A High-Frequency, Narrow-Beam Sub Bottom Profiler for Archaeological Applications

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Abstract- Shipwrecks in deep water are often found by their surface expressions, such as exposed ceramic containers. Fully investigating or excavating those sites, however, requires understanding what is buried beneath, including organic materials and the remains of ship structure. This paper lays out the archaeological and technical justification for a high-frequency, narrow-beam sub-bottom profiler. It describes an ultrasonic (150 kHz) device built to image local areas of the seafloor beneath the mud. The final section presents a data set collected with the instrument operating on the ROV JASON over an 8th-century B.C. shipwreck found off the coast of Israel. Precise sub-bottom imagery can aid in characterizing a site before excavation, and enables a three-dimensional computer model of a buried structure to be built with acoustic techniques, without ever disturbing a wreck.

I. INTRODUCTION

In 1997, a team of archaeologists, engineers, and oceanographers discovered a remarkable shipwreck off Sicily. Dating from about the 2nd century B.C.E., the wreck consisted of about 70 "amphora" or ancient ceramic shipping containers. The amphora were dispersed over an area of about 10 by 30 meters, roughly corresponding to the outline of the ship that originally carried them, which had long since rotted away. Two lead anchor stocks indicated the bow. The wreck was dubbed "Skerki D," (the fourth wreck found in the area of Skerki Bank), and was notable for its mixed cargo of numerous different shapes and sizes of amphora [1].

The wreck had another intriguing characteristic: the amphoras were in two distinct piles, separated by 5 to 10 meters of flat bottom. Were there two distinct holds, with an empty hold between them? Did a center hold carry perishable cargo? Or did the ship break up into two pieces, as it sank or when it hit bottom? Whatever the cause, the space between the amphora piles was as intriguing as the piles themselves. Experimental excavations on other wrecks in the area indicated the presence of well preserved wood buried in the mud. On Skerki D, the space between the piles may well have hidden wood, just a few centimeters from the surface. Author Mindell directed the search in the US Navy's NR-1 submersible that discovered the wreck, and looking out the window of the submarine was intriguing and frustrating: there was no simple way to determine if the ship's structure was indeed just below the surface, nor to map the depth and extent of whatever might be there.

In response to the challenge of this unique wreck, then, we developed a high-frequency, narrow-beam sub-bottom profiler. This paper presents the technical and archaeological justification for the device and describes a prototype instrument built out of components from a side-scan sonar. It presents data from an initial test on an 8th-century B.C.E. Phoenician wreck in the Mediterranean, analyzes the data, and describes additional tests to characterize the device. The paper then proposes future paths for technology development, and presents the challenge of mapping an entire buried shipwreck in three dimensions without ever touching the site. Throughout, we aim to demonstrate the symbiotic relationship between archaeology and technology in the deep ocean [2]. Archaeological sites pose new and interesting problems for engineers, and new technologies allow archaeologists to peer into the past in new and revealing ways.

II. ARCHAEOLOGICAL AND TECHNICAL JUSTIFICATION

Available data indicate that ancient ships, when they sank in deep water, tended to land upright, and where the bottom is silty tended to "float" at a level just higher than their water line. After some time, probably at least several centuries, wood boring organisms (teredo worms) eat the unburied wood, exposing the ship's cargo on the seafloor. These cargoes, frequently ceramic containers called amphoras, retain the patterns of their original stacking in the hull. Hence ancient shipwrecks (or at least those we can find) tend to appear as piles or scatters of amphora on the seafloor.

We can learn a great deal from these artifacts: their shape and size suggests the date and place of manufacture, and traces inside often indicate the cargo (e.g. wine or fish products), and provide materials for Carbon-14 dating or other chemical analyses. Analysis of the pottery can even indicate the source of the clay. Yet most organic materials (including the ship's structure), if they are preserved, will be found below the seafloor in the anoxic mud.

Currently, Remotely Operated Vehicles (ROV's) can recover objects from the surface of the seafloor, but the ability to dig beneath to excavate buried artifacts according to scientific archaeological standards is still under development [27]. Since the organic materials are often buried underneath the amphora pile, they can only be accessed after the amphoras above them have been

recovered or moved. Yet even small samples of the hull can reveal a great deal about the ship, including materials, date, and construction technique. Where a paleontologist can reconstruct much of a dinosaur from a footprint or a few vertebrae, a nautical archaeologist can often extrapolate the shape of the hull from just a few feet of the keel [26].

It would be of extraordinary value to be able to remotely sense these buried structures in a focused and precise way. The low attenuation of acoustic energy in saltwater suggests a solution: an acoustic instrument to peer through the sediment – a high-frequency, narrow-beam sub-bottom profiler.

Sub-bottom profilers, of course, have long been in use for in geology and other oceanographic applications. Typically, they run at frequencies from 2 to 20kHz and can penetrate the seafloor to tens and even hundreds of meters. They have utility for geophysical applications such as mapping, and have even been used for archeology: either to image sites directly, or to compliment side-scan sonar data (easing the distinction between geological features and man-made ones) [3][4]. The recently-developed chirp systems, utilizing pulse compression techniques inherited from radar, have vertical resolution in bottom sediment on the order of ten centimeters [5]. Chirps, as well as parametric profilers, have been used for applications like imaging buried objects, mine-hunting, cable detection, and sediment classification [6][7]. Some experimental work has been done with very high frequency penetrators for faunal mapping [8]. A sub-bottom array has been proposed for buried objects, which might have applications for archaeological search [25].

