3D Imaging of the Environment

Mapping and Monitoring

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Development of a Toolkit for the 3D Documentation and Analysis of the Marine and Coastal Historic Environment

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INTRODUCTION

CHERISH is a EU-funded Ireland-Wales project that aims to raise awareness and the understanding of the past, present, and near-future impacts of climate change on the rich cultural heritage of the Irish and Welsh regional seas and coast. The project began in January 2017 and will run until June 2023 and will benefit from €4.9 million of EU funds through the Ireland Wales Co-operation Programme 2014–2020.

The project is targeting work in several studies, 5 areas of Ireland from Co. Meath on the east coast to Co. Kerry on the west coast, and 13 areas in Wales covering Anglesey, Gwynedd, Ceredigion, and Pembrokeshire (Figure 9.1). These study areas encompass both individual sites and wider landscapes, from promontory forts and shipwrecks through to islands and dune systems, including a range of environments from marine inshore waters into the intertidal zone and onto the coast edge.

PHILOSOPHY OF THE TOOLKIT

During project planning, it was realised that a complementary range of approaches and methods used across research domains that include archaeology, geography, and geology was required to better understand, record, and monitor the coastal and marine historic environment. Following input from all project partners and external agencies, the CHERISH toolkit was developed to provide an integrated approach to coastal and marine recording (see Figure 9.2). Several factors influenced the selection of appropriate methods. This chapter explores some of the methods employed to digitally document the coastal and marine historic environment in 3D. Other

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FIGURE 9.1 Illustration identifying the 5 Irish and 13 Welsh study areas within the CHERISH Project and some of the selected sites where the toolkit is being employed.

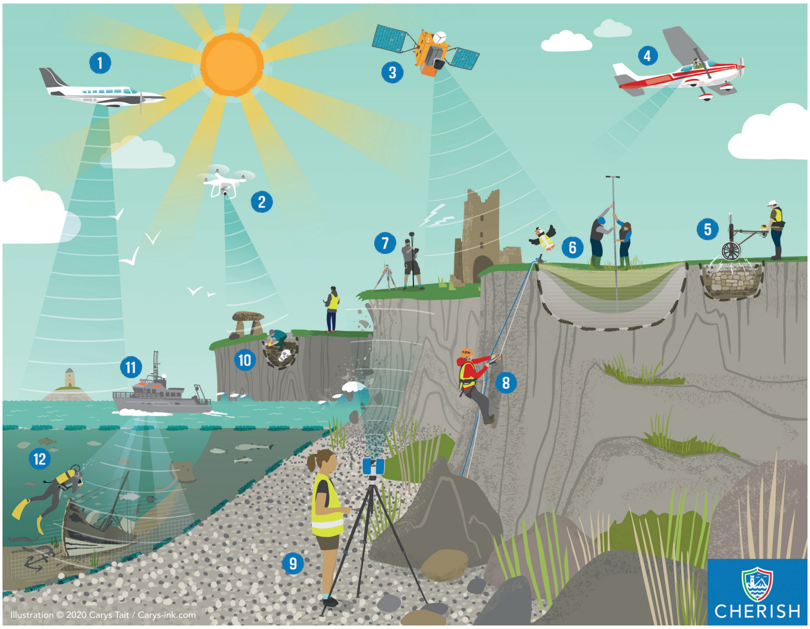

FIGURE 9.2 Illustration of the different survey approaches employed by CHERISH to record the coastal and marine environment 1. Airborne laser scanning (ALS), 2. Unmanned aerial vehicle (UAV or drone) survey 3. Satellite mapping, 4. Aerial survey, 5. Geophysical survey, 6. Coring, 7. Precision survey, 8. Erosion monitoring, 9. Terrestrial laser scanning, 10. Excavation, sampling, and dating, 11. Marine mapping, 12. Underwater archaeological survey.

components employed in this research such as peat coring and sampling are not covered in detail here.

Working in a Dynamic Environment

Effective and accurate surveying and recording in the marine and coastal environment can be difficult due to the practicalities of access, tides, and the exposed environment (Kotilainen and Kaskela 2017). The nearshore marine and coastal environment are often referred to as the 'white ribbon' (Leon et al. 2013) due to the highly dynamic environment between high and low water, creating challenges for the efficient collection and integration of elevation data (Driver and Hunt 2018). Using a combination of methods and techniques, the CHERISH toolkit approach enables this zone to be effectively recorded. Remote aerial technologies such as ALS and UAV surveying allow accurate recording with reduced risk to the surveyors. It can be more challenging to effectively record wrecks and other structures beneath the sea. Selecting methods that can be safe and relatively easily applied underwater and on the surface increases the opportunities for successful data collection—these include remotely operated underwater vehicles (ROVs) and multi-beam bathymetry.

Scale, Accuracy, Resolution, and Efficiency

When selecting relevant geomatic techniques, the ability to identify, detect, and monitor change in cultural and environmental features must be considered (Guisado-Pintado et al. 2019). The scale and nature of cultural features and coastal change which may occur will influence which technique is appropriate (Boehler et al. 2001) (Figure 9.3). The ability to record high-resolution and accurate data must also be offset against the efficiency of the proposed method and the overall size of the survey area. Employing an approach such as terrestrial laser scanning (TLS) may produce the most accurate method of recording a coastline. However, the time and cost required to employ such a method on a regional scale would be prohibitively expensive. In addition, when selecting appropriate methods, consideration must be given to the temporal resolution which can be achieved with the chosen method, particularly with respect to the frequency of repeat survey and the relative ease and costs.

