Using sector scan sonar for the survey and management of submerged archaeological sites

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Abstract

This paper reports the results of using a sector scan sonar to record a range of submerged archaeological sites in both shallow and deep water locations. The Kongsberg MS 1000 sector scan sonar was developed for the commercial sector typically to carry out underwater inspections and surveys of bridges, dams, ports and harbours. However, as will be demonstrated below, the ability of the device to rapidly generate high quality, geometrically accurate scans of submerged features, coupled with its relative ease of use and deployment, make it a potentially important new tool for the survey and effective management of underwater archaeological sites.

Introduction

Any strategy involving the protection of underwater cultural heritage involves quantifying, recording and, ideally, monitoring the submerged resource. The ability to carry out easily repeatable and accurate surveys of submerged archaeological sites quickly and cost effectively remains a fundamental problem for the world heritage sector. At present sites are usually identified and located using side-scan sonar. This approach often lacks the resolution needed to assess levels of site preservation. If a more detailed description and plan of a site is needed it is common practice to carry out multi-beam surveys and/or deploy divers to record and photograph the site by hand but such approaches can be very expensive and time consuming. Collaborative work over the last seven years between the Underwater Archaeology Research Centre (University of Nottingham, UK) and Nautilus Marine Group International (Michigan, USA) has focused on assessing the utility of using sector scan sonar as a cheap, fast and easy to deploy tool which can accurately locate, interrogate and produce geometric plans of submerged archaeological sites.

Side-scan sonar and multi-beam echosounders have been traditionally used in maritime archaeology to locate archaeological sites and map areas of seabed (Green, 2004: 74-84; Ballard, 2007; Bowens, 2009: 103-111; Plets et al. 2011). These devices emit low and high frequency sound waves through the water column which reflect against different surfaces and return a set of data enabling the mapping of features on the seabed. Sector scan sonar functions in much the same way by sending high frequency sound through the water column in order to create highly detailed sonar images. Specifications and models of side-scan and multi-beam vary but all must either be hull-mounted to a vessel or towed behind one. To recover data the survey vessel must be in constant motion through the water which can not only lead to distortions and geometric inaccuracies in the resulting imagery but also makes it difficult to use in confined areas or in shallow water close to shore (less than 3 to 4 metres).

As an acoustic technique, sector scan sonar functions in much the same way – by sending high frequency sound through the water column – but in contrast to side-scan and multi-beam it can operate from a stationary position on the seabed which serves to enhance the accuracy of the sonar data recovered and makes the device more suited to the archaeological objective of mapping smaller areas and features in detail. Sector scan units generally have scanning ranges of 5 to 1500 metres and perform full 360° sonar sweeps, creating highly detailed circular sonar maps of the area around the units location. Sector scan sonar units can be deployed in depths of up to 3000m but they can also be used in extremely shallow water.

Sector Scan Sonar

Sector scan sonar, also sometimes referred to as mechanically scanning sonar, are acoustical imaging sonars capable of carrying out full 360 degree sonar sweeps in a series of mechanised sectored steps. Each sector is essentially a portion of a circle bounded by two radii and the outer arc (like the slice of a pie), the size of which is determined by the horizontal scanning beam angle of the sonar. Different models use different beam angles (5, 10, 15 up to 45 degrees). The wider the angle, the quicker a complete 360 degree scan can be completed but there is a resulting trade off in resolution as generally narrower angles, although they take longer to complete a full circular sweep, produce more geometrically reliable images. As the sonar sweeps in 360 degree circle (or any potion of 360) the objects in the sonars 'field of view' are displayed in real time on the computer monitor, making it a useful prospection and identification tool during seabed surveys. Originally designed as forward looking sonars for obstacle avoidance, the resolution of current sector scan models make them ideal for carrying out measured geometric surveys of submerged features.

Sector scan sonars are used in the commercial sector to carry out a range of functions including structural inspections (bridges, docks, piers and dams), positioning structures and pipelines, monitoring (dredging, scouring, sediment accumulation), directing underwater equipment or divers, seabed searches and survey, as well as being attached to ROVs and other vessels for obstacle avoidance and target identification. Recently they have also been effectively used by police divers for search and recovery operations. Sector scan sonars are particularly suited to operations requiring the quick and confident recognition of underwater structures and individual features on those structures.

A range of models of sector scanning systems are available produced by most of the offshore marine engineering companies including Tritech, Furono, Sonavision, JW Fishers and Kongsberg Martime. The work reported in this paper was carried out using the Kongsberg Mesotech MS 1000 Sector Scanning System. The system consists of a MS 1000 sonar head connected through a high tensile weight cable to a notebook, laptop or server system on the surface running the MS 1000 sonar operating software (**Figure 1**). The tripod can be deployed from a small boat, ship, platform or directly from the shore (if the site to be surveyed is close enough and there is enough cable to reach it) (**Figure 2**). The only requirement needed is the ability to power the soar and the laptop that it connects to which can be done from the vessel itself or the use of a portable generator. Once the tripod has been placed in position, scanning can proceed and the sonar image can be viewed in real time on the surface as it is collected. The MS 1000 fan-bean imaging sonar head transmits a very narrow acoustic beam which is swept vertically so that the returning echoes indicate the distance and angle of depression to the many reflectors. Since the position of the transmitter is fixed, it can obtain higher levels of resolution of acoustic data than conventional side-scan or echo sounder units. The sonar head has a 675 kHz transducer with .9 degree and 30 degree beam angles and a stepped motor which allows full 360^{o} scan coverage of the area surrounding the unit, with successive high resolution pulses. A high frequency 675 KHz acoustic ping is transmitted from the sonar head and the system waits to receive the echoed returns. Once the return is received the motor steps the transducer in parts of a degree to a new azimuth angle, and the process is repeated. This is done until a full 360^{o} circular sweep is carried out. The scan radius is set by the operator and may range in distance from 5m to 1500m. It normally takes between 2 and 5 minutes to complete an individual scan once the head is deployed on the seabed. As with any sonar technique once the distance from the scanning head increases, the quality of the image decreases.

Case studies: shipwrecks, sunken settlements, harbours, marine landscapes and rivers

Since 2009 the authors have deployed the MS 1000 sector scanner over a range of archaeological sites in a wide variety of water conditions and depths. This evaluation work has included the full range of sites an underwater archaeologist may reasonably expect to encounter from shipwrecks and drowned settlements to harbours and sunken archaeological landscapes in both freshwater and marine environments. This paper presents some of the results of this work and considers the potential of the sector scanner as a survey tool for underwater archaeologists in the coming years.

It is possible to obtain measurable, geometrically accurate images of archaeological features in a matter of minutes from a single drop. Though, of course, the number of scans needed of course depends on the size of the feature being imaged and the level of detailed required. For example, The Tramp shipwreck – a tug built in 1926 that sank in 14 metres in Grand Traverse Bay, Lake Michigan, USA in the 1970's - was imaged from one drop in just under five minutes (**Figure 3**). The resulting 30m radius scan reveals a full plan of the semi-intact 16.7m tug with some wreckage just to the south. Significantly, to the east of the vessel, which sits in 14m of water, a clear anchor drag mark can be seen in the lake bed. This drag line is less than 10cm in depth and reveals the level of detail that can be obtained. Such detailed information on the surrounding environment of shipwrecks is vital in determining levels of preservation and identifying possible threats.

As can be seen from the Tramp image, in much the same way as a terrestrial laser-scanner cannot see through solid objects, the sector scan will produce an acoustic 'shadow' behind upstanding features. To overcome the problems of acoustic 'shadow', the in-water sonar unit can be redeployed at additional locations around structures to map the areas in 'shadow'. A mosaic can then be created of all the scans taken of a given area to eliminate shadows and produce a highly detailed and accurate measured composite master image. With shipwrecks this would normally consist of at least four separate scans locations around the wreck to eliminate areas of acoustic 'shadow'. For example, a mosaic image of the SS Milwaukee, a railroad car ferry which sank in Lake Michigan in 1929, was created from six 10m radius scans (**Figure 4**).

In 2009 and 2010 the sector scanner was deployed at the sunken Bronze Age town of Pavlopetri located off the Pounta shore, opposite the island of Elaphonisos, in southern Laconia, Greece (Harding et al. 1969). It was used as part of the Pavlopetri Underwater Archaeology Project which, as it is committed to recording the submerged remains of the town in as much detail as possible, has become a testing ground for new and innovative scientific approaches to underwater survey. This meant that the performance of the sector scan sonar could be tested against the various other techniques used on the site including high resolution swath bathymetry, side-scan sonar, sub-bottom profiling, optical robotic techniques and shore-based total station survey (Henderson et al. 2011; 2013).

The town appears as a series of large spreads of stones amongst which a network of stone walls can be traced (**Figure 5**). The main upstanding remains cover an area of around 4 hectares of seabed, beginning almost immediately from the shore and extending up to a depth of 3.5 metres. The walls themselves are made of uncut aeolianite, sandstone and limestone blocks and were built without mortar. They can survive up to 3 stones in height but the vast majority survive only one course high or embedded into and flush with the sea bed.