Of these techniques, chirp sonars have been used most extensively for mapping and identifying archaeological sites. For example, Quinn et al. [9] used such a system to map the site of the *Invincible* and reveal its depositional and post-depositional history, and to map the full extent of the site. Similar work on the *Mary Rose* site provided evidence for the nature and chronology of the wreck's degradation, and identified areas away from the major wreckage where additional materials are likely to be found [10]. Similar work yielded valuable data on acoustic impedances of wood likely to be found on shipwrecks, and showed that compressional wave velocities are heavily dependent on the orientation of the grain in relation to the acoustic wave [11][12].

Still, these instruments, including the chirps, tend to have wide beam patterns (20-30 degrees), making them unsuitable for precision mapping of an archaeological site. The *Invincible* survey, for example, was conducted with 10m track lines with an instrument towed from a ship. Precision characterization of a site in deep water, however, where no human presence is possible, requires track lines spaced on the order of a meter apart, ideally closer to 10cm, and hence a narrower beam.

To overcome the limitations of existing sub-bottom system for close-in survey, we built a high-frequency, narrow-beam profiler, with a beam width of only 2-3 degrees. Because of frequency dependent attenuation in sediments, the greatest trade-off is penetration depth, which may well reduce to only a few meters. But these depths should suffice to characterize an archaeological site with a known surface expression.

III. THE INSTRUMENT

To demonstrate the promise of narrow-beam sub-bottom profiling, we assembled a prototype instrument to project a narrow sonar beam into the seafloor, record the reflections, and assemble them into images. The transducer, drive electronics, and preamplifier was developed by Marine Sonic Technology corporation (Gloucester, Virginia), a well-respected maker of side-scan sonars. The device, in fact, is essentially a commercial side-scan, with rectangular transducers laid out in rows to approximate a circle (the beam is projected directly into the bottom, rather than at an oblique angle). The MIT team supplied supporting electronics, time varying gain (TVG), the analog to digital converter, signal-processing, and software, integrated the sensor with the JASON ROV and control system, and conducted data analysis.

The device has a high frequency (150kHz), a very narrow beam (~2 degrees), and a short, broadband pulse (~40 μsec), enabling vertical resolution on the order of a centimeter (Table 1). Echoes are recorded as the envelope of the 150kHz reflections, and (like a side-scan) are assembled into images as the instrument moves across a site. While it doesn't penetrate nearly as deep into the bottom as its lower-frequency cousins, the narrow beam allows the instrument to make detailed images that depict small, buried features in the top few meters of the sediment. Acoustic penetration depth is limited by the energy of the pulse, the acoustic absorption and/or reflection of the marine sediment, and the sensitivity of the receiver. In marine sediments, these losses can be as high as 75 dB/m for 150kHz [17][21].

TABLE I
Specifications for a prototype sub-bottom profiler.

Array size	30 cm, circular
Beam width	2-3°
Center frequency	150 kHz
Pulse length	40 μsec (~ 6 cycles)
Bandwidth	34 kHz
Output power	~220 db (re 1 μPa @ 1 m)
Receiver pre-amp noise	~1 μV
Amplifier gain	12-108 dB
Time varying gain	12 bits, @400 μsec/step
A/D converter resolution	12 bits

Because its scope is so narrow, this device must be operated in a controlled manner that allows numerous measurements to be assembled into an image. A team at the Deep Submergence Laboratory of the Woods Hole Oceanographic Institution developed a system that provides closed-loop control capabilities for the JASON ROV. A precision acoustic navigation system, called EXACT, developed by author Mindell and Dana Yoerger

at Woods Hole, provides centimeter-scale positioning in three dimensions over roughly a 100 meter square. Within this space, JASON can run straight, repeatable track lines at low speeds (<10 cm/sec.) over an archaeological site [13]. When combined with other sensors, such as cameras or scanning sonars, precise maps of archaeological sites can be created under automatic control, in a matter of hours [14][15]. Such techniques are critical for conducting archaeology in deep water with remote equipment, where no human presence is possible [16]. Similarly, in precision sub bottom profiling, each individual profile is tagged with an x,y, and z position, accurate to the order of centimeters – these can then be combined into images, and referenced precisely to other data sets and to the site itself.

IV. PRECISION SUB BOTTOM IMAGERY OF A PHONECIAN SHIPWRECK

In 1999, an interdisciplinary team of scientists, led by oceanographer Dr. Robert Ballard of the Institute for Exploration and archaeologist Dr. Larry Stager of Harvard University, investigated two shipwrecks lying in 300 meters of water about 70 miles off the coast of Israel in the eastern Mediterranean. The two ships are Phoenician, and were most likely travelling from Tyre (in modern day Lebanon) to Egypt, with a load of wine. They date from about 750 B.C. [20] (Fig. 1). As is typical of ancient wrecks, the ships appear as exposed piles of amphoras, in this case about two meters high The entire site is surrounded by a scour crater, and the top of the amphora pile is about level with the ambient seafloor. On the larger of the sites, nicknamed "Tanit" after the Phoenician goddess of seafarers, JASON conducted a closed-loop survey that included the sub bottom profiler.