Data Integration, Presentation, and Reuse

In the collection of 3D data for the marine and coastal environment, techniques have been selected which offer the best integration of data sets into several methodological processes which enable the maximum amount of research return from their collection. Standardised data outputs such as point clouds, digital elevation models (DEMs), and orthoimagery can be utilised with geoprocessing analysis to inform experts on a range of features and change detections, including the identification of new archaeological sites to the monitoring of erosion of submerged wrecks. This data can also be repurposed into highly informative and engaging visualisations to enable experts to advise and educate wider non-scientific stakeholders about the

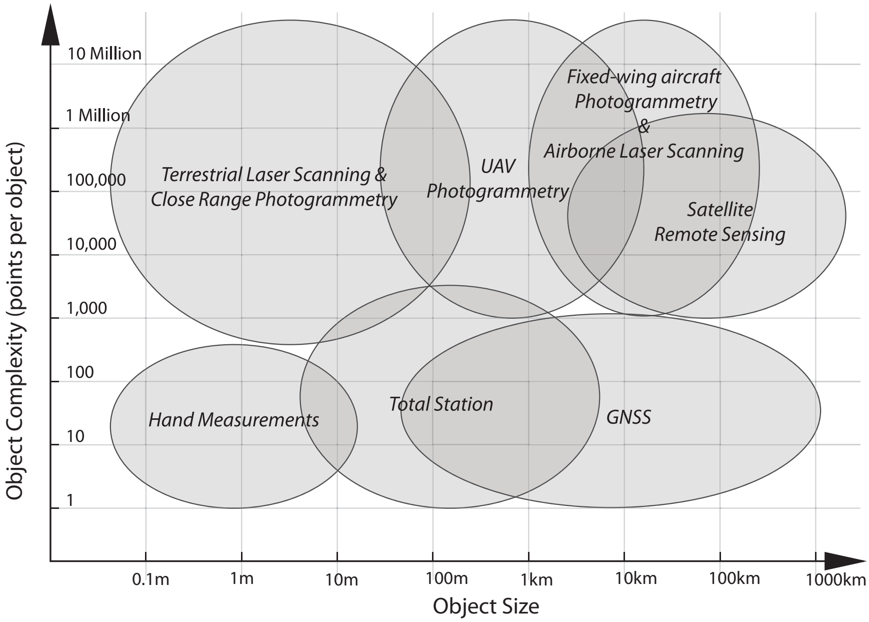

FIGURE 9.3 Illustration of the relationship between appropriate survey techniques for the scale of objects and the relative complexity of recording (after Boehler 2001).

challenges faced in mitigating and managing the effects of climate change on coastal and historic marine environments.

TERRESTRIAL MAPPING AND MONITORING OF COASTAL SITES AND LANDSCAPES

Establishing Monitoring Networks—Using Global Navigation Satellite Systems (GNSS) in the Coastal Zone

At the heart of any recording/monitoring project is the need to collect highly accurate and precise measurements. Using Global Navigation Satellite Systems (GNSS) to establish survey networks allows for the successful integration and comparison of 3D data sets (Figure 9.4). This is particularly important when working in the coastal zone (Figure 9.5) where it is traditionally difficult to identify stable permanent survey reference points to monitor coastal change and where there can be insufficient cellular internet coverage for real-time measurement corrections. To address these challenges both post-processed kinematic (PPK) and real-time kinematic (RTK) methods were used to establish networks. This combination of methods provided a robust and versatile approach to using GNSS at the coast, ensuring each site was recorded to the same level of detail regardless of the method used (RICS 2010).

To ensure that any future, post-CHERISH surveys used to identify change are aligned with data captured during the project, permanent survey markers were also established at several priority sites using GNSS.

FIGURE 9.4 Member of the CHERISH team carrying out a RTK GNSS survey of the eroding coastline of Bardsey Island, Gwynedd.

UPSTANDING HISTORIC STRUCTURES—TERRESTRIAL LASER SCANNING (TLS)

Terrestrial laser scanning (TLS) was developed towards the end of the 20th century, largely to conduct as-built surveys of complicated industrial complexes (Ebrahim 2014). However, the potential value in 3D documentation of archaeology and built heritage was soon apparent. Terrestrial laser scanners are contact-free, non-destructive measuring devices that record objects in the form of hyper-dense data sets of individual measurements commonly referred to as point clouds. Each of these points is assigned x,y,z coordinates, a reflectance/intensity value, and, after processing, an RGB value. Complete structures are captured by combining scans from multiple locations, registered (joined together to form one data set) by using common targets in individual scans, or, increasingly, as manufacturer's software becomes more sophisticated, by automatic cloud-to-cloud–based registration.

There are several applications where monitoring heritage sites in the coastal environment by TLS presents significant advantages. Being highly accurate (~2 mm) and if selected, high-density point clouds (<5 mm spacing) can represent structures in detail (Figure 9.6), documenting their complex geometries and creating a time-stamped record. The value of such data is immense: documentation at this resolution highlights the irregularities associated with most historic structures and can offer the potential to unravel construction phasing for researchers. Further detailed analysis of the point cloud can contribute to conservation. Crack lines or slumping may be detected, and through cloud comparison of repeat surveys, even minor changes can be detected