Over the space of just ten days the whole site was mapped using the sector scanner. Given the shallow nature of the site the position of the sector scanner was surveyed using a shore based Total Station. All of the upstanding structural elements of the site - buildings, streets, courtyards, walls and graves – were recorded alongside details of the topography of the seabed. Typical scan radii used for the submerged structures at Pavlopetri ranged from 100m scans of building complexes (covering a total sea floor area of 31,000 sq metres) down to high resolution 5 m scans of areas of importance such as cist graves (**Figure 6** and **7**). Image resolution in terms of recognising individual features was generally improved by moving the sonar head closer to the feature being imaged. In terms of recording individual buildings, scan radii between 15 to 30m were found to be most effective producing measured scans in which the individual stones used in the construction of the walls were visible (**Figure 8**). In order to fully image individual buildings at Pavlopetri at least one scan from within a building was needed backed up by at least four separate scan locations around the perimeter of the building to eliminate areas of acoustic 'shadow'.

In addition to the recording of the 30,000 square metres of buildings first identified in 1968, over 9,000 square metres of new structures, buildings and cist graves were discovered using the sector scanner as a prospection tool on the site. One of the most important discoveries was the identification and recording of a large trapezoidal structure, measuring c. 34m in length and 12m to 17m in width (**Figure 9**). On the seabed viewed by a diver it was difficult to visualise how the walls of this structure related to each other due to the scale. Scans revealed the structure contained at least three separate rooms and was either a fully roofed building or an open walled courtyard with buildings situated within. The scanner was also effective in scanning the remains of rock cut tombs on a bedrock ridge in shallow water of less than a metre (**Figure 10**).

In 2012 the sector scan was deployed in Loch na h-Àirde on the Rubh' an Dùnain peninsula of Skye to record the submerged remains of suspected Viking harbour works (Martin 2009). The site presented a challenge in that it is located in a shallow, silty loch with poor visibility ranging from 1m to nil. The resulting sonar map of the site in **Figure 11**, made from mosaicking three 50m radius scans, clearly shows a large stone built linear structure, interpreted as a quay, extending some 80 metres in a SW/NE direction. The quay structure sits some 0.75 metres off the silty loch bed and features a gap providing access for boats to an artificially cut channel to the south leading to the sea. The work was completed in just two hours, acoustic scans were carried out from three locations – two in the loch itself at depths of 1.3 and 1.5 metres and one from the entrance of the artificial channel cut into the loch in a water depth of less than 50cm. The scanner performed well despite the poor visibility and shallow depths, with the scan of the channel clearly demonstrating that as long as the sonar head of the unit is submerged scanning can take place.

To contrast the shallow conditions encountered in Skye, the sector scanner was used in 80 to 100 metres of water off the coast of western Sicily as part of the 2013 season of the Battle of the Egadi Islands Project. The battle site of the Egadi Islands, a decisive naval encounter between the Carthaginians and Romans which effectively ended the First Punic War in 241 BC, is the first ancient naval battle site to have been located on the seabed. The general location of the battle was identified in 2004 and since then over 210 km2 of the seafloor has been mapped using multi-beam sonar by a joint team from the Soprintendenza del Mare della Regione Sicilia and RPM Nautical Foundation (Royal and Tusa 2012). As the resolution of the multi-beam used - a 297-303 MHz hull-mounted Kongsberg EM3002D - was insufficient to identify the remains of the battle site on the seabed, a Panther XT SAAB ROV was deployed from the research vessel to painstakingly search the seabed. Using this search method two main concentrations of artefacts across 10 km2 have been identified consisting of bronze warship rams (of which 11 have so far been identified), helmets, amphorae, ballast stones, ship fittings and a possible stone anchor. Finds located by the ROV were given GPS co-ordinates using the transponder on the ROV and underwater acoustic beacons.

The sector scanner was used to provide more detail on the position and, crucially, orientation of artefacts on the seabed than is possible through simply obtaining GPS position fixes (**Figure 12**). As the discovery of a submerged ancient sea battle landscape is currently unique, there is an enhanced responsibility to map the layout of the remains as accurately as possible. The exact recording of the positions of artefacts and ship remains on the site is of paramount importance as only with this contextual information can we begin to reconstruct how the battle was fought and examine how the remains on the seabed relate to the classical accounts of the battle. In particular the position of the bronze warship rams and associated material may reveal something about the naval tactics used during the battle. The sector scanner was also useful as a prospection tool as it was capable of identifying targets sitting just 10 to 20 cm proud of the flat sandy seabed at Egadi. The location of a bronze warship ram (Egadi 11) sitting on the seabed is instantly recognisable through the distinctive acoustic shadow it casts (**Figure 13**) while a further scan reveals details of the ram itself with the cowl and shape of the fins clearly visible (**Figure 14**).

As the awareness of the importance of submerged landscapes in examining key questions in human development develops, the need for quick and effective means of imaging the often ephemeral features of prehistoric submerged remains will increase. Techniques such as the sector scanner will have an important role to play in future prospection and recording of submerged landscapes. In 2014 the sector scanner was used to record the remains of a 9000 year old caribou hunting structure 37 metres beneath the surface of Lake Huron in the North American Great Lakes (O'Shea et al 2014). The 50m radius acoustic scan (**Figure 15**, B) revealed the structure through the non-random arrangement of stones on the lake bottom – the light coloured areas are stones that produce a strong acoustic signature, whereas dark areas are acoustic shadows. From this scan it was possible to produce a topographic plan of the cultural features of the hunting trap (**Figure 15**, A) with black dots representing the location of placed stones revealing the locations of hunting blinds, cobbled surfaces and bedrock. The resolution of the scanner allowed the locations of individual worked lithics to be recorded which could later be recovered by divers.

The archaeological survey of rivers though they are likely to be rich in archaeological remains has been largely neglected mainly due to the difficulties involved in surveying in shallow water with often poor visibility. In 2015 the sector scanner was tested along parts of the Thames in water depths of 1.5 metres and less. Measured scans of the river channel were easily obtained showing submerged remains and features such as dredging marks, piers and weirs in considerable detail (**Figure 16)**. At this level of resolution unknown submerged structures such as river crossings, bridges and historic watercraft can be easily identified and mapped. Details of the character of river channels and impact of activities such as dredging are likely to be of considerable importance in terms of river management and the impact of this on historic sites. The ease of deployment and speed of the scanner suggest it could be a valuable tool in tracking historic changes in river channels over time.

Discussion

It is clear, from the examples quoted above, that when used with a fan-beam imaging sonar head, the MS 1000 system can capture real time imagery of submerged features to the level of detail required for effective archaeological work. Being a sonar technique image resolution is dependent on range - as the distance of an object from the scanning head increases, the quality of the image of the object decreases due to the beam spreading out as it travels through the water column. Effective scan radii for archaeological purposes were found to be in the 20 to 100 metre range – with scan ranges below 50 metres more suited to obtaining accurate geometric plans of archaeological sites and those above 50 metres useful for prospecting the seabed to locate potential targets. The trade off between range versus resolution depends upon the size of the target being imaged and the archaeological objectives of the survey. For example, during our work, large shipwrecks were best scanned in the 40 to 60 metre range while detailed stone by stone images of the buildings at Pavlopteri were best achieved using 20 to 30 metre scan radii. Detailed scans of smaller objects such as cist graves or bronze rams were done in the 5 to 15 metre range. Full 360º scans of areas normally took between 2 and 5 minutes to complete once the sonar was positioned on the seabed.

The sector scan sonar can be deployed in depths of up to 3000m but crucially for archaeological application, it can also be used in extremely shallow water – as long as the sonar head is immersed it will function. It can thus operate in depths of water as shallow as 0.5 m and obtain accurate data. As we have seen the scanner has been effectively used for shallow coastal marine and river survey and could be even potentially be used in wetland locations. Just as important for use on archaeological sites in a range of submerged environments, image quality was not seen to be impacted by water currents, poor water visibility or other optical impediments. As the scanner uses sound to image underwater the amount of sediment in the water column does not affect the image quality (though it is not possible to scan through mud or oils). Determining as accurately as possible the speed of sound in the water was found to be the most important factor in obtaining high quality imagery – as indeed is the case when using all sonar techniques. Knowing the depth, salinity and especially the temperature of the water column are the essential factors in measuring the speed of sound in the water. This information can be entered into the MS 1000 sonar operating software prior to operating the sonar head and can be adjusted as is necessary while data is being acquired.

Obtaining accurate locations of the in-water sonar unit on the seabed is the biggest challenge in using the scanner. In shallow water (<8m) GPS fixes can be taken by boats or swimmers by taking a position from the taught connecting cable on the surface. In deeper water, locations can be measured in and established by divers (obviously negatively affecting the speed and cost effectiveness of the technique) or positioned through the use of acoustic underwater beacons. The beacons must have the ability to be switched off before sector scanning takes place otherwise they will interfere with the ability of the sector scan sonar to obtain clear images. It is also worth noting that the MS 1000 comes with an optional internal compass – this feature is essential for archaeological work especially when mosaicking multiple scans together.

