High Resolution Optical Imaging for Deep Water Archaeology

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Abstract

High resolution imaging in the context of deep water archaeology presents some unique challenges. The constraints of the underwater environment on optical and acoustic modalities, the characteristics of underwater imaging platforms, the lack of sufficiently high update rate, high resolution navigation, and the requirements for highly precise mapping all contribute to making this a particularly difficult problem.

In this paper we examine each of these constraints and discuss algorithmic and practical methodologies towards the goal of precise and repeatable high resolution mapping of archaeological sites of interest underwater. We present these techniques with illustrative examples based on optical black and white and color imagery and multibeam data taken with platforms as diverse as the NR1 nuclear submarine, the Jason and Hercules ROVs at a variety of archaeological sites including Roman shipwrecks at Skerki Bank, Phoenician shipwrecks off the coast of Israel and the wreck of the RMS Titanic in the North Atlantic.

I. Introduction

The physical characteristics of the medium lead to fundamental constraints on high resolution imaging underwater (Jaffe 1990; Singh, Adams et al. 2000)for both optical and acoustic imaging. In addition, the platforms(Yoerger and Mindell 1992; Singh, Armstrong et al. In Review) from which these imaging sensors are deployed impose their own set of operating constraints as does the infrastructure associated with navigating(Whitcomb, Yoerger et al. 1999) these assets. In this tutorial we look at these effects separately and in combination with a particular emphasis on the applications for deep water archaeology.

If we consider optical imaging, the primary consideration is that of the rapid and nonlinear attenuation of the visible spectrum in seawater(McGlamery 1975). Individual images may be degraded in intensity due to non-uniform lighting and degraded in color due to the nonlinear attenuation of color. Also large objects cannot be framed within a video or other optical camera's field of view. Thus obtaining a global perspective of an archaeological site of interest on the seafloor cannot be accomplished with a single image. Instead this involves running a carefully planned survey over the site, collecting a series of overlapping images, identifying common features in the overlapping imagery, and then merging these images into a composite photomosaic(Pizarro and Singh to appear).

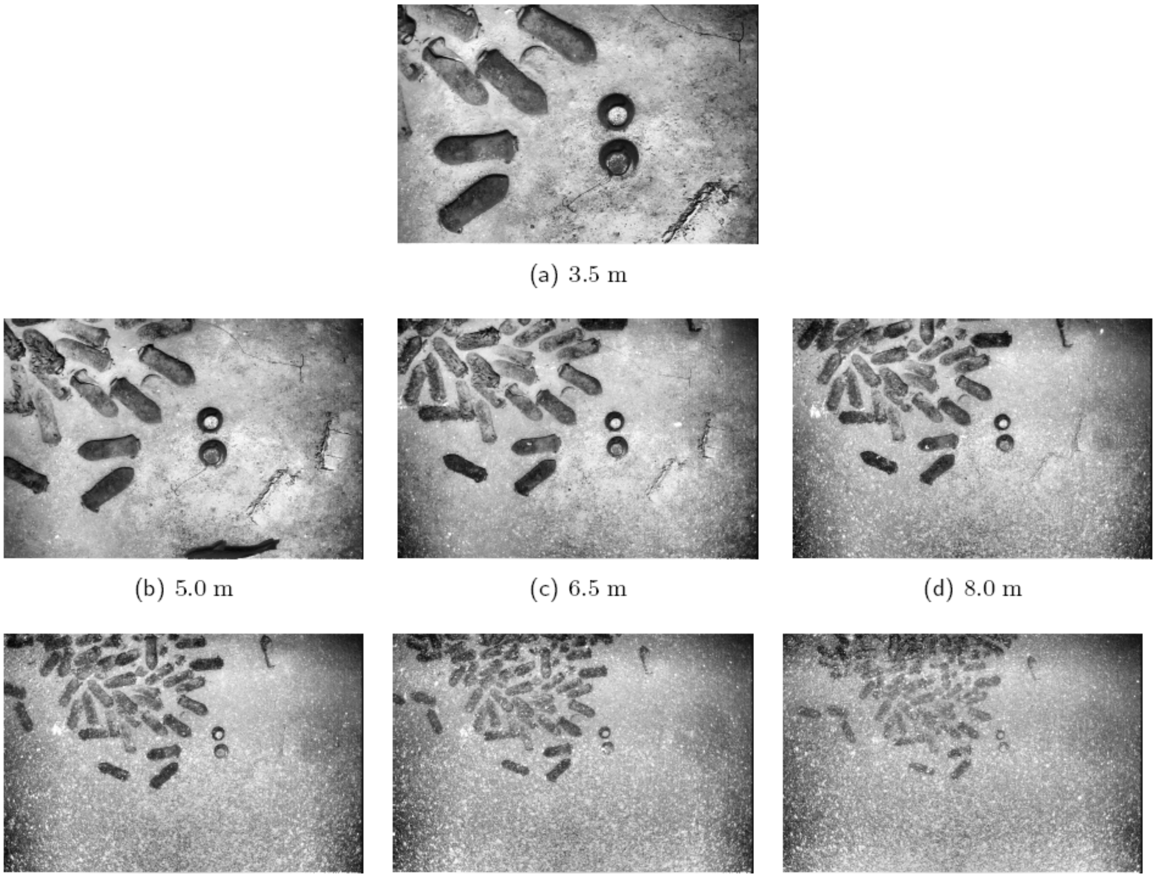
Several factors make this a hard problem. There may be constraints on the way underwater vehicles can perform surveys due to insufficient accuracy in small-area navigation and a lack of mechanisms to automatically control the vehicle. Physical constraints on the distance separating cameras and lights as well as constraints on the energy available for operating the lights also constitute major impediments. Finally, and most important, the unstructured nature of the underwater terrain introduces incremental distortions into the photomosaic as successive images are added into the composite mosaic.