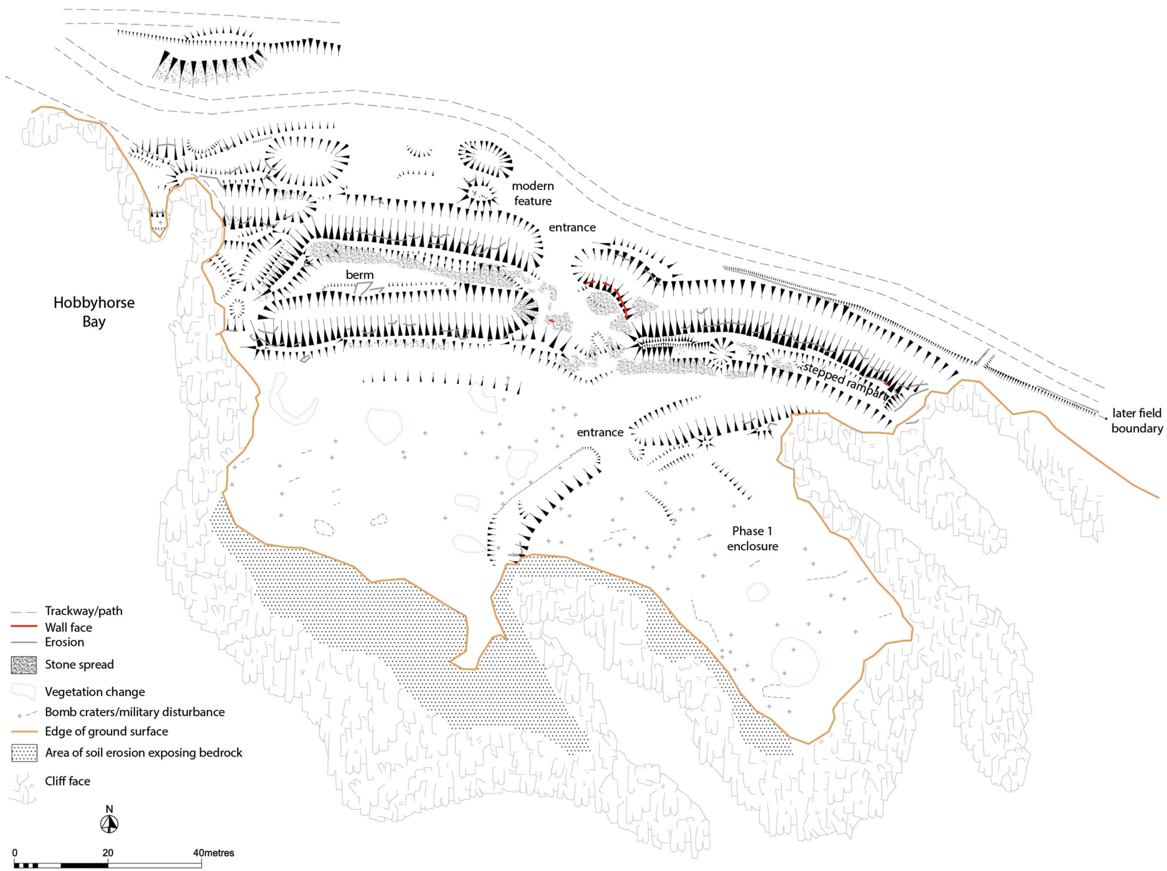

FIGURE 9.5 Archaeological plan generated from GNSS survey of Linney Head Promontory Fort, Pembrokeshire.

FIGURE 9.6 TLS-derived 3D point cloud of McCarthy's Castle, Ballinskelligs, Co. Kerry.

(Meneely 2009). Being a remote sensing technique, hazardous, often inaccessible structures can be surveyed from a safe location.

Although the technique is firmly embedded in the toolbox of 3D documentation methods, it does have limitations and present challenges. No 3D laser scan survey is ever 100% complete; data gaps due to laser shadow effects are often significant and can compromise the value of the survey (Grussenmeyer et al. 2008). An example would be the tops of walls or roof detail which cannot be seen from a ground station set up of the scanner. Solutions exist through integration of UAV-generated survey data (Xu et al. 2014), but this requires additional equipment and expertise. Planning the survey to minimise the impact of these gaps is a considerable challenge for the surveyor. Georeferencing 3D point clouds significantly enhances their value, particularly in the context of baseline surveys against which future change can be measured. This can be achieved using GNSS surveying of targets, with fixed permanent markers established as an additional valuable resource (Sairuamyat et al. 2020). Interaction and interrogation of 3D point clouds remains a significant challenge. A level of experience and expertise is required to use 3D viewing software or 3D interfaces, and consequently, users are often more comfortable with conventional outputs such as plans and sections.

As part of the CHERISH project, georeferenced 3D point cloud data sets have been established by TLS for 14 sites of archaeological or cultural heritage significance (Figure 9.7). These data sets are archived with the appropriate metadata to ensure they fulfil the function of a baseline survey against which future change may be detected.

FIGURE 9.7 Operation of phased-based TLS in the field by CHERISH staff recording an eroding cliff face.

3D point clouds may be further processed into 3D textured surface models for re-use in public engagement or educational resources. They provide rich research resources for future understanding and are an important management and conservation resource for future management of the site.

Coastal Recording—Mobile Laser Scanning (MLS)

Terrestrial mobile laser scanning (MLS) is achieved by mounting an ALS sensor(s) on a vehicle (Barber et al. 2008), boat (Vaaja et al. 2011), or backpack (Sayama et al. 2019). Techniques have developed over the last two decades (Kukko et al. 2012), and MLS has become widely applied for acquiring high-resolution 3D topographic data in urban (Susaki and Kubota 2017), natural (Vaaja et al. 2011), and coastal environments (Barber and Mills 2007), with systems capable of measuring up to 106 points per second. MLS systems rely on the integration of an inertial measurement unit (IMU) with GNSS to directly obtain georeferenced point clouds that can rapidly acquire large, cost-effective 3D point clouds over extensive areas. Positional accuracy of scan data can range from 14 cm for backpack units (Sayama et al. 2019) to 2–3 cm for vehicle-mounted systems (Barber et al. 2008; Guan et al. 2016), rising to 8 cm for longer-range systems (Di Stefano et al. 2020). Scanning data can be complemented by synchronous camera images.

The overall accuracy of the georeferenced point cloud is generally determined by the accuracy of the navigation GNSS component systems, which work better in open areas with unobstructed views of satellite constellations (Guan et al. 2016). Systems are best deployed over relatively small areas, where it is not cost-effective to deploy airborne ALS, or complex, corridor environments, where multiple viewpoints are required to record the scene accurately (e.g., beach surface, profile, and lower cliffs). Due to the rapid deployment capabilities, systems operate well in environments where data collection is time-limited (e.g., intertidal/coastal areas) or when a high temporal resolution is required. Due to the nature of laser returns, vegetation classification can be more complex than for airborne systems (Lim and Suter 2009; Susaki and Kubota 2017).

Within the CHERISH project, a Trimble MX2 dual-head MLS system was utilised in North County Dublin on a Polaris Ranger ATV. Beach profiles and eroding sand dunes at several sites have been recorded.

