	5	5	5	5	5	3	4
9	Monitoring over long time period	3	5	5	5	5	4	5	5
10	Monitor changes over large area	3	4	4	4	5	4	3	5
11	Changes of ~50 cm	5	5	5	2	5	5	3	1
12	Monitor storm damage	3	2	4	3	3	3	2	2
13	Exposure time*	1/2	1/2	1/2	1/2	5/2	1/2	1/2	1/2
14	Sediment type	5/2	5/2	1/2	2/2	2/2	2/2	2/2	4/2
15	Salt marsh changes	4/2	5/2	3/2	2/2	2/2	2/2	2/2	4/2
16	Map minor channels	2/2	5/2	5/2	3/2	3/2	3/2	2/2	3/2
17	Must be easy to understand	5/2	3/2	5/2	3/2	3/2	2/2	3/2	3/2
	% score	77 (66)	78	74	60	70	63	55	56
	Rank	2 (4)	1	3 (2)	6	4 (3)	5	8	7

*a tide model would be required to obtain length of exposure.

Table 4. A. Assessment for narrow beach survey. **B.** Assessment for large area environmental survey.

A. No.	Requirements	Ground survey	Airborne stereo	Airborne LiDAR	Airborne InSAR	Water-line	Wave-current	Satellite InSAR	Optical satellite
1	Vertical & planimetric accuracy 1 cm	5 (2)	2	1	1	1	1	1	1
4	10 cm vertical accuracy	5 (3)	4	3	1	2	2	1	1
5	10-50 cm planimetric accuracy	5 (2)	5	3	1	1	1	1	1
2	Winter & summer survey	4	3	4	4	4	4	5	2
3	Annual repeat survey	5	5	5	5	5	5	5	3
6	Cover full beach/near-shore zone	5	3	3	3	2	3	1	3
12	Monitor storm damage	3	2	4	3	3	3	2	2
17	Must be easy to understand	5/2	3/2	5/2	3/2	3/2	2/2	3/2	3/2
	% score	92 (71)	71	68	52	52	53	47	39
	Rank	1 (1=)	2 (1=)	3	5=	5=	4	7	8
B.									
1	1 cm vertical accuracy	5 (2)	2	1	1	1	1	1	1
4	10 cm vertical accuracy	5 (3)	3	3	1	2	2	1	1
11	Changes of ~50cms	5	5	5	2	5	5	3	1
3	Annual repeat survey	5	5	5	5	5	5	5	3
6	Cover complete beach/near-shore zone	3	3	3	3	2	3	1	3
7	Synoptic view	1	4	4	4	5	3	5	5
8	Map extent of exposed areas	1	5	5	5	5	5	3	4
9	Monitoring over long time period	3	5	5	5	5	4	5	5
10	Monitor changes over large area	2	4	4	4	5	4	3	5
12	Monitor storm damage	3	2	4	3	3	3	2	2
13	Exposure time*	1/2	1/2	1/2	1/2	5/2	1/2	1/2	1/2
14	Sediment type	5/2	5/2	1/2	2/2	2/2	2/2	2/2	4/2
15	Salt marsh changes	4/2	5/2	3/2	2/2	2/2	2/2	2/2	4/2
16	Map minor channels	1/2	5/2	5/2	3/2	3/2	3/2	2/2	3/2
17	Must be easy to understand	5/2	3/2	5/2	3/2	3/2	2/2	3/2	3/2
	% score	66 (58)	76	74	62	73	64	54	60
	Rank	4 (7)	1	2	6 (5)	3	5 (4)	8	7 (6)

this type of area are clearly apparent. The satellite–based waterline method emerges as a strong contender for survey of this type of beach.

It is recognized that this scoring system is both quite crude and qualitative. Several alternative scoring systems were tried experimentally and all gave broadly similar rankings. Hence the final ranking is considered robust, giving from best (1) to worst (8) (Table 5).