The profiling transducer was mounted on the bottom of JASON, giving it a clear, unobstructed view as the vehicle traversed above the site. After an initial video survey, JASON deployed two EXACT transponders around the edges of the site, to provide the precision navigation data for closed-loop control (two ranges plus depth - Fig. 2). After calibration, the vehicle ran a series of five survey lines along a roughly east-west axis over the site, spaced about 1.5 meters apart. During this survey, both digital still camera images and scanning sonar data were also recorded – for generating digital photomosaics and microbathymetry, respectively. The height of the vehicle was about 3.5 meters above the site, set by the field of view requirements for the camera and the near-field of the transducer. Data from the sub bottom instrument seemed invariant over the range 1-4 meters, with the exception of a bounce from the transducer. Hence the 3.5 meter altitude provided at least 3.5 meters of penetration before the signal was corrupted by a second return. During the survey, the sub-bottom pinged about twice per second, a rate imposed by the time necessary to send the data up the cable to a real-time console on the surface. Precision navigation associated every ping with a six-degree of freedom position and attitude vector (Fig. 3).

Figure 4 (a-f) shows the images from the profiler and navigation data, which can be viewed as cross sections through the amphora pile. Brighter colors indicate stronger returns, and the black at the top indicates the homogeneous water column with little echo. Transmit power and pre-amp gain are fixed and sealed in the transducer head, imposing some operational limits on signal strength. The prominent orange stripe is a function of front-end amplifier saturation in response to strong signal returns, and roughly indicates the region where a valid signal is received (about 1.5 msec of travel time in the bottom). Because of the large, rapid attenuation of the signal, a fast, high-dynamic range TVG is required to increase the gain rapidly (by tens of dB in a few ms) after the first bottom return is detected – a feature implemented in a later version of the system. The pixels here are approximately square, although the vertical scale does not map directly to vertical distance because of sound speed changes between the water and the sediment and within the sediment. Hence the horizontal data are marked in meters, whereas the vertical data are marked in milliseconds of travel time. The data have been corrected for changes in vehicle depth during the survey, so all data are referenced to a single pressure depth, not to the altitude of the vehicle (which would produce an artificially flat bottom).

These remarkable images clearly display the shape of the amphora pile, as well as the line separating ceramics from underlying sediment. The upward slope at the edges of the image indicates the scour crater. The amphoras themselves provide a confused return, although when one or two are in an ideal orientation they appear as cross-sections (4c, to the right edge of the pile). Most of the amphoras were filled with sediment, which reduced the tendency of the acoustic energy to resonate inside the ceramic, but occasionally such a resonance is visible (4c, d, e, vertical returns in the sediment). Immediately apparent is the fact that the pile is not all amphoras, but rests on an underlying mound of sediment. Furthermore, the shape of that sediment varies over the pile as the vehicle's track lines move south. Most important, a series of bright and dark anomalies are visible within the sediment, which are likely to be buried artifacts associated with the wreck. The darker regions, which correspond to a homogeneous material with little reflection, may even indicate waterlogged wood [11]. The anomalies indicate some spatial coherence, which varies from scan to scan.

Two additional pieces of data support the conclusion that these anomalies are buried objects, and not simply artifacts of the acoustics. First, a survey line was conducted, in a "control" area away from the wreck. (Fig. 5) It indicated the same orange stripe (again, an artifact of the amplifiers), but the data contained no targets or anomalies as appear on the site. Secondly, on the wreck site the sonar displays anomalies in places where there are no amphoras (e.g. 4b, 4f) - supporting the conclusion that they are not artifacts of complex reflection from ceramics on the surface.

IV. OBSERVATIONS

Anyone who has ever used a side-scan sonar knows that interpreting acoustic images is an uncertain affair.

This is especially true when dealing with a new sensor, in a new frequency regime, around complex sites such as this where so little is known about what lies beneath. We have not yet excavated this site so we have no "ground truth" data to compare against the sonar data. Nevertheless, the data do permit several observations and conclusions, and point the direction for further studies.

For the archaeologists this data proved valuable as indication of the extent of the buried materials on the site. Initially, some in the archaeological team suggested that the wreck had fallen over, and was lying on its side. A precise, 10cm-spaced set of sub bottom track lines running down the north side of the wreck showed few buried materials laying off the wreck, in comparison to the large number of returns from directly below the amphora pile. These data indicate that the wreck sank in an upright condition, and that those remains of the hull that do exist are directly below the amphora pile and not off to the side. Several cores of the surrounding sediment were collected, using the sub bottom data as a guide for choosing core locations.

The side lobes in the array are estimated to be 20-30db down below the central lobe, and they also have a greater angle of incidence on the bottom than the main lobe. These factors attenuate the side lobe reflections down to a point where they do not interfere with the main return – a point confirmed by preliminary results from the transducer. Were side lobe reflections dominant, one would see an effective broadening of the beam with the effect that point-source reflectors would be spread out into hyberbola-shaped returns as the sensor passed over the target (as happens with the wide-beams in traditional sub-bottom profilers or ground penetrating radar). No hyperbolas were observed, and objects in the mud display crisp outlines.

Attenuation is also a concern, as 150kHz acoustic signals are greatly attenuated in sediment [21]. We are only seeking, however, data from the top few meters, and in our preliminary investigations with the profiler off of Ashkelon, we detected returns from at least a meter down. Since then we have doubled the transmit power of the transducer by improving the drive electronics. Still, the effects of attenuation loss on the ability to image sub-bottom with high frequencies require further study. The technology may well not work well in highly reflective or absorptive bottom types. Still, most ancient wrecks found in deep water (e.g. at Skerki Bank, off Ashkelon, off Sinop) are in bottoms of fine silt or silty clay, hence the technique will still be worthwhile in deep water, even if it yields fewer results in sand.