AIRBORNE MAPPING AND MONITORING COASTAL SITES AND LANDSCAPES

Unmanned Aerial Vehicle (UAV) Photogrammetric Survey

Unmanned aerial vehicle (UAV) platforms are a valuable source of image data that can be used in the recording of the historic environment, both in the production of 3D data through post-processing of the imagery and in providing an accessible means of capturing aerial imagery of sites and landscapes. A combination of ‘structure from motion’ (SfM) photogrammetry for environmental monitoring (Westoby et al. 2012) and recent technological advances have made off-the-shelf UAVs a viable low-cost alternative to airborne survey methodologies (Colomina and Parc Mediterrani de la Tecnologia 2008; Eisenbeiß 2009; Shahbazi et al. 2014), making them more accessible to conservation and environmental researchers and managers (Coveney and Roberts 2017). An image-based UAV survey delivering centimetre-level resolution requires mission planning, ground control points (or checkpoints), image acquisition, camera calibration, image orientations, and post-processing software for 3D information extraction (Remondino et al. 2011). UAVs have been fundamental in the successful capture of detailed 3D data for the CHERISH Project, where they have been used to good effect to navigate the countless challenges encountered in the coastal zone.

Two types of UAV are used by CHERISH: multi-rotor and fixed-wing. Utilising both types has allowed the project to maximise flexibility in the resolution and speed of data capture across many project areas. The rationale for a UAV survey on the project was as follows:

- To capture high-resolution, highly precise, and accurate geolocated 3D baseline data sets for threatened coastal sites and landscapes
- To conduct repeat monitoring surveys over the course of the project
- To capture 3D data for analysis and interpretation of upstanding archaeological remains
- To provide 3D data to be used for public outreach products such as physical and digital models and animations

The applications for both UAVs types for this project are outlined next:

FIGURE 9.8 A selection of some of the fixed-wing and multicopter UAVs employed by the CHERISH project.

Multicopter UAV Surveys

Recent developments in reliable and user-friendly multicopter platforms (Figure 9.8) have led to an exponential rise in their use by the surveying and archaeological communities (Gonçalves and Henriques 2017). Broadly speaking, multicopters are best suited for surveying small-scale sites and landscapes due to their manoeuvrability and capacity to carry powerful sensors. There is, however, a trade-off between these benefits and the amount of time they are able to stay in the air; the heavier the payload, the shorter the airtime (Boon et al. 2017). Increasing the size of the UAV (and, thus, its battery capacity) can, to a degree, redress this balance; however, this makes transport of equipment increasingly difficult, especially when surveying in remote coastal locations.

Multicopter systems were largely employed by the project as a rapid and safe means of surveying archaeological sites situated within a diverse range of coastal landscapes (Figure 9.9). With each type of coastal environment comes different challenges, such as precipitous cliffs, inaccessible caves, coastal stacks, and changing tides. The flexibility of multicopter platforms was ideal for accessing challenging coastal environments, particularly in Pembrokeshire, County Kerry, County Waterford, and County Wexford, where more traditional terrestrial survey methods were unsuitable.

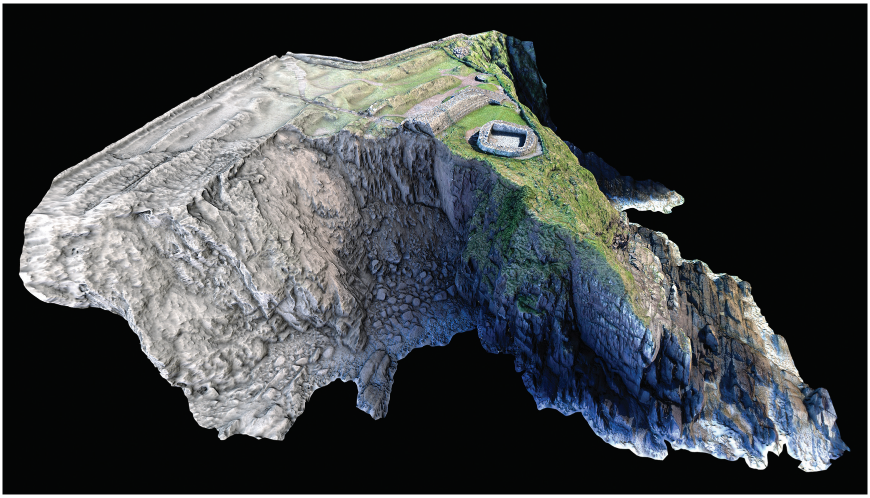

FIGURE 9.9 Mulicopter UAV derived SfM 3D model of Dunbeg Promontory Fort, County Kerry. Left of image displays underlying geometric details, whilst the right of the image displays the photogrammetric orthoimagery texture.

FIXED-WING UAV SURVEY

Fixed-wing UAVs capable of photogrammetric data acquisition can operate in manual, semi-autonomous, and autonomous modes. UAV systems are capable of rapidly delivering high resolution spatial and temporal images for ecological, topographical, geomorphological, vegetation, and erosion applications (Boon et al. 2017; Colomina and Molina 2014; Coveney and Roberts 2017).

Fixed-wing UAVs generally have longer flight endurance (>40 min) and faster flight speeds >15 m/s, resulting in increased ground coverage acquisition per unit of time in air, so they are better applied for surveying large areas (Boon et al. 2017). However, they generally take a lighter payload, have less stable image capturing (resulting in lower data precision), and have increased requirements for takeoff and landing, including a suitable area without obstacles to land without damage (Boon et al. 2017). The outputs from fixed-wing UAV surveys are similar to multi-rotor UAVs, including digital elevation models, orthophotos, contour lines, 3D models, and vector data (Figure 9.10).