In the rest of this paper we look some of the issues highlighted above. Section II looks at the issues associated with obtaining the best possible imagery in underwater environs. Section III looks at how we register individual overlapping images to form a composite or photomosaic. Section IV examines how we can utilize such imagery to construct three dimensional image reconstructions or stereo photomosaics using a single moving camera. Finally Section V concludes with a look at other modalities for high resolution imaging and how they complement optical imagery.

II. Obtaining High Quality High Resolution Imagery Underwater

II.1 Lighting, Backscatter, and Camera-to-light Separation

For the purposes of high resolution imaging underwater one of the primary issues is the amount of power available for lighting. The rapid attenuation of the visible spectrum underwater implies that we considerable light energy to image objects that are far away from the imaging platform. However, it is not enough to simply put more energy in the water. One other complication arises in underwater imagery due to the presence of suspended particles in the water column. As we increase the amount of light energy in the water, it winds up being backscattered by the suspended particles and obscuring the object of interest. Instead one must make an effort to separate the camera and light source to minimize the common volume illuminated while ensuring uniform lighting over the area of interest. A good example of this phenomenon is illustrated in the image sequence shown in Figure 1. The images vividly illustrate the trade-off in image quality versus image coverage for a given (in this case the Jason ROV) imaging platform.


(a) 3.5 m

(b) 5.0 m

(c) 6.5 m

(d) 8.0 m

Figure 1. The effects of backscatter for a particular geometry can be clearly seen in this image sequence. Imagery was acquired from the same camera and lighting geometry every 1.5m as the Jason ROV went up vertically over the site of a shipwreck in the eastern Mediterranean. One can clearly see the degradation due to backscatter as the distance between the vehicle and the site of interest increases.

Imaging platforms with larger baseline separation are thus preferable but ultimately the separation can become so large as to cast virtual shadows due to inadequate light energy being reflected along the direct path from object to camera(Singh, Howland et al. 2000).

II.2 Lighting Equalization

The nonlinear attenuation of the visible spectrum often yields non-uniform lighting across an image. Non-uniform lighting may arise in an image due to difference in path lengths between different parts of the image in relation to the light source. For example the center of an image may be more brightly lit than the edges. Standard methods exist in the image processing literature for dealing with such situations. They vary from simple adjustments to methodologies for adaptive histogram equalization based on different intensity distributions(Eustice, Pizarro et al. 2002). Figure 2 shows a typical low contrast image on the right as taken by the ABE AUV that manifests non-uniform lighting with a brighter center and a dropoff in image intensity towards the corners. The left image is the result of adaptive histogram equalization applied to the image on the right. While measures for image enhancement are subjective the left image is more uniformly lit and has far greater contrast.