Will artifacts simply reflect all acoustic energy, limiting the modeling to only the top layer of artifacts? This may indeed be the case, although in some waterlogged woods the transmission loss is not expected to be significantly greater than that in water. Still, we would expect hard objects will produce acoustic shadows (similar to those in side-scan imagery) that will block out imagery behind them. In itself, this will serve to identify materials of high loss or reflectivity, which is a useful result. Even if one were able to image *only* the top layer of buried artifacts, this would still be a worthwhile technique. Restating the problem in three dimensions: what if one can only image the "outline" of a buried wreck, and not its contents? Such imagery would add a great deal to our knowledge of a buried site beyond its surface expression.

V. CONCLUSION: TOWARD VIRTUAL EXCAVATION

The Ashkelon sub bottom data, with its 1.5m line spacing, is too sparse to generate 3-d images, but arranging several profiles into a perspective view gives a preliminary sense for what is possible (Fig. 6). A precise, three-dimensional map of a buried shipwreck would be of extraordinary value. Rendered volumetrically, it would indicate the nature and shape of buried structure. When cut horizontally, the data could present plan views of the site at different depths, allowing archaeologist to "virtually excavate" by peeling layers off of the site, all inside a computer without ever touching it. A precedent for such investigations exists in archaeology on land, where ground-penetrating radar (GPR) data are "time sliced" into similar horizontal layers, and even modeled in 3-D [22][23]. Similar techniques have also been extensively developed for medical applications, and may have applications for sub bottom data sets, when the latter improve in density and quality [24].

Virtual excavation will not obviate the need for actual excavation. But in deep water, with remote systems, excavation will be a slow and expensive affair. Because digging is inherently destructive, archaeological ethics dictate the minimum amount necessary to recover the desired information. For instance, precise sub-bottom imagery can aid in characterizing a site to determine if it is worthy of excavation. Many wrecks could be so imaged and left in a database for future investigation. As the Ashkelon survey demonstrated, precision sub-bottom imagery can also direct exploratory sampling, reducing the need for destructive and time-consuming trenches. And during a remote excavation, such data can aid in planning and operations by providing a preview of what the site holds beneath the surface.

The ability to precisely map below the seafloor in three dimensions is critical for understanding buried shipwrecks as archaeological sites, but it may also have applications in other areas such as environmental assessment and monitoring, geology, construction, and sub-bottom search and survey. During the Ashkelon surveys, a number of cold-seep methane vents were discovered. Similar surveys using this profiler aided geologists in characterizing the site [19].

The 1999 data proved the validity of the high-frequency, sub bottom approach combined with closed-loop control. Because the site has not yet been excavated, the data have not been ground truthed to any known structures. Hence the next logical step is to perform a similar survey with a known site. The shipwreck *Defense*, from the American Revolutionary War in Penobscot Bay, Maine, provides an ideal location for such tests. During the 1970s divers excavated the wreck, recovered many

artifacts, and mapped the structure. They left the ship itself in place and reburied it in the sediment, leaving a well-documented, buried shipwreck against which to compare a sub-bottom survey. This effort is currently underway and will be reported in future publications.
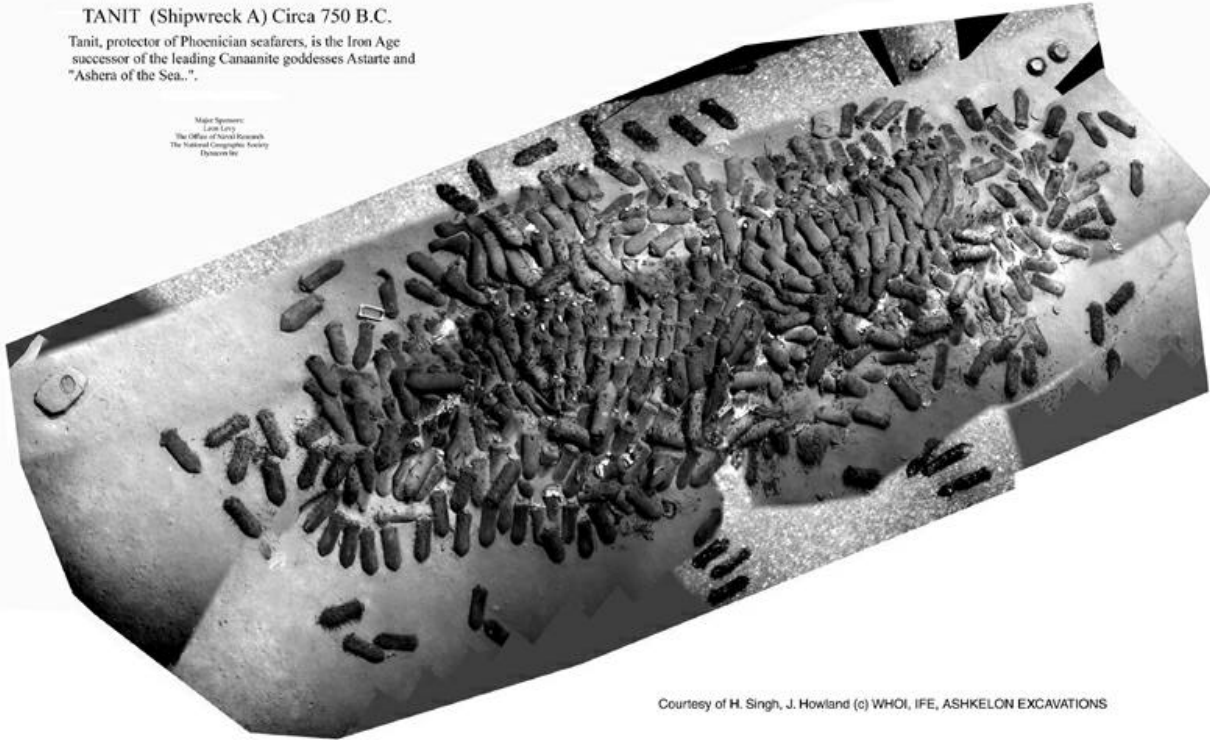
REFERENCES