Airborne Laser Scanning (ALS)

Since its adoption as a survey technique during the 1990s, airborne laser scanning (ALS) has transformed into a rapid and cost-effective way of collecting high-resolution 3D data of landscapes (Historic England 2018). ALS survey was identified by the CHERISH Project as an effective way of collecting high-resolution surveys of large coastal landscapes that lacked any pre-existing 3D data sets. The rationale for ALS data capture by CHERISH was threefold:

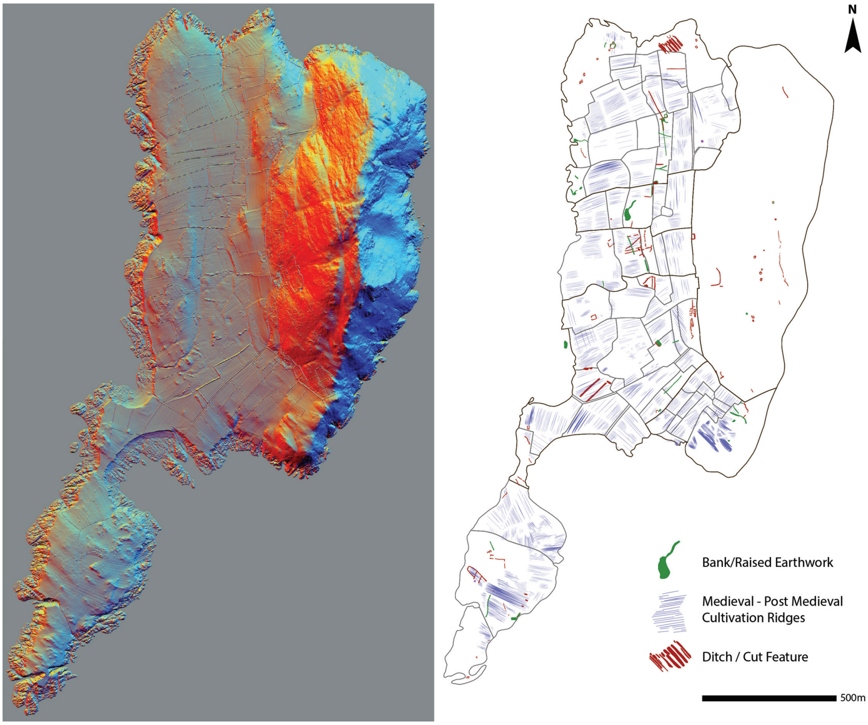

FIGURE 9.10 Fixed-wing UAV survey of Ballinskelligs Bay, Co Kerry, conducted over three days in 2019 covering about 8 km of coastline. Inset of Horse Island at the SW end of the Bay.

- To capture high-resolution 3D baseline data sets for coastal landscapes that lacked any pre-existing 3D data for future coastal erosion monitoring (e.g., six Welsh islands and a section of Dublin's coastline)
- To produce comprehensive archaeological mapping for all upstanding archaeological remains visible within the surveyed landscapes
- To provide data suitable for integration with marine bathymetric data to produce seamless 3D data linking terrestrial and submerged marine landscapes

ALS has been used to good effect by CHERISH in a wide variety of geomorphological and archaeological applications (Driver and Hunt 2018). Its main advantages come with the mapping of human-made, natural features in hillslope, fluvial, glacial, and coastal environments. Its high spatial resolution data over extensive spatial scales (Dong and Qi 2017) allow for subtle topographic features (e.g., archaeological earthworks, river paleochannels, and river terraces) to be identified and mapped more easily, more quickly, and at a lower cost than via traditional field survey methods. Although ground-truthing is still essential (Historic England 2018), ALS also allows for the mapping of remote or inaccessible areas to be undertaken for the production of base maps during desk surveys and for the identification of sites for more targeted, detailed field investigation (Jones et al. 2007). Repeat ALS surveys also allow for temporal change detection (Okyay et al. 2019). For CHERISH, this was fundamental in mapping coastal change and erosion in the dynamic coastal landscapes of both nations, where events such as mass movement and sand dune dynamics were identified.

For each site, an ALS survey was conducted and a series of visualisations that highlight different properties in the data were created based on the raw point data. For this work, visualisations were created using the relief visualisation toolbox (RVT) (Kokalj and Hesse 2017; Kokalj and Somrak 2019). The following visualisations were created for analysis and transcription:

- 16 band multi-directional hillshade
- Slope
- Simple local relief model
- Sky-view factor
- Local dominance

Utilising a range of visualisations aided in providing the best feature interpretation prior to ground-truthing. Each visualisation was imported into a GIS where they could be overlain and manipulated for interpretations and transcription. Using these methods, comprehensive maps of upstanding remains were produced, allowing features to be identified for more in-depth investigation. Figure 9.11 is an example of ALS data and the subsequent transcription of features for Bardsey Island, Gwynedd.

The collection and archiving of 3D ALS data is also important for future monitoring of erosion to coastal heritage. Whilst the resolution of the data (typically between 0.25 m—2 m) does not compare with the much higher resolutions offered by other

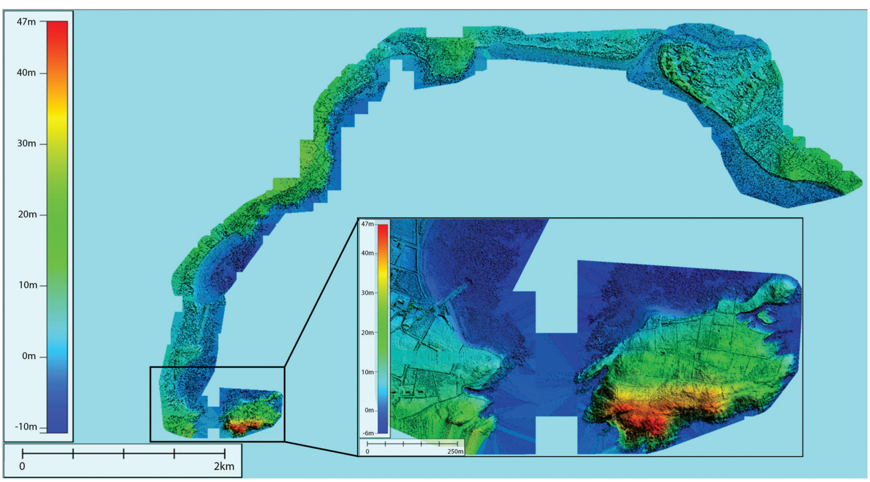

FIGURE 9.11 Multi-Hillshade visualisation of Bardsey Island generated from ALS. Digital transcription of archaeological features visible on the ALS on Bardsey Island, Gwynedd.

methods, such as terrestrial laser scanning or UAV photogrammetry, ALS data sets can be replicated remotely, rapidly, and on a landscape-wide scale. The changes detected through comparison of temporal ALS data sets will only ever be as good as the resolution of the collected data and the accuracy and precision of the GNSS correction data.