Airborne stereo clearly performs best as an overall method. Ground based methods perform best on narrow beaches, but less well on wide beaches. Airborne LiDAR gives good performance on both narrow and wide beaches. The waterline method also performs well on wide beaches, where photo-interpretation may be limited by lack of reference points over large featureless areas. Optical satellite methods and current airborne and satellite interferometry perform consistently poorly.

In any practical monitoring system more than one method could likely be used. For example, ground sur-

Table 5. Technical assessment.

	General	Narrow beach	Wide beach
Ground survey	2 (4)	1 (1=)	4 (7)
Airborne stereo	1	2 (1=)	1
Airborne LiDAR	3 (2)	3	2
Airborne InSAR	6	5=	6 (5)
Waterline method	4 (3)	5=	3
Wave-current interaction	5	4	5 (4)
Satellite InSAR	8	7	8
Optical satellite	7	8	7 (6)

vey could be used in conjunction with airborne LiDAR to improve the heighting accuracy of the latter. Such potential improvements are not considered here.

Cost comparison

The assessment of requirements should consider costs as well as technical feasibility. Full cost data are not available for all the methods, and there is understandably some reluctance amongst users to release cost information. The figures quoted here must therefore be considered only as a guide. A UK. context is assumed. Examples of possible costs are given below for a survey of Morecambe Bay (ca. 340 km^2) at as near as possible to the required vertical height accuracy of 10 cm. Costs are not assessed for satellite interferometry or optical satellite methods because of their relatively poor technical performance.

1. Ground survey

Ground survey costs assume two operators with standard survey equipment and GPS packs. Costs within the EA Anglian region were ca. £12000 for 80 transects in N. Norfolk which took about three weeks to complete (A. McClean pers. comm.). However, Lancaster City Council quote a 3-week period required to survey the ca. 10-km stretch of foreshore at Morecambe using similar equipment. Clearly, the actual time taken will depend upon tide and weather conditions, the length of transects and the actual condition of the survey area, such as the extent of dangerous or inaccessible area. However, ground survey is relatively inexpensive with an approximate cost of £ 150 per km. Additional costs would have to be added for data processing and analysis. Assuming a 1000-m separation between transects, the ground survey cost is thus about £ 150 per km^2. For a 200-m separation between transects, this would increase to £ 750 per km^2. Only for the latter separation would the average vertical error be 10 cm.

2. Airborne stereophotogrammetry

Survey costs are highly dependent on the shape of the area and the required resolution. Using Morecambe Bay as an example, in order to obtain 10 cm height accuracy, 1:3000 flying is required. Based on NRSC costings, data collection costs would be £ 35 000 (3055 exposures required), and interpretation at £ 2 000 per km^2 would be £680 000, giving a total of about £ 2 000 per km^2. The cost is clearly dominated by the expense of producing the photogrammetric heighting to the high level of accuracy required. Assuming a 1:10 000 scale flight, which would provide ca. 50 cm height accuracy, the cost would be £12 000 for flying and £500 per km^2 for interpretation, giving a total of about £500 per km^2.

3. Airborne LiDAR

LiDAR figures are based on the Environment Agency's own analysis of costs following a LiDAR test programme in December 1996 (Anon. 1997b). The EA suggest a cost of £77 - £143 per km^2 for a LiDAR owned by EA and operated by contractors, the range allowing for a contingency component. LiDAR would not quite achieve the 10-cm vertical accuracy requirement.

4. Airborne interferometry

Airborne interferometry fails to meet users' requirements regarding 10-cm height accuracy. However, its cost of £17 per km^2 is low compared with LiDAR due to the plane flying higher and covering a larger swath, and also assumes multiple data sales.

5. Waterline method

Data costs of £ 10 000 assume that 9 ERS SAR scenes and 1 RADARSAT scene are acquired distributed throughout the tidal cycle. Costs for shoreline extraction and tide-surge model setup and running are £ 12 000, resulting in a total cost of £22 000. This would result in a DEM for the whole of the intertidal area in the SAR scene (100 km × 100 km). As Morecambe Bay is easily contained within a scene, the cost to produce a DEM for the Bay would be £65 - 73 per km^2. Further details are contained in (Mason et al. 1998). As with LiDAR, the method would not quite achieve the 10-cm vertical accuracy requirement.