[1] R.D. Ballard, A.M. McCann, D.R. Yoerger, L.L. Whitcomb, D. A. Mindell, J. Oleson, H. Singh, B. Foley, J. Adams, and D. Piechota, 2000. "The discovery of ancient history in the deep sea using advanced deep submergence technology," *Deep Sea Research I*, vol. 47 pp. 1591-1620, 2000.

[2] D. Mindell and F. Hiebert, eds.,. *Technology, Archaeology, and the Deep Sea: Proceedings from the First MIT Conference* (Plenum Press), in press.

[3] H.E. Edgerton, and P. Throckmorton, "Exploring sub bottom features of a harbor with sonar and magnetometer", *National Geographic Society Research Reports*, Washington, DC, 1969.

[4] H.E. Edgerton, E. Linder, and M. Klein, , "Sonar search at Ashdod, Israel", *National Geographic Society Research Reports –1967 Projects*, Washington, DC, 1967.

[5] S.G. Schock, L.R. LeBlanc, "Some applications of the chirp sonar," *IEEE Oceans '90*, 69-75, 1990.

[6] S. Szender, and J. Kosalos, "Development and feasibility testing of an acoustic buried cable detection system," *IEEE Oceans '97*, pp. 913-20, 1997.

[7] D. Boulinguez, A. Quinquis, "A new way of identifying buried objects." *IEEE Oceans '99* vol. 3, pp. 1552 –1556, 1999.

[8] M.H. Orr, and D.C. Rhoads, "Acoustic imaging of structures in the upper 10cm of sediments using a megahertz backscattering system: preliminary results." *Marine Geology* vol. 46, pp. 117-29, 1982.

[9] R. Quinn, J. Adams, J. Bull and J. Dix, "A high resolution geophysical investigation of the Invincible wreck site; East Solent." *International Journal of Nautical Archaeology*, vol. 27.3, pp. 126-138, 1998.

[10] R. Quinn, J. M. Bull, J. K. Dix and J. R. Adams, "The Mary Rose site - geophysical evidence for palaeo-scour marks." *International Journal of Nautical Archaeology*, vol. 26.1, pp. 3-16, 1997.

[11] R. Quinn, J. M. Bull and J. K. Dix, "Imaging wooden artefacts with chirp sources." *Archaeological Prospection* vol. 4, pp. 25-35, 1997.

[12] J. M. Bull, R. Quinn and J. K. Dix, "Reflection coefficient calculation from marine high resolution seismic reflection (chirp) data." *Marine Geophysical Researches*, vol. 20, pp. 1-11, 1998.

[13] D.R. Yoerger and D. Mindell, "Precise navigation and control of an ROV at 2200 meters depth," *ROV '92*, San Diego, CA, 1992.

[14] L.L. Whitcomb, D. Yoerger, H. Singh, and D. Mindell, "Toward precision robotic maneuvering, survey, and manipulation in unstructured undersea environments," in Y. Shirai and S. Hirose, eds., *Robotics Research—The Eighth International Symposium*, London: Springer-Verlag, 1998.

[15] H.L. Singh, L.L. Whitcomb, D. Yoerger, O. Pizarro, "Microbathymetric mapping from underwater vehicles in the deep ocean," *Journal of Computer Vision and Image Understanding* vol. 79.1, pp. 143-161, 2000.

[16] H. Singh, J. Adams, B.P. Foley, D. Mindell, "Imaging for underwater archaeology", *American Journal of Field Archaeology* vol. 27.3, 2000.

[17] R.J. Urick, *Principles of Underwater Sound* , Los Altos, CA: Peninsula Publishing, 3d edition, 1983.

[18] D. Mindell, and B. Bingham, "New archaeological uses of autonomous underwater vehicles," *IEEE Oceans '01*, Honolulu, Hawaii, November, 2001.

[19] D.F. Coleman and R.D. Ballard, "A highly concentrated region of cold hydrocarbon seeps in the southeastern Mediterranean sea," submitted to *Geo Marine Letters*.

[20] R. Ballard, L. Stager, D. Master, D. Yoerger, D. Mindell, L. Whitcomb, H. Singh, and D. Piechota, "Iron age shipwrecks in deep water off Ashkelon, Israel," *American Journal of Archaeology*, Oct. 2001.

[21] L.R. LeBlanc, S. Panda, and S.G. Shock, "Sonar attenuation modeling for classification of marine sediments," *Journal of the Acoustical Society of America,* 91 (1):116-124, 1992.