The MS 1000 sonar operating software is user friendly and, most usefully for the archaeologist, has built in tools allowing the real time measurement of underwater target dimensions and the spatial relationships of multiple underwater targets. Given a known GPS reference point, the software can calculate and display the GPS points of any other objects in view. As the sonar head rotates it produces a constantly updating image of the seabed that can be viewed on the computer screen and used to assess and monitor features or direct divers to them in real time. The data stream is recordable and can be stored digitally as individual (.smb) files that can be replayed and examined in detail at any time using the MS1000 software. Stills of the images can be extracted from the .smb data stream files as geo-referenced TIFFs which can then be loaded into widely available GIS or digital image applications for further work. For example, a series of TIFFs of an archaeological site taken from different vantage points around the site can be mosaicked together to produce highly-detailed composite images. In this regard, the sector scan sonar is similar to terrestrial-based laser-scanners which are repositioned around targets to ensure that the survey captures all the visible features of an individual site.

Conclusion

The ability to visualise submerged archaeological features and produce measured scans of them in a matter of minutes has obvious advantages to the practice of underwater archaeology. The sector scanner is easy to use in the field and is particularly suited to the prospection and rapid mapping of features. No single technology provides a complete underwater survey solution and in terms of scale the sector scanner sits somewhere in the middle ground between the use of multi-beam and side-scan for large area seabed survey and the use of localised diver intensive approaches such as photogrammetry for individual site survey. As the sector scan sonar can operate from a fixed position on the seabed it can effectively perform the archaeological objective of planning individual sites in detail as the location of areas being scanned can be tightly controlled. While this is ideal for producing plans of submerged features, the scans produced are two-dimensional TIFFs and not three dimensional photogrammetric or multi-beam models.

Sector scan sonar units are portable and robust and are suitable for use from the shore or from vessels or platforms of all sizes, from inflatable RIBs to ships – the key factor being that a power source is present. Other than the unit itself, it requires no specialist equipment, no intensive training course to operate, can be quickly deployed and produces high resolution measured scans with little or no need for further post processing of the data. It can be used in almost any submerged environment, is not dependent on calm water or good visibility, and can operate in depths of less than half a metre to 3000 metres. This makes it particularly suited to operations in modern ports or rivers where visibility can be an issue. It is possible to investigate and scan a range of sites in a single day using the sector scan sonar and the fact that it produces instantaneous results in the field could have an importance when decisions regarding mitigating threats to sites need to be made on the spot.

The potential role of the scanner in future site monitoring and management strategies is perhaps its most important aspect. Not only can it be positioned at a remove from a feature while still acquiring a full survey, it is relatively simple to deploy the scanner over known points, to revisit and quickly rescan important areas, and as a result build up a detailed record of a site over time. In this way changing levels of deterioration and degradation on submerged sites could be more quickly and cost-effectively monitored over time than strategies involving the deployment of divers and/or underwater robotic vehicles.

The sector scan sonar effectively solves one of the constant challenges in underwater archaeology – namely obtaining geometric surveys of underwater sites quickly, accurately and cost effectively. The final point may be the most important in terms of the development of the underwater archaeology. Certainly more technically advanced systems exist, particularly in the commercial sphere, but in terms of ease of use, deployment and overall financial cost of using the kit, the sector scan sonar is an attractive option for a poorly resourced and underfunded discipline. It produces easy to understand images of underwater sites and as such has the potential to allow not only archaeologists but also the wider public to more easily visualise, interpret and understand marine cultural heritage.

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Figures

Figure 1 - The Kongsberg MS 1000 sector scanner as it is deployed underwater. The device is secured within a protective tripod, which is lowered on to the seabed. Note the large circular pads on the legs of the tripod to ensure the seabed is not penetrated or damaged during deployment (Photo: Andy Torbet).

Figure 2 – The sector scanner being deployed from a small boat over the submerged Bronze Age town at Pavlopetri, Laconia, Greece (Photo: Jon Henderson).

Figure 3 – 30m radius scan of The Tramp Shipwreck, Grand Traverse Bay, Lake Michigan, USA .

Figure 4 – Six 10m radius scans of the SS Milwaukee, Lake Michigan, USA.

Figure 5 – View of a room in a building complex at Pavlopetri. The diver is positioned over the entrance threshold stone to the room (Photo: Chris Doyal).

Figure 6 – 100 metre radius sector scan of Pavlopetri. Scanner is located 10 metres to the south of Building IX in Area C. (map of area included to compare scan).

Figure 7 – Close up 10m radius scan of a cist grave.

Figure 8 – 15 metre radius scan of Building IX at Pavlopetri.

Figure 9 – Large trapezoidal structure, measuring c. 34m in length and 12m to 17m in width, found with the sector scanner at Pavlopetri in 2009.

Figure 10 – Two 20 metre radius scan of two rock cut tombs at Pavlopetri combined to create a 40 metre diameter scan – the upstanding edges of the tombs are clearly defined.

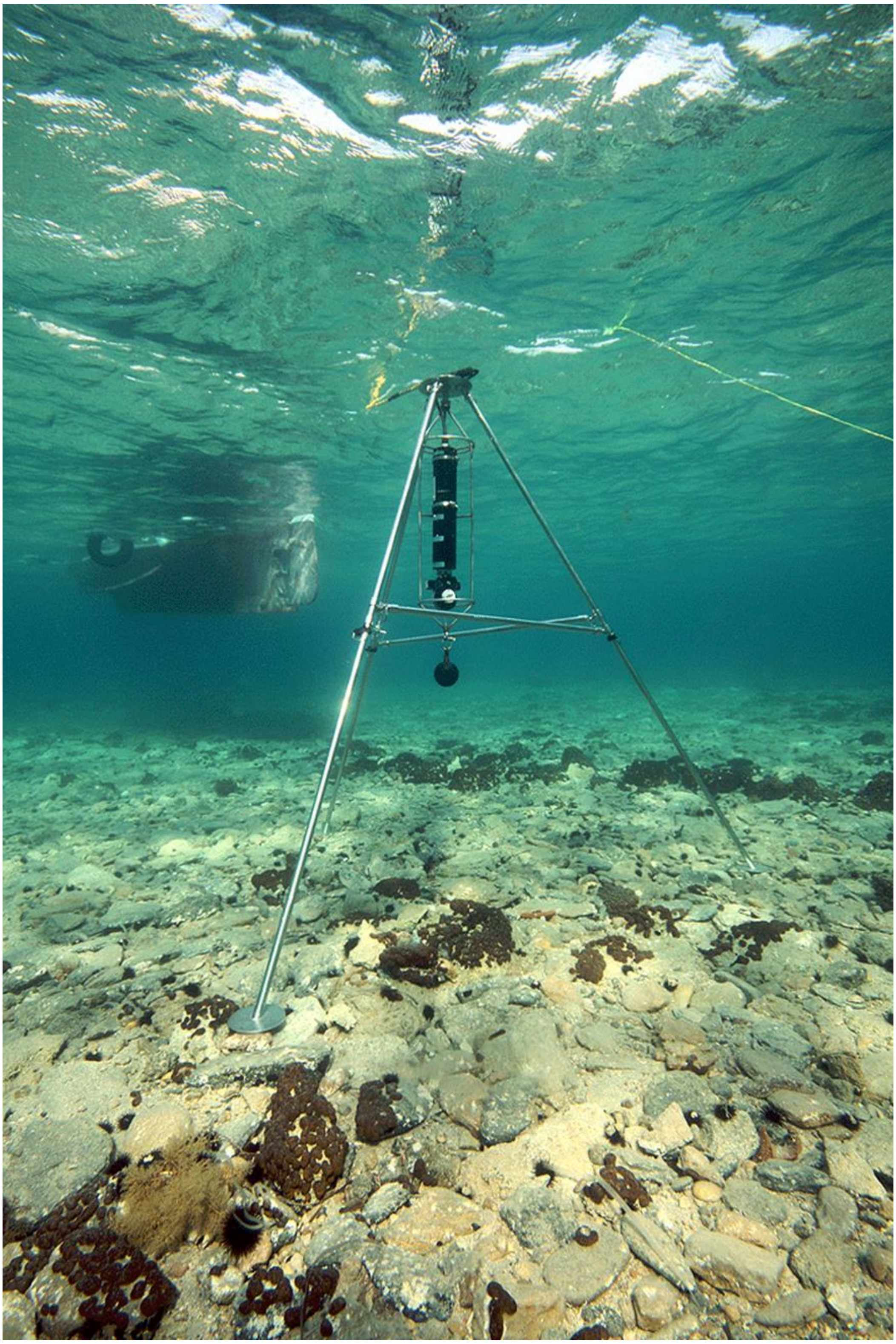
Figure 11 – 'Viking harbour' feature in in Loch na h-Àirde, Skye – composed of three 50m radius mosaicked scans.

Figure 12 - 30m diameter scan of Egadi seabed – the centre triangle is the sector scan unit itself, to the left of the unit the ROV can clearly be seen, the other upstanding features are amphora targets on the seabed.

Figure 13 - 15m scan with the clear profile and acoustic shadow of a new bronze ram (Egadi 11) as located on the seabed.

Figure 14 – Scan of the Egadi 11 ram with cowl and fin detail.
Figure 15 – Plan (A) based on the sector scan (B) of a 9000 year old caribou hunting structure on the bottom of Lake Huron in the North American Great Lakes, USA.