6. Wave-current interaction

Guide costs of about £36 600 for SAR data acquisition and processing and about £41 000 for field survey are quoted for survey of an area of 300 km^2 (Anon. 1997a), giving a cost per km^2 of ca. £260. Again, the method would not achieve the 10-cm vertical accuracy requirement.

Fig. 1 illustrates the costs of the various methods set against the achievable vertical accuracy. Ground survey errors are average errors of DEMs interpolated from 1000 m- and 200 m-separation transects respectively

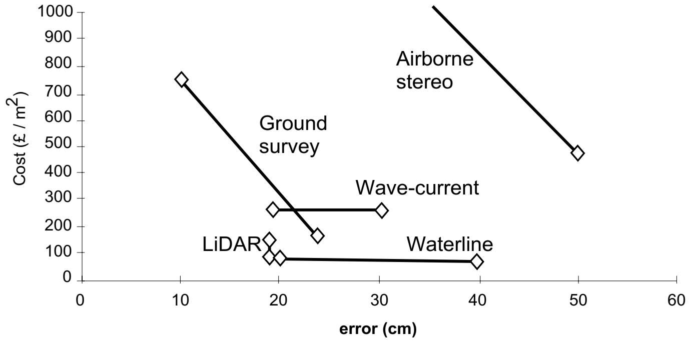

Fig. 1. Cost vs. vertical error for various methods of DEM productions.

(Mason et al. 1997). LiDAR errors (19 cm) are from EA's analysis of test data from Wrangle Flats, western Wash (Anon. 1997b). Airborne stereo errors are from NRSC. Waterline errors are 20 - 40 cm (Mason et al. 1998). Airborne interferometry errors (1 m) are off the scale.

Conclusions

In the selection of any survey method a trade-off has to be made between technical performance and cost. Table 6 ranks the specified methods for cost using data from the previous section, and repeats the technical rankings from Table 5 (satellite interferometry and optical satellite methods are not included because of their relatively poor technical performance). The rank in brackets again relates to performance of ground survey for an entire beach.

The actual selection of a method by a particular user will inevitably depend upon individual circumstances and preferences and the weights attached to the requirements; therefore these rankings have not been combined into a single assessment. For example, Fig. 1 shows that all the methods except airborne interferometry are able to achieve a vertical accuracy of 20 cm, so that if this level of accuracy (together with other technical specifications) is acceptable, airborne LiDAR and the waterline method are the cheapest options. However, if vertical accuracy of better than 20 cm is required, then either ground survey or large scale airborne stereophotogrammetry must be used.

Table 6. Costs and performance of DEM production by method.

Method	Cost	Technical Performance Ranking		
	ranking	General	Narrow beach	Wide beach
Ground survey	4 (5)	2 (4)	1 (1=)	4 (6)
Airborne stereo	6	1	2 (1=)	1
Airborne LiDAR	3	3 (2)	3	2
Airborne InSAR	1	6	5=	6 (5)
Waterline method	2	4 (3)	5=	3
Wave-current interaction	5 (4)	5	4	5 (4)

In an interesting reflection of a trend displayed by many other types of product, the method which is the best overall technically (airborne stereo) is also the most expensive, whilst the method which is currently the poorest technically (airborne InSAR) is also the cheapest. Ground survey provides very good technical performance on narrower beaches at moderate cost. However, airborne LiDAR can achieve good performance on both narrow and wide beaches, and at a lower cost. Costs for the waterline method are slightly lower still, with satisfactory performance on wide beaches. An overall conclusion is that, while the tradional methods of ground survey and airborne stereophotogrammetry remain the best for engineering-related surveys requiring high levels of accuracy, airborne LiDAR in particular looks set to have a significant impact on beach survey for applications for which a vertical accuracy of 20 cm is acceptable, provided that its technology evolves satisfactorily.

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