[22] L.B. Conyers and D. Goodman, *Ground Penetrating Radar: An Introduction for Archaeologists* (Walnut Creek, Calif.: Altamira Press, 1997).

[23] Geophysical Survey Systems Inc., Sales literature, RADAN 3-d imaging software, 2000.

[24] See, for example, MIT A.I. Lab, Medical Vision Group, http://www.ai.mit.edu/projects/medical-vision/

[25] S.G. Schock, "Buried object scanning sonar." Proceedings, *Oceanology International'98*, Brighton, U.K., v. 2: 10-13, March, 1998.

[26] J. Delgado ed., *Encyclopedia of underwater and maritime archaeology*, New Haven: Yale, 1997.

[27] F. Soreide and M.E. Jasinski, "The *Unicorn* wreck, central Norway – underwater archaeological investigations of an 18th-century Russian pink, using remotely-controlled equipment." *International Journal of Nautical Archaeology* 27.2, pp.95-112, 1998.

TANIT (Shipwreck A) Circa 750 B.C.

Tanit, protector of Phoenician seafarers, is the Iron Age successor of the leading Canaanite goddesses Astarte and "Ashera of the Sea..".

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Figure 1: Photomosaic of "Tanit" 8th-century B.C. Phoenician shipwreck found off of Ashkelon, Israel. Note the stone anchor at extreme left, indicating the bow, and two cooking pots for the crew at upper right, indicating the stern. The amphora pile is roughly 18 x 6 meters, and rises up about two meters from the seafloor. Courtesy H. Singh, J. Howland. © WHOI, IFE, Ashkelon Excavations.
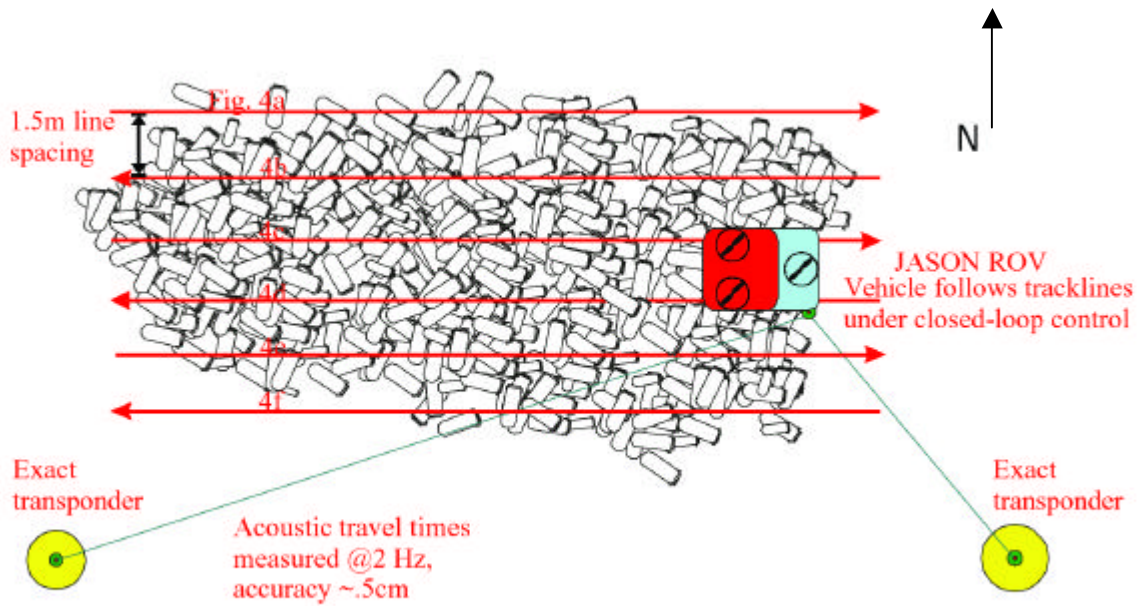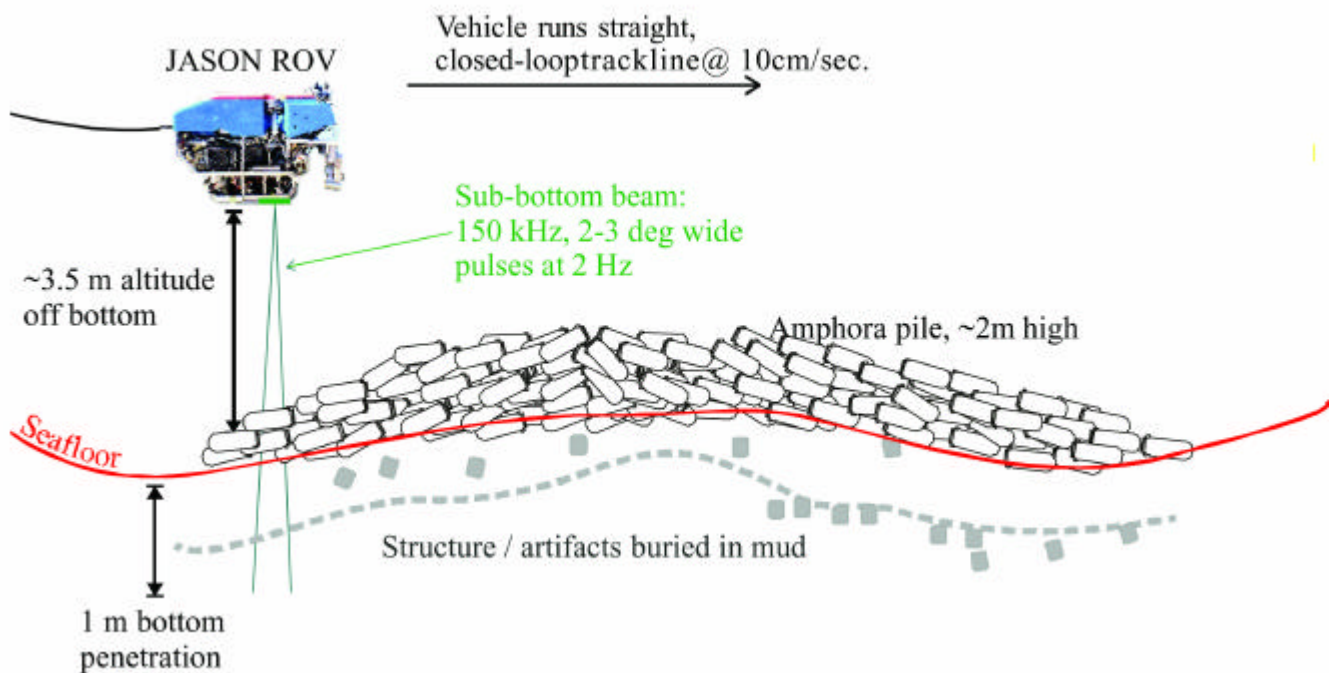
Figure 2: Top view of geometry of JASON "closed-loop" control. EXACT transponders are laid next to the wreck by the ROV, and then provide absolute positioning accuracy for the vehicle to run slow, precise track lines while collecting optical, sonar, and sub bottom data. Track lines shown are approximate, for clarity.