Figure 16 – Four 50 metre radius scans mosaicked to provide a plan of the submerged structure of the historic Sunbury Weir in the River Thames built in 1812. The edges and floor of the river channel are clearly defined and evidence of the remnants of dredging can be seen in the upper northern part of the scan.



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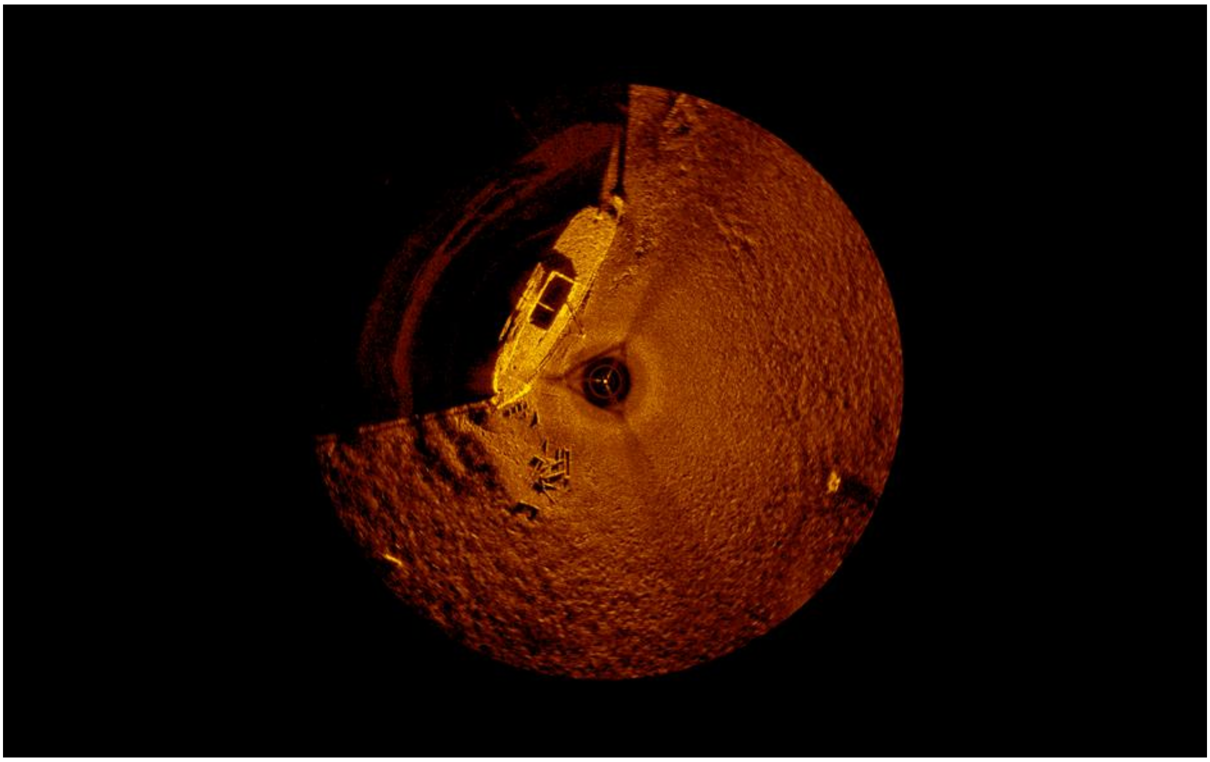


Figure 3 – 30m radius scan of The Tramp Shipwreck, Grand Traverse Bay, Lake Michigan, USA

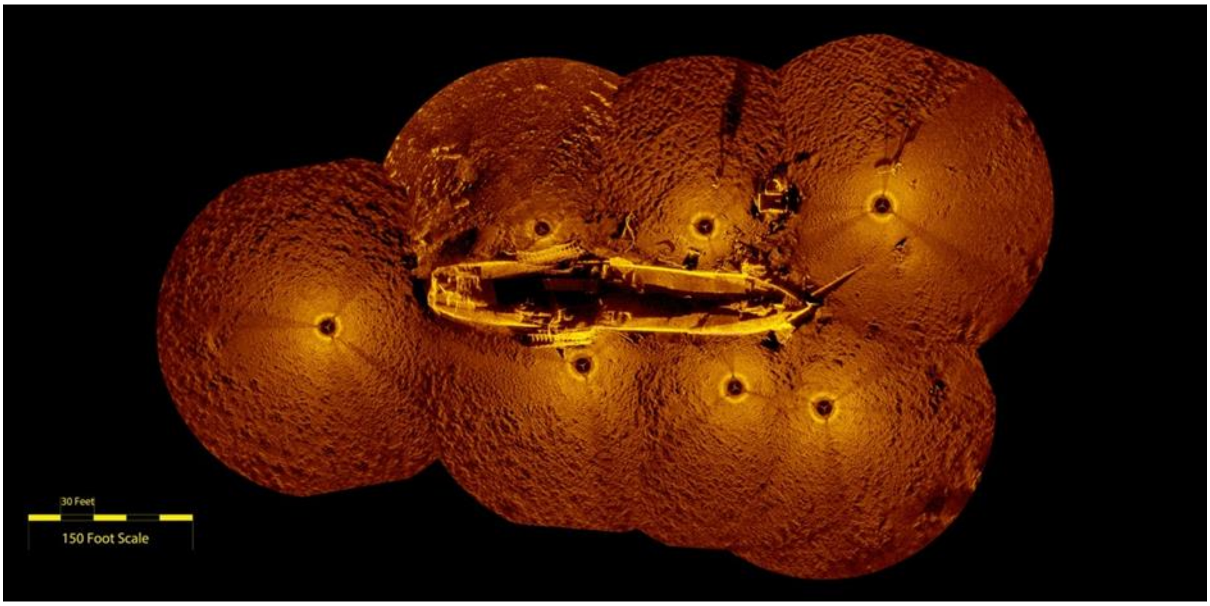


Figure 4 – Six 10m radius scans of the SS Milwaukee, Lake Michigan, USA

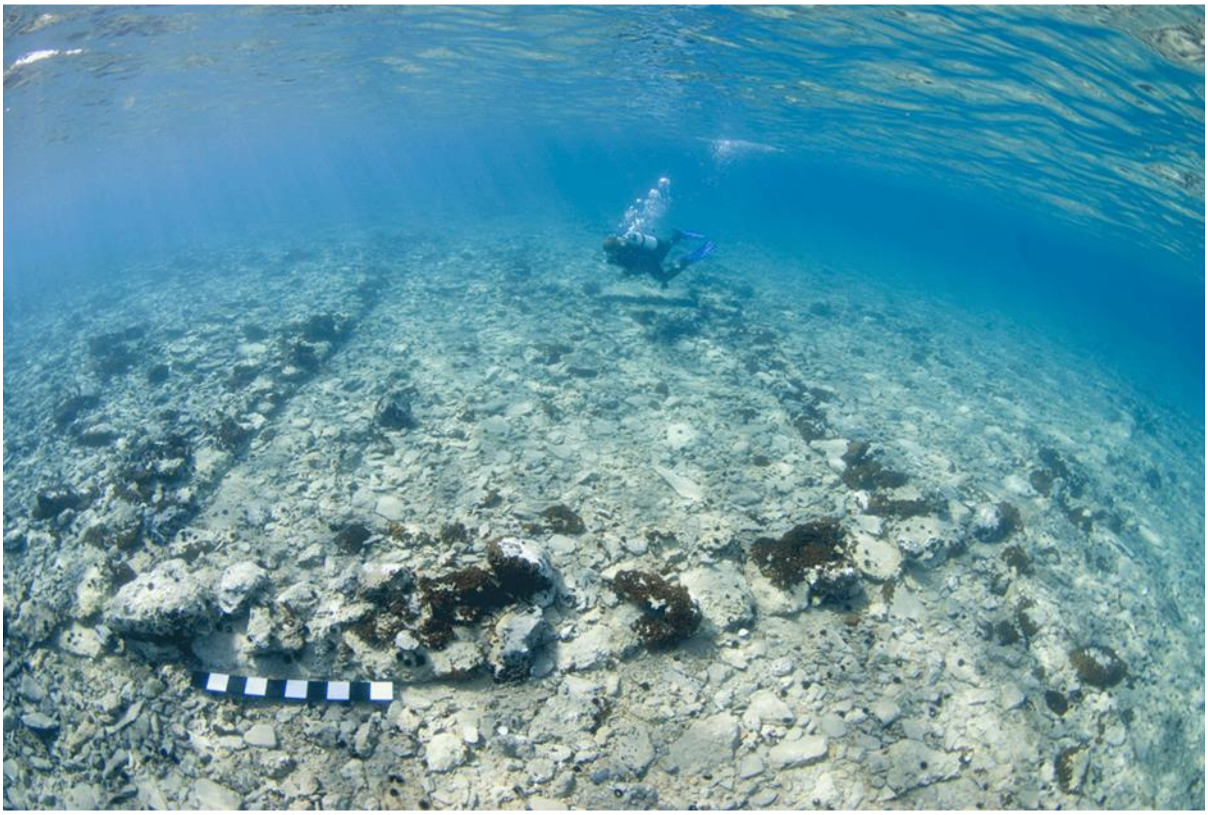


Figure 5 – View of a room in a building complex at Pavlopetri. The diver is positioned over the entrance threshold stone to the room (Photo: Chris Doyal).