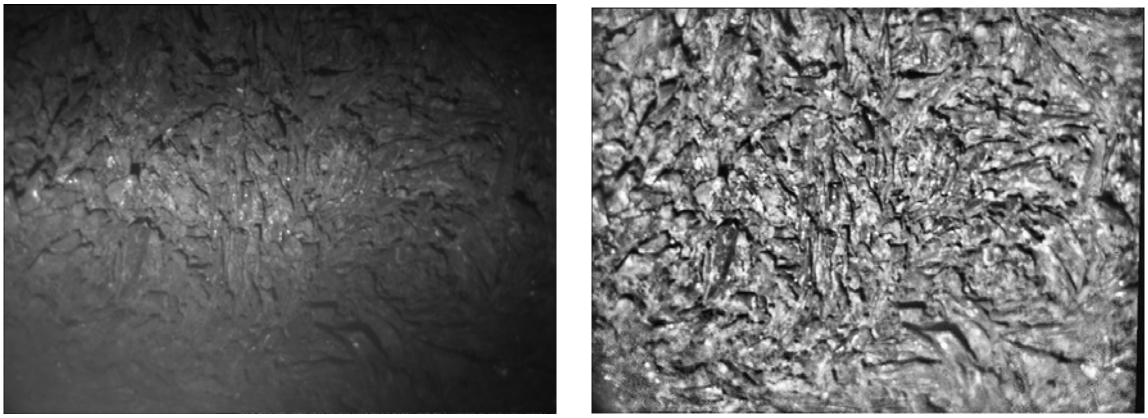


Figure 2. Original low contrast imagery (left), and its adaptively histogram equalized counterpart (right). The image on the right is more uniformly lit and has far greater contrast.

II.3 Color compensation

One other aspect of individual images underwater is that associated with color imagery. The nonlinear attenuation of the visible spectrum underwater leads to imagery that, depending upon the emitted light spectrum, color response of the camera and distance to the object can yield imagery that has preponderance of green or blue.

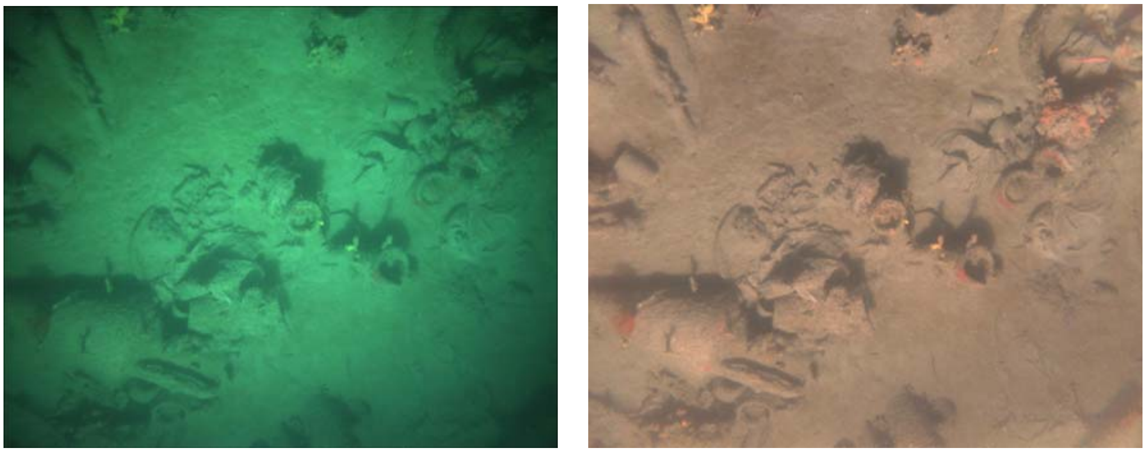


Figure 3. Original color imagery (left) and its color compensated counterpart (right). The image on the right shows color fidelity that is independent of the camera, lighting system and distance between camera and object.