Figure 3: Side-view geometry of JASON track lines, high-frequency sub bottom coverage and data interpretation for slices generated by sub bottom profiler (figures 4a-f).
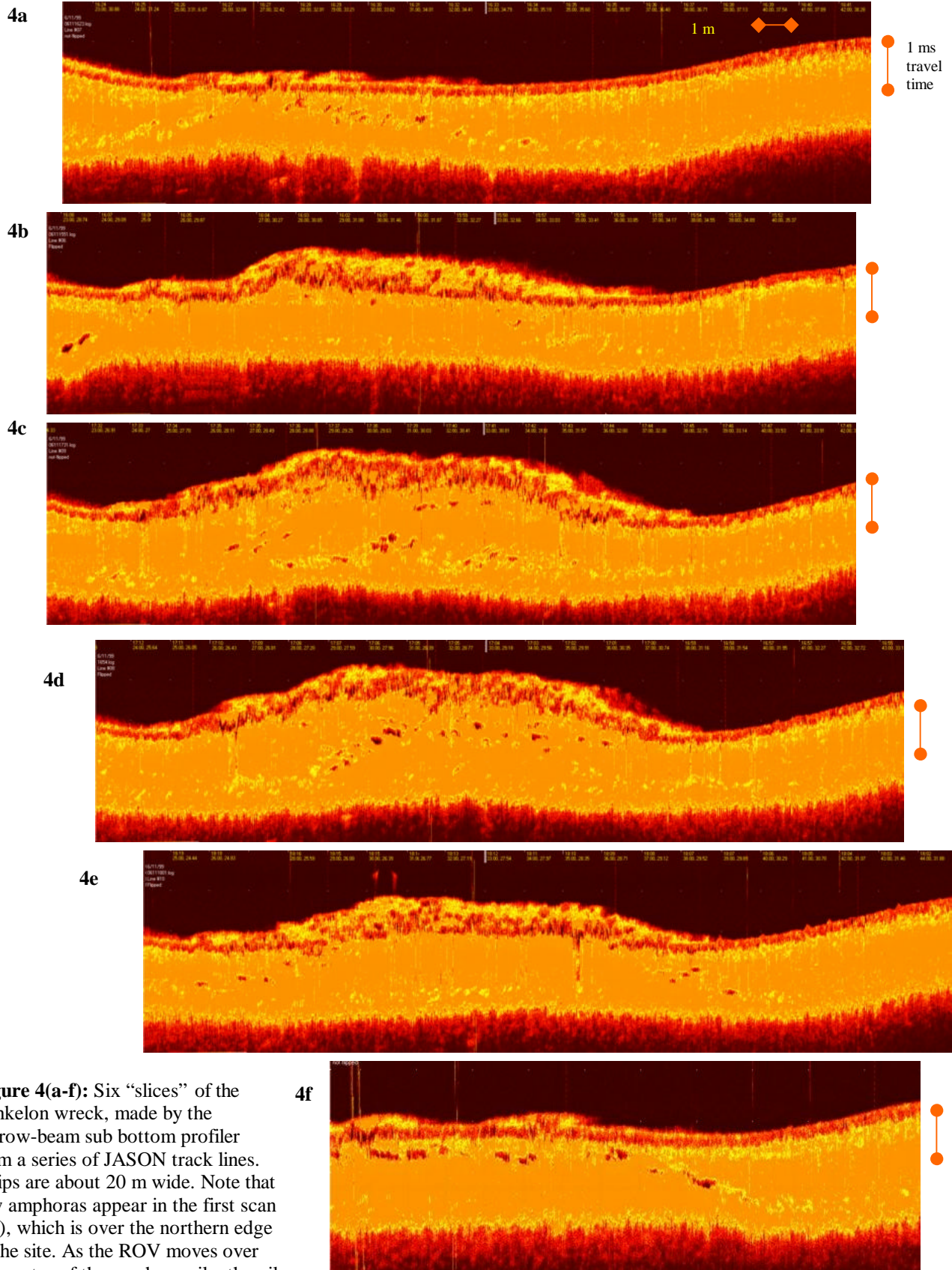
Figure 4(a-f): Six "slices" of the Ashkelon wreck, made by the narrow-beam sub bottom profiler from a series of JASON track lines. Strips are about 20 m wide. Note that few amphoras appear in the first scan (4a), which is over the northern edge of the site. As the ROV moves over the center