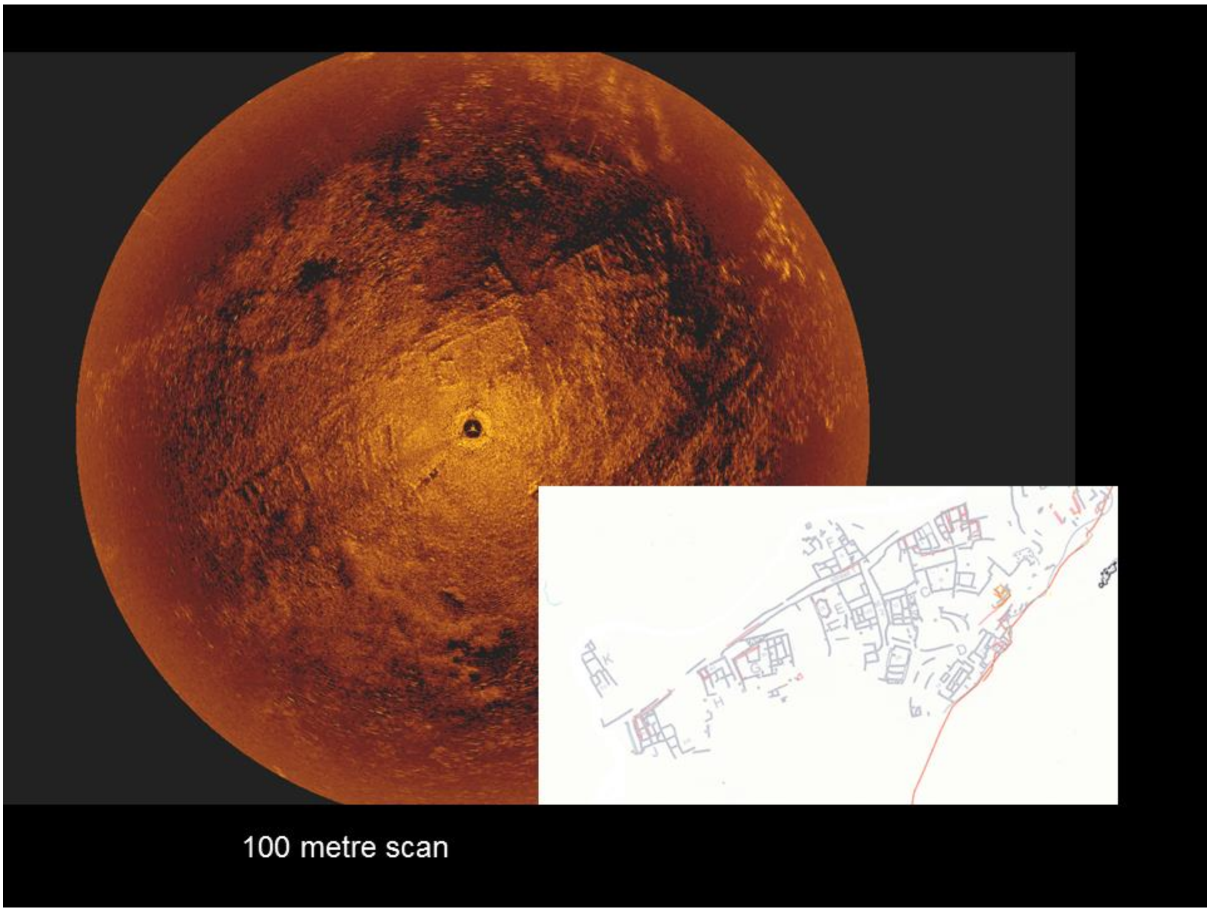
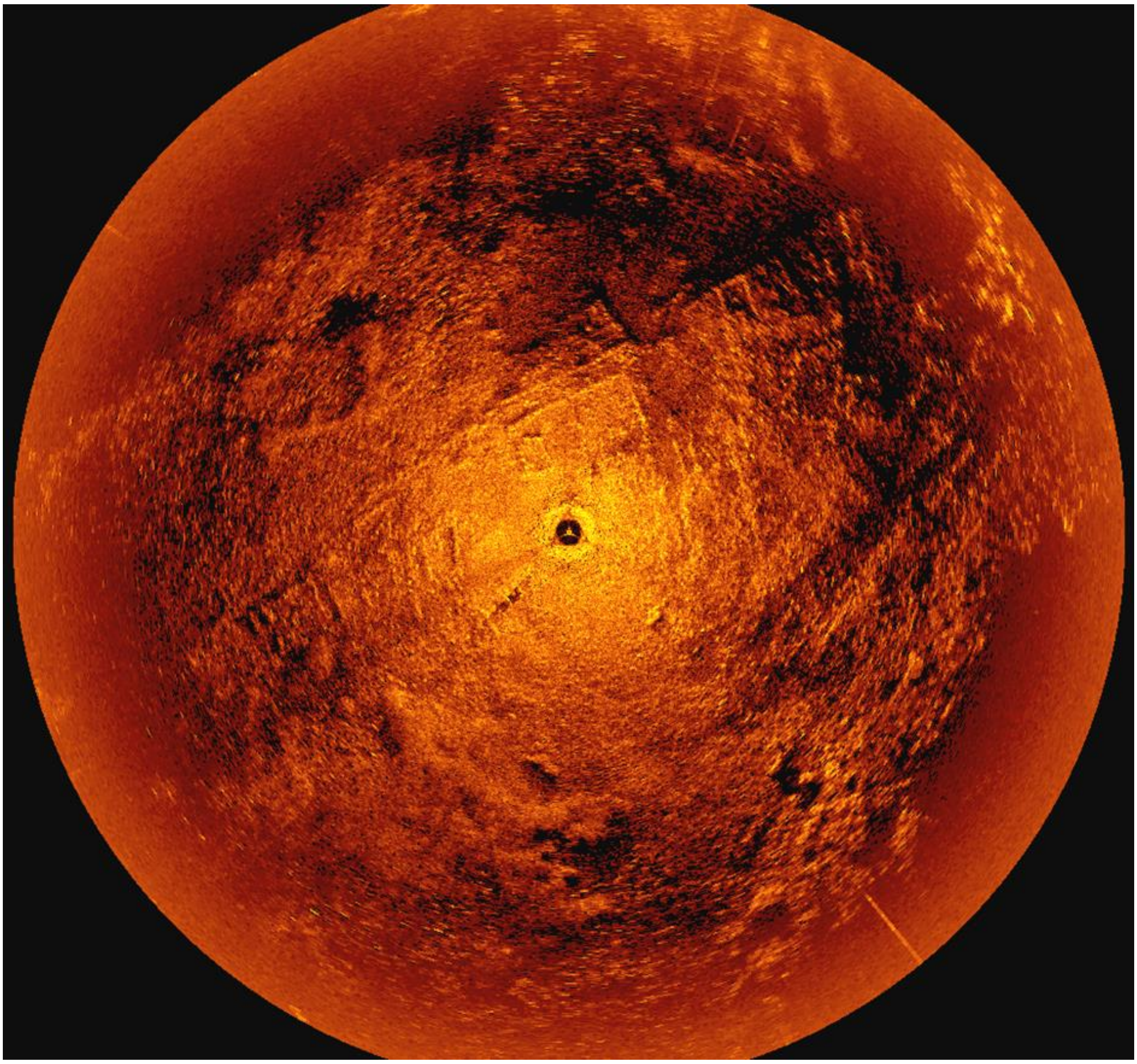


Figure 6 – 100 metre radius sector scan of Pavlopetri. Scanner is located 10 metres to the south of Building IX in Area C. (include map to compare scan)