MARINE MAPPING AND MONITORING COASTAL SITES AND LANDSCAPES

Marine Geophysics—Multibeam Echosounder Systems (MBES)

Over the last three decades, multibeam echosounder systems (MBES) have become established as the principal means to map large areas of the seafloor for geological, geomorphological, biological, and archaeological purposes (Brown and Blondel 2009; Craven et al. 2021; Kostylev et al. 2001; Quinn and Boland 2010; Westley et al. 2011). Their use has become widespread for coastal and continental shelf investigations due to the simultaneous and continuous collection of both high-resolution bathymetry and backscatter data. This allows site or regional maps to be compiled on which to base more detailed investigations.

Acoustic seabed surveying projects sound energy into the water at a known time and discern the echo from the sediment-water interface. The speed of sound through the water column is used to derive the distance to the reflecting body. MBES transmit multiple acoustic beams (up to >200 depending on system) beneath the vessel in a swath. This allows simultaneous 2D measurements at adjacent beam footprints across the swath width; up to 20 times water depth. As the vessel moves forward, these 2D soundings combine to form a continuous 3D coverage of the seabed. Additionally, measurements of the variation in acoustic backscatter strength provides information on the seabed type (e.g., bedrock gives a stronger backscatter signal than mud).

MBES systems provide cost-effective, continuous acoustic coverage of the seafloor in a range of water depths (from m to km depths), with data coverage and resolution superseding other conventional acoustic survey systems (e.g., side-scan sonar) as a mapping tool (Brown and Blondel 2009). Two factors control the MBES potential bathymetric target resolution capability: distance between soundings and the size of the nadir footprint. Decreasing these results in higher resolution capability (Kenny et al. 2003). However, MBES are relatively expensive compared to other survey techniques (survey-grade systems start about €60k), and due to the large volume of data generated, significant processing of the data is required, with cleaning by experienced personnel to reduce noise (O’Toole et al. 2020). Sonar performance is limited during data acquisition by weather conditions, vessel speed, beam setup, ping period, and sequence, while sources of depth error include sensor configuration, calibration, sound velocity measurements, and tidal corrections that must be identified and minimised (Hughes Clarke et al. 1996). Surveying in shallow water has increased limitations to deeper water due to the increased risk of navigational hazards, decreased swath width, and increased density of depth soundings. This results in the difficult to map ‘white

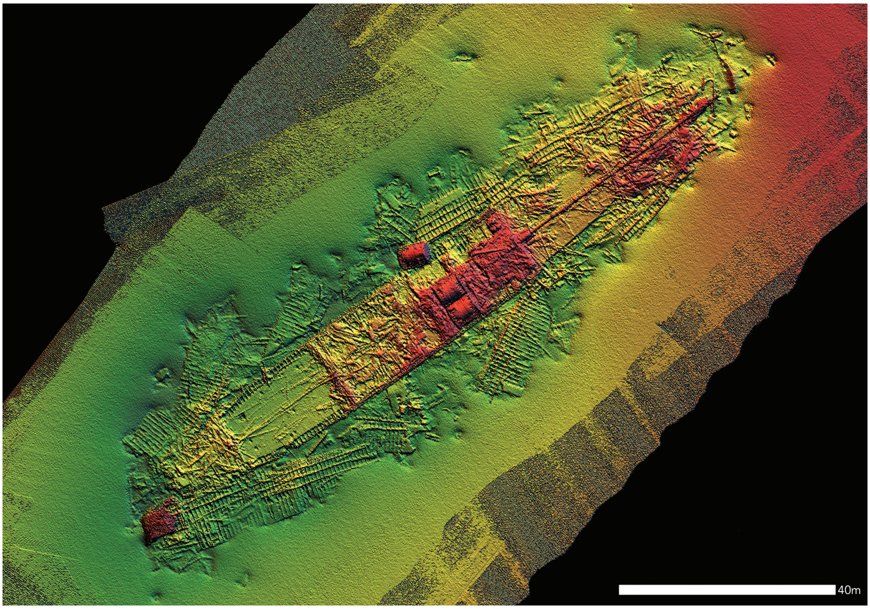

FIGURE 9.12 Multibeam survey of the Manchester Merchant wreck site, Co Kerry, from 2019.