of the amphora pile, the pile becomes more prominent (4b-e), and then recedes (4f) as the vehicle moves off the pile. See figure 3 for interpretation.
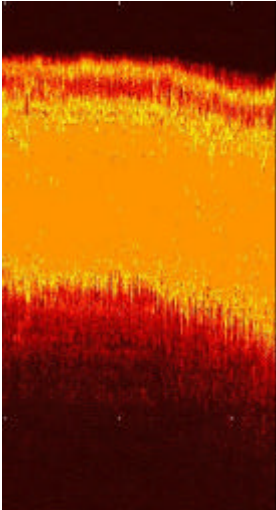
Figure 5: Portion of control survey, nearby the wreck but outside the debris field. No targets are visible within the scanned region.
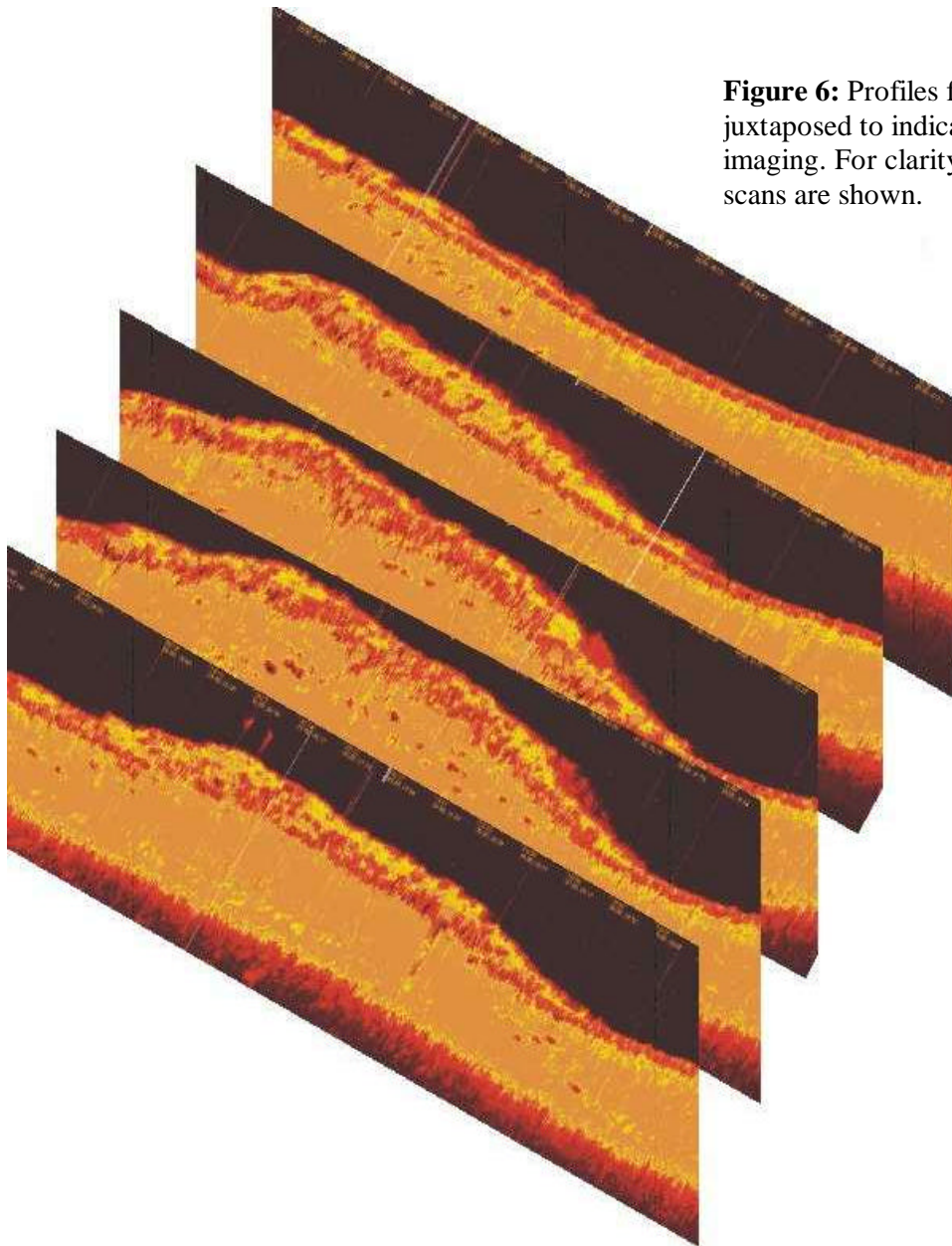

Figure 6: Profiles from figure 4 juxtaposed to indicate the potential of 3-d imaging. For clarity, only five of six scans are shown.