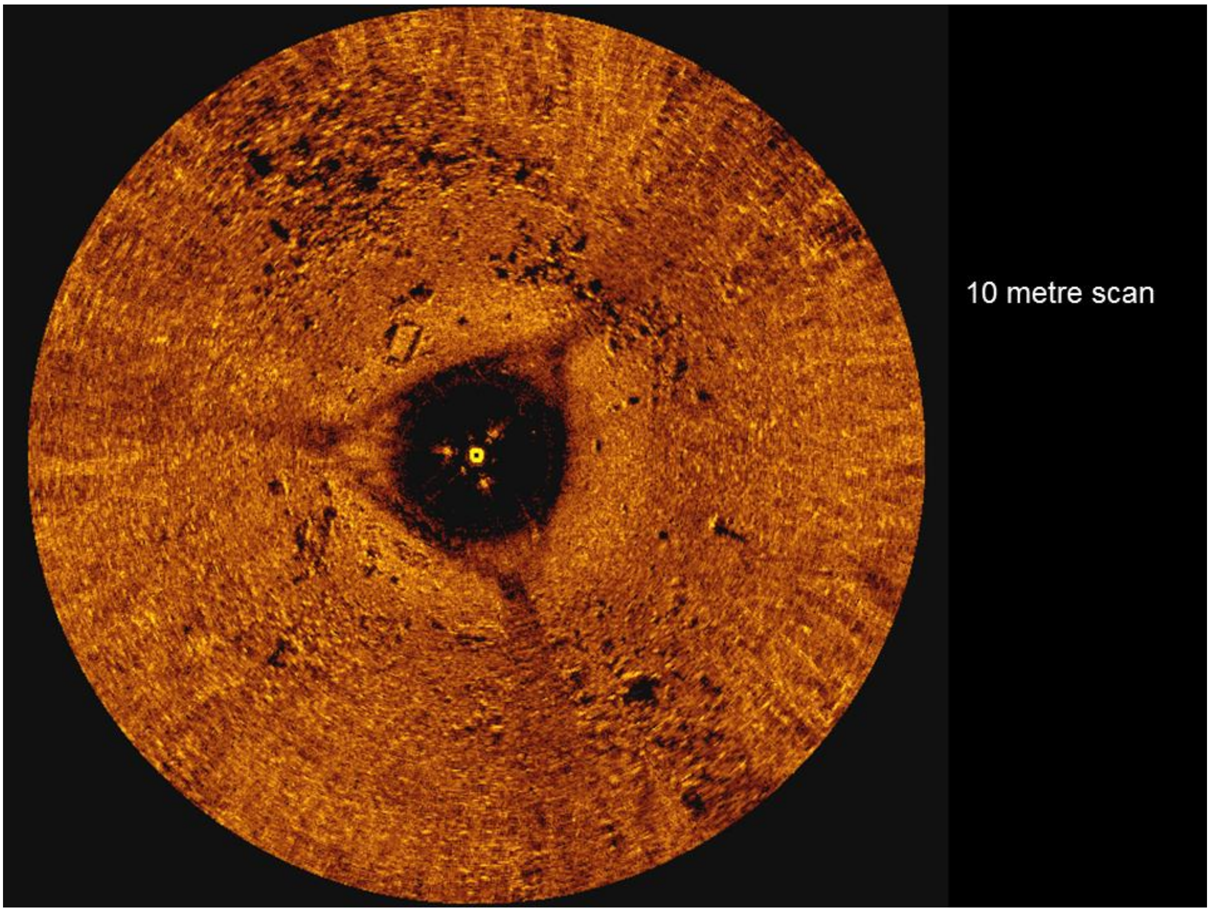


Figure 7 – Close up 10m radius scan of a cist grave

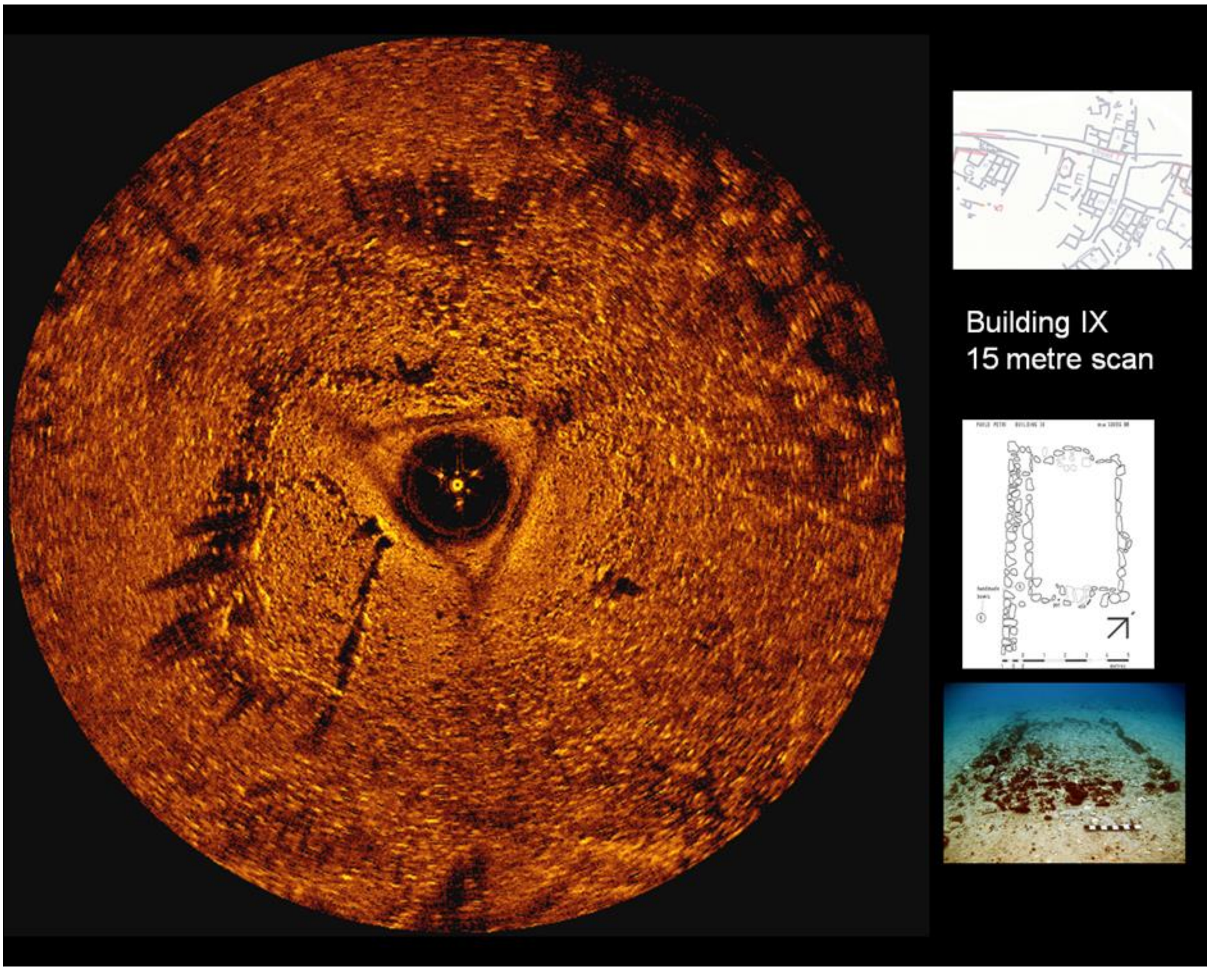


Figure 8 – 15 metre radius scan of Building IX at Pavlopetri

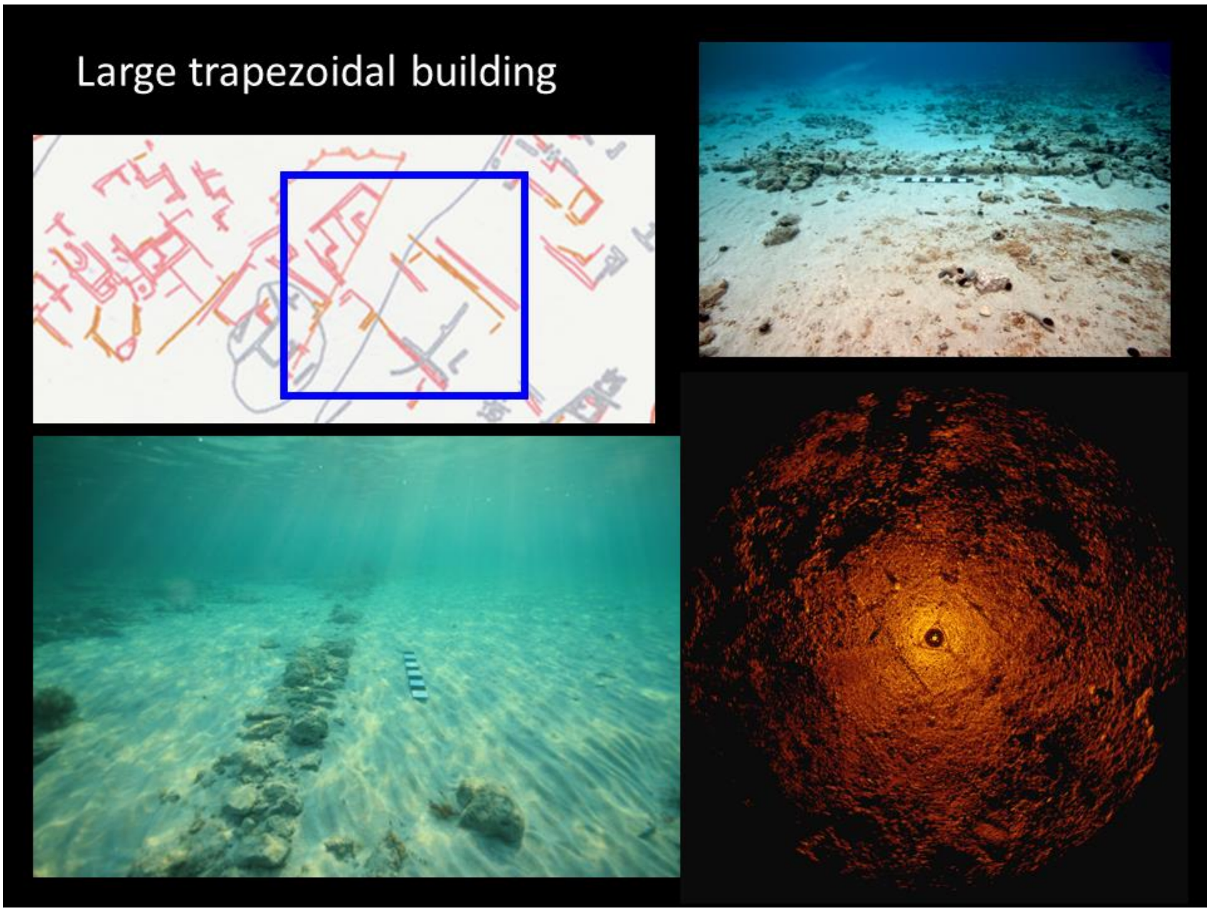


Figure 9 – Large trapezoidal structure, measuring c. 34m in length and 12m to 17m in width, found with the sector scanner at Pavlopetri in 2009.