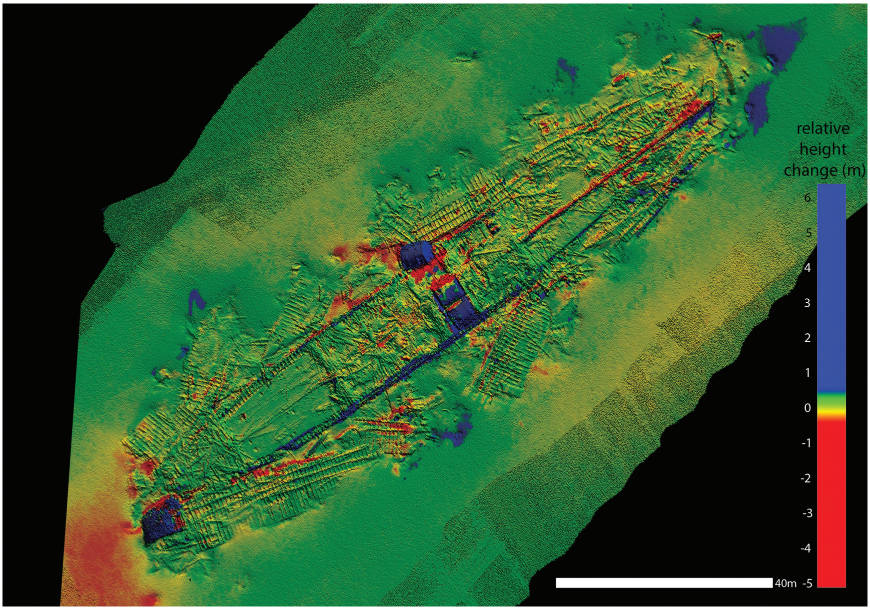

FIGURE 9.13 Analysis of change between the two MBES surveys carried out on the Manchester Merchant wreck site, between 2009 and 2019: erosion in the southwest end of wreck, deposition in the northeast, with degradation of the superstructure including boilers; (prevailing weather is from the southwest. Elevation change scale is from –5.2 m (red) to +6.3 m (blue)).

ribbon' surrounding coastlines, requiring multiple survey methodologies to map (See Seamless Data section).

MBES bathymetric surveying has been deployed by CHERISH in both Ireland and Wales to establish baseline conditions and assess change (Figures 9.12 and 9.13). Target areas have focussed on unmapped shallow marine environments adjacent to sites of cultural significance. Baseline data from some of these sites have been merged with ALS and photogrammetric data to produce seamless coastal maps. Maps of slope, roughness, and relative bathymetry have been produced to provide further contextual information on the seafloor with backscatter data being used to inform submerged sediment type and distribution. Repeat surveys at selected shipwreck sites are assessing ongoing change.

Remotely Operated Vehicle (ROV) and Diver-Derived Marine Photogrammetry

The introduction of underwater photogrammetric mapping to the marine environment occurred in the early 1960s, developed by leading practitioners including George Bass and Ole Jacobi at the Institute of Photogrammetry and Topography of Karlsruhe University (Whittlesey 1974; Bass 1966). Similarly to UAV survey, the use of SfM in marine archaeological recording has been accelerated by continual camera development and improvement in image quality, positioning systems, and processing software (Remondino et al. 2011; Nex and Remondino 2014). These advances have enabled multi-image photogrammetry of submerged cultural heritage to become commonplace in underwater archaeological investigations, utilising both divers and ROVs for image capture (Waldus et al. 2019; Nornes et al. 2015; Beltrame and Costa 2018; McCarthy and Benjamin 2014; Henderson et al. 2013; Demesticha et al. 2014). To provide local 3D SfM models within a geographical coordinate system, recent studies (Kan et al. 2018) have investigated the use of incorporating precise control points from multibeam echosounder data sets. The CHERISH project captures SfM data through both diver and ROV platforms, with resultant models overlain onto the MBES data set, producing high-resolution and accurate visualisations of underwater cultural heritage sites, which are largely inaccessible to the public.

Marine SfM enables larger areas to be mapped at a high resolution and accuracy in a much shorter timespan than traditional underwater archaeological recording and surveying techniques. Photogrammetric surveys can complement other remote survey such as MBES. Underwater SfM also informs the current condition of the wreck site, its wider environment, and site formation processes while also acting as a tool to monitor sites and rates of change over time. This data capture provides an extensive resource; with the adaption of a more analytical and critical approach to 3D data, it goes far beyond simple measurement and the generation of 2D plans, profiles, and cross-sections. It informs not just individual structures but also their context and environs (Campana 2017). The products from marine photogrammetric surveys include orthoimages, digital surface models, 3D visualisations, and the extraction of metric information. Creating accurate maps and visualising underwater sites is important for the future preservation, long-term study, and use of underwater archaeological sites (Kan et al. 2018).

Satellite-Derived Bathymetry

Marine acoustic surveys using surface vessels enable high-resolution bathymetric data acquisition (O'Toole et al. 2020; Westley et al. 2011). However, these survey methods are costly, time-consuming, and restricted by coastal morphology, navigation hazards, or protected areas. While airborne ALS surveys provide spatial continuity, hardware and operational costs, coupled with logistical requirements, can reduce the frequency of repeat survey. As such, earth observation (EO) has been increasingly used as an alternative to traditional bathymetric survey techniques (Brando et al. 2009; Monteys et al. 2015).

Satellite-derived bathymetry (SDB) from optical satellite images relies on deriving depth data from shallow water environments where light penetrates the water column and from the rate of spectral light attenuation through water. SDB can be divided into two main approaches: empirical and physics-based model inversion. Empirical approaches rely on known bathymetry data points to estimate unknown depths through statistical regression of light attenuation (Lyons et al. 2011; Stumpf et al. 2003), while physics-based methods more tightly constrain unknown depths and attempt to derive them at each pixel in the image, based on water column and bottom substrate reflectance (Dekker et al. 2011; Hedley et al. 2016).

Due to the systematic collection of satellite images over the past decades, extensive image databases exist that can be analysed to provide temporal and spatial continuity, facilitating large areas to be assessed and time series changes to be identified (Hedley 2018).

However, seabed type and conditions of both the water column and atmosphere impact SDB, with this method operating best in calm, shallow, sandy, low turbidity environments with an absence of cloud cover (Hedley 2018; Lyons et al. 2011). Due to fluctuating coastal variables, case-specific modelling techniques for coastlines are required. Therefore, while bathymetry can be modelled over large areas, validation of data is an essential requirement to ensure the accuracy of results.

For CHERISH, suitable optical images were selected from sites around Ireland. Sentinel-2 images were downloaded from the Copernicus Scientific Data Hub website as Level-1C, top-of-atmosphere (TOA) reflectance in 100 km x 100 km tile format. Three 10 m spatial resolution bands were considered (B2–B4) and images were corrected for atmospheric and sunlight effect. Satellite-derived bathymetry was derived using a model inversion method (Casal et al. 2020).