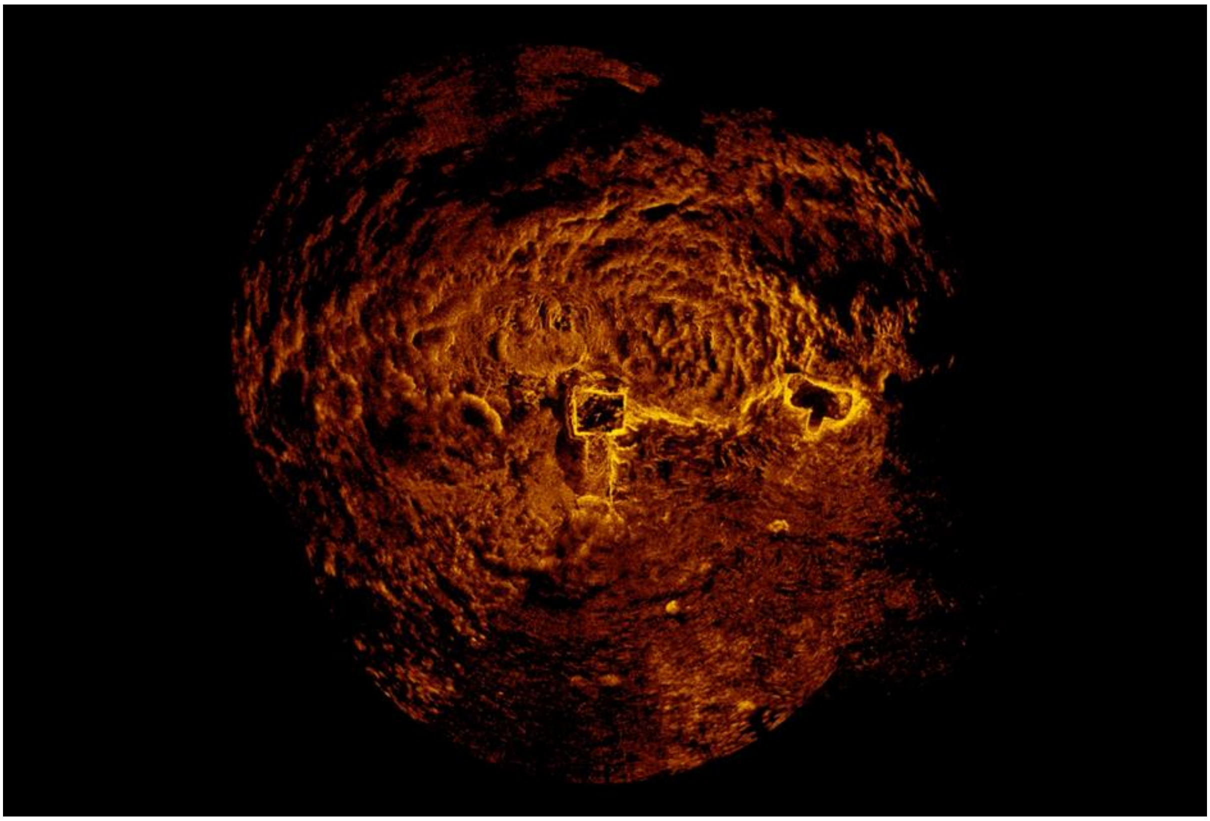


Figure 10 – Two 20 metre radius scan of two rock cut tombs at Pavlopetri combined to create a 40 metre diameter scan – the upstanding edges of the tombs are clearly defined.

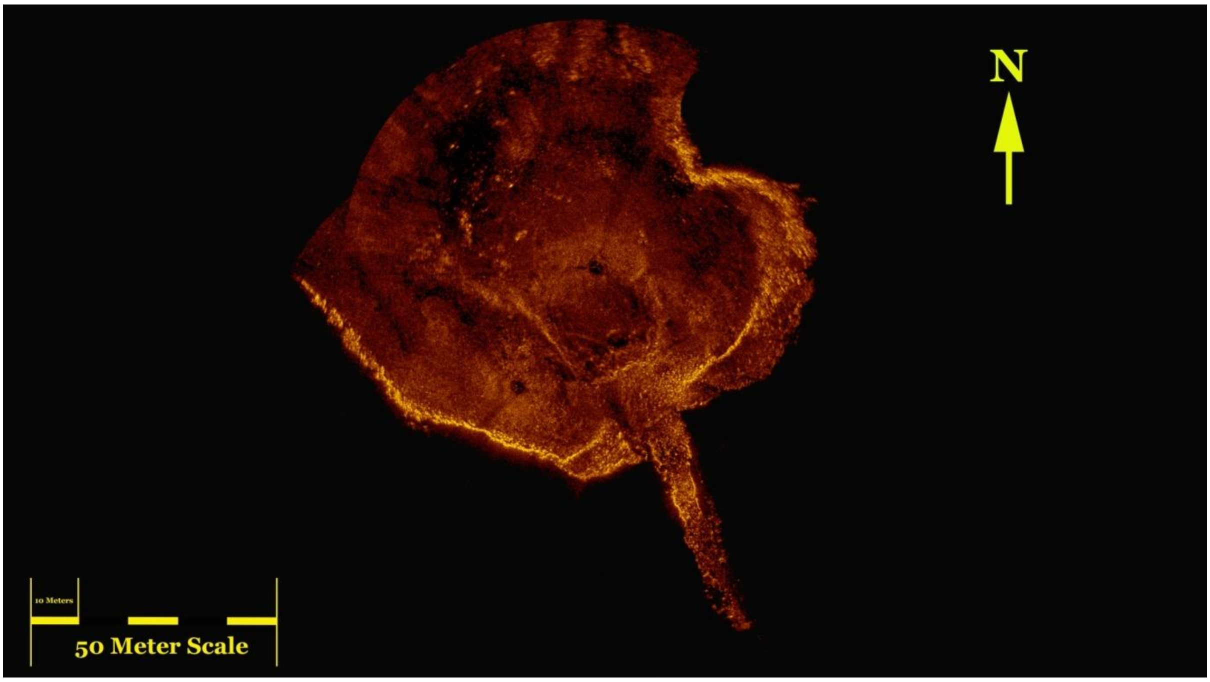


Figure 11 – 'Viking harbour' feature in in Loch na h-Àirde, Skye – composed of three 50m radius mosaicked scans.

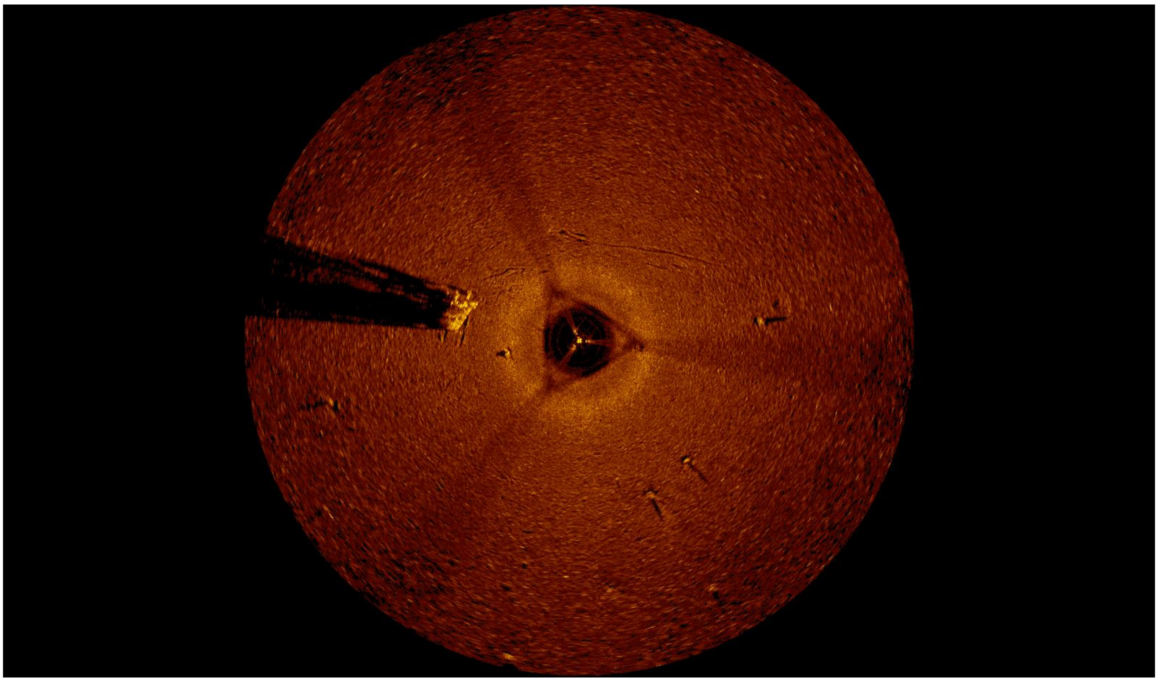


Figure 12 - 30m diameter scan of Egadi seabed – the centre triangle is the sector scan unit itself, to the left of the unit the ROV can clearly be seen, the other upstanding features are amphora targets on the seabed.

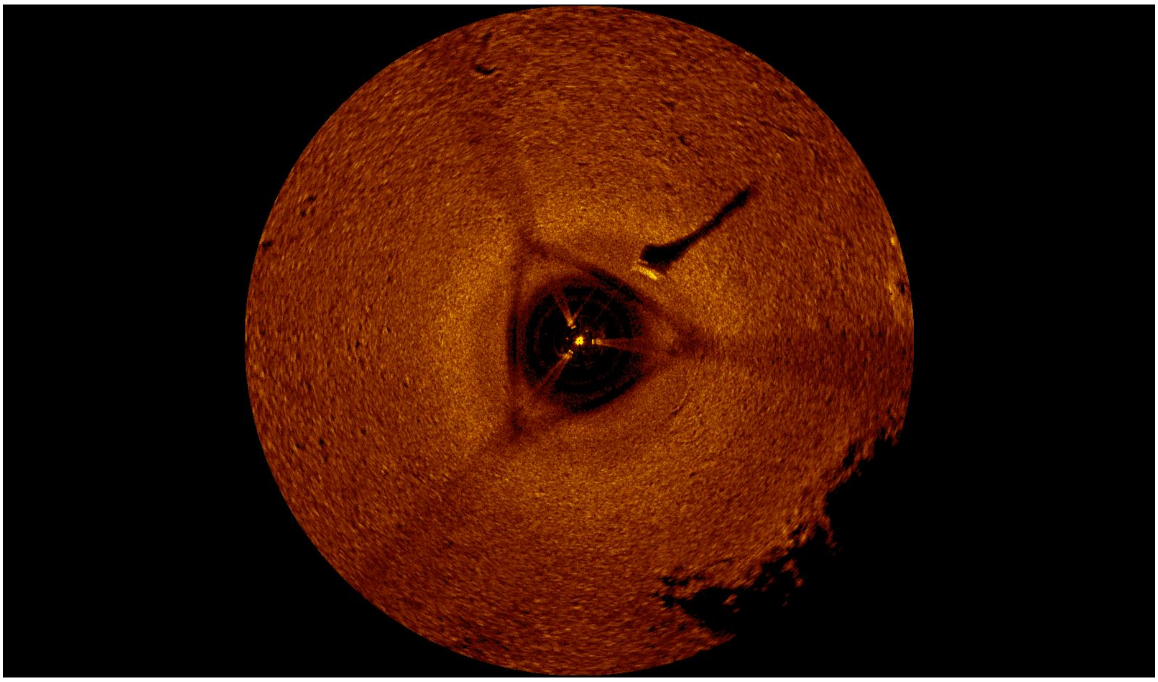


Figure 13 - 15m scan with the clear profile and acoustic shadow of a bronze ram (Egadi 11) as located on the seabed (include inset photo of ram attached).

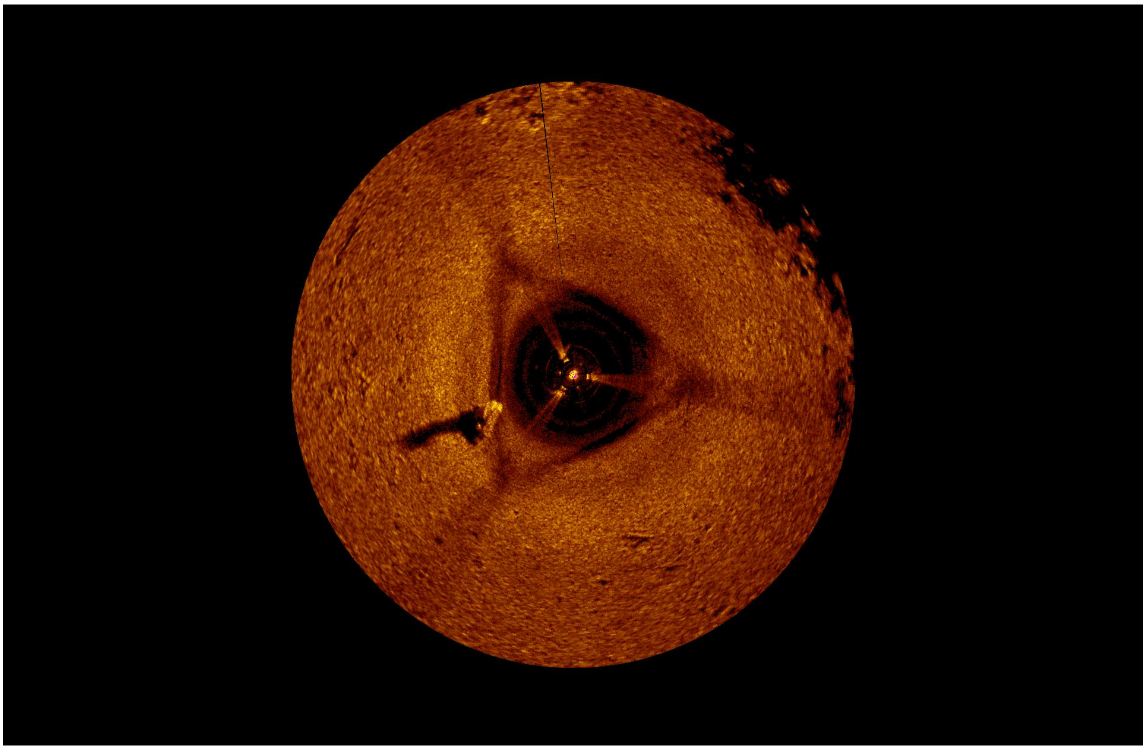


Figure 14 – 5m radius scan of the Egadi 11 ram showing cowl and fin detail.

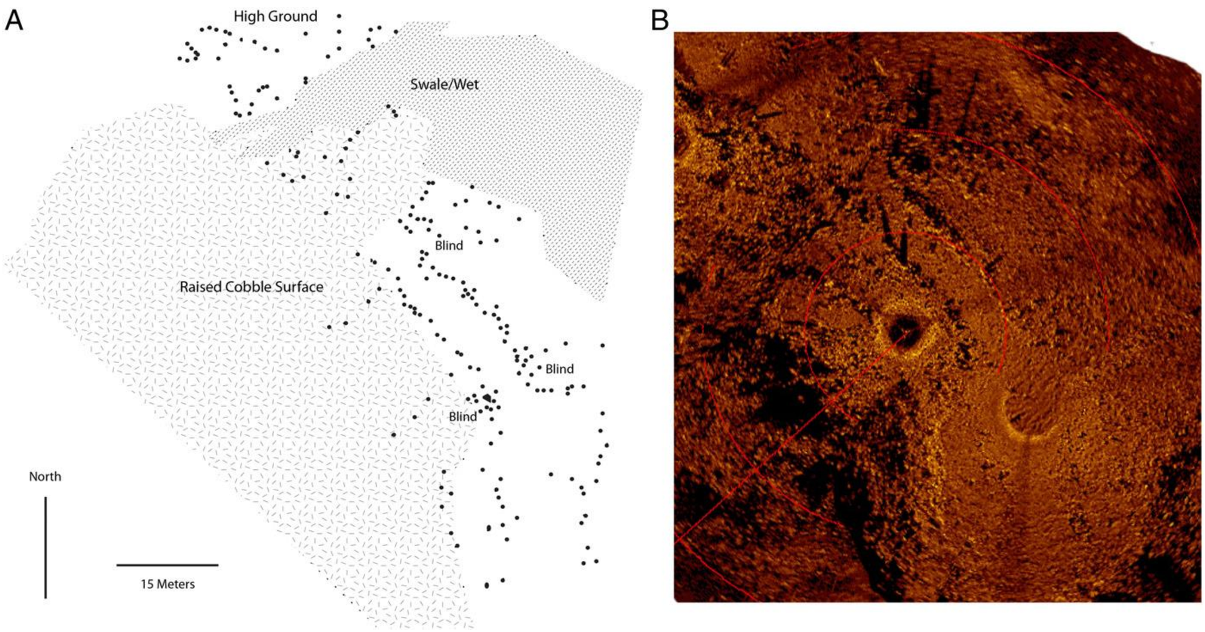


Figure 15 – Plan (A) based on the sector scan (B) of a 9000 year old caribou hunting structure on the bottom of Lake Huron in the North American Great Lakes, USA.

Figure 16 – Four 50 metre radius scans mosaicked to provide a plan of the submerged structure of the historic Sunbury Weir in the River Thames built in 1812. The edges and floor of the river channel are clearly defined and evidence of the remnants of dredging can be seen in the upper northern part of the scan.