DATA INTEGRATION AND ANALYSIS

Seamless Data

Coastal sites occur at the transition between terrestrial and marine environments and are affected by processes that occur in both these environments (e.g., fluvial, waves, tidal). Understanding environmental change occurring at coastal sites, therefore, requires accurate integration of both terrestrial and submerged elevation data sets. However, while a key process for mapping, modelling, and forecasting the climate-driven changes to geomorphic processes and environmental responses, these integrated products are difficult to produce due to surveying challenges (and costs) in the shallow water zone (Jiang et al. 2004; Leon et al. 2013; Li et al. 2001; Prampolini et al. 2020).

The 'white ribbon' refers to the dynamic coastal nearshore area at the transition between terrestrial and marine environments, where accurate elevation data is challenging to acquire. A combination of satellite, UAV, terrestrial laser scanning, and acoustic remote sensing technologies can provide data for seamless coastal terrain models (CTMs). However, technical issues, including differences in resolution, precision, and accuracy, can make data integration difficult.

In the CHERISH project, CTMs were produced using data acquired with multiple remote sensing methods deployed through the project. Marine surveying at key coastal sites coincided with high tides to extend bathymetry into shallow water, while UAV photogrammetry surveying and/or aerial ALS data was conducted at times of low water. Data was gridded to a common resolution and vertical elevation datum and merged using a geographic information systems (GIS) software package to produce seamless onshore/offshore CTMs (Figure 9.14).

At other localities, satellite-derived bathymetry, extending to 8 m water depth, was generated from suitable satellite images (cloud and turbidity free at times of high water) and validated using up-to-date bathymetry data. This satellite-derived

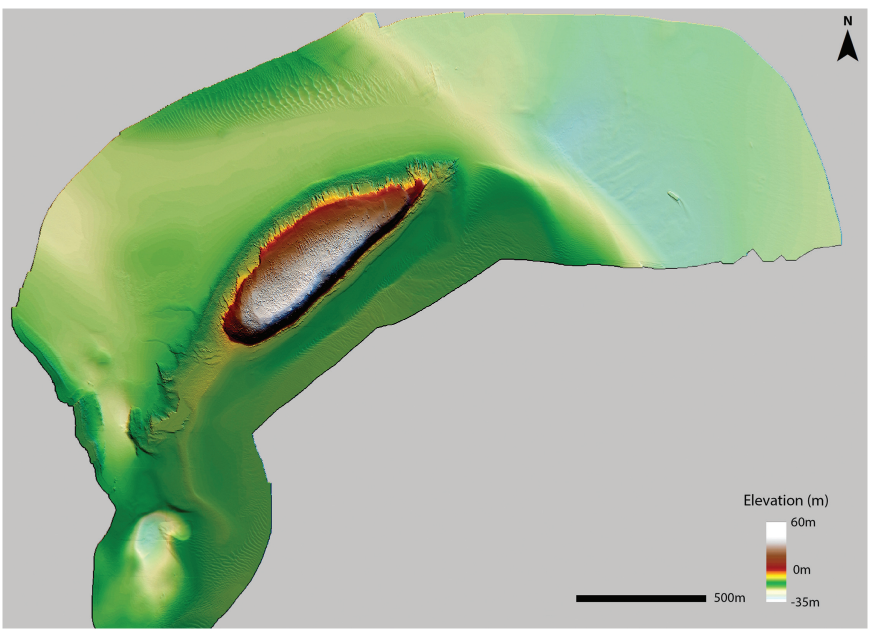

FIGURE 9.14 Seamless integration of ALS- and MBES-derived elevation models from Puffin Island, North Wales.

bathymetry was merged with terrestrial topographic and marine acoustic bathymetric data to create seamless maps.

Change Detection

Coastal sites are under constant geomorphological evolution, with seasonal and tidal changes continually altering these habitats. Climate change is expected to increase

FIGURE 9.15 'DEM of Difference' (DoD) analysis for UAV-derived DEM between 2018 and 2019 at Glascarrig Motte and Bailey site on the County Wexford coastline.

the number and frequency of droughts, storms, and heavy precipitation along with rising sea levels, exacerbating this change (IPCC 2018). Historical records, oral testimonies, and early to modern mapping have provided real evidence of change in recent history (Pollard et al. 2020). Therefore, to study the impact of climate change on the coast, remote sensing techniques are required to establish baseline data from which to measure this change (Micallef et al. 2013; Tysiac 2020). Recording and understanding geomorphic evolution is also important for coastal managers and planners, particularly with regard to climate-driven future changes (Esposito et al. 2017; Tysiac 2020).

The comparison of sequential DEMs to produce a 'DEM of Difference' (DoD) is a particularly powerful technique (James et al. 2012). This is a 2D analysis that measures vertical offsets in raster images on a pixel-by-pixel basis (Figure 9.15), with change detection constrained by the resolution of the DEM. However, complex topography, often found in eroding coastal sites with vertical slopes, landscape roughness, and overhangs, are not accurately represented in DEMs. Such sites can experience complex change at varying scales and are, therefore, problematic for change analysis using the DoD method. In these cases, direct comparison between 3D point clouds to evaluate change can be advantageous, although uncertainties can still remain (Esposito et al. 2017; Lague et al. 2013).

The CHERISH project has applied both these methodologies to study change on its sites. DoDs were produced using GIS software for local landscape change analysis (up to 2 km), where impacts of landscape roughness and gridded cell resolution are reduced. At higher scales on individual sites (up to 500 m), volumetric assessments of change on eroding cliff faces were compared using cloud-to-cloud algorithms.

UAV photogrammetry surveys of promontory forts in Co. Waterford and Co. Kerry have revealed missing sections of embankment defences and hut sites with the walls running over the cliff. In the case of the latter, cliff collapse has been recorded over the course of the project. In Waterford, these hut sites on sea stacks and islets would originally have been connected to the mainland around 1,500 years ago when the forts were inhabited (Pollard et al. 2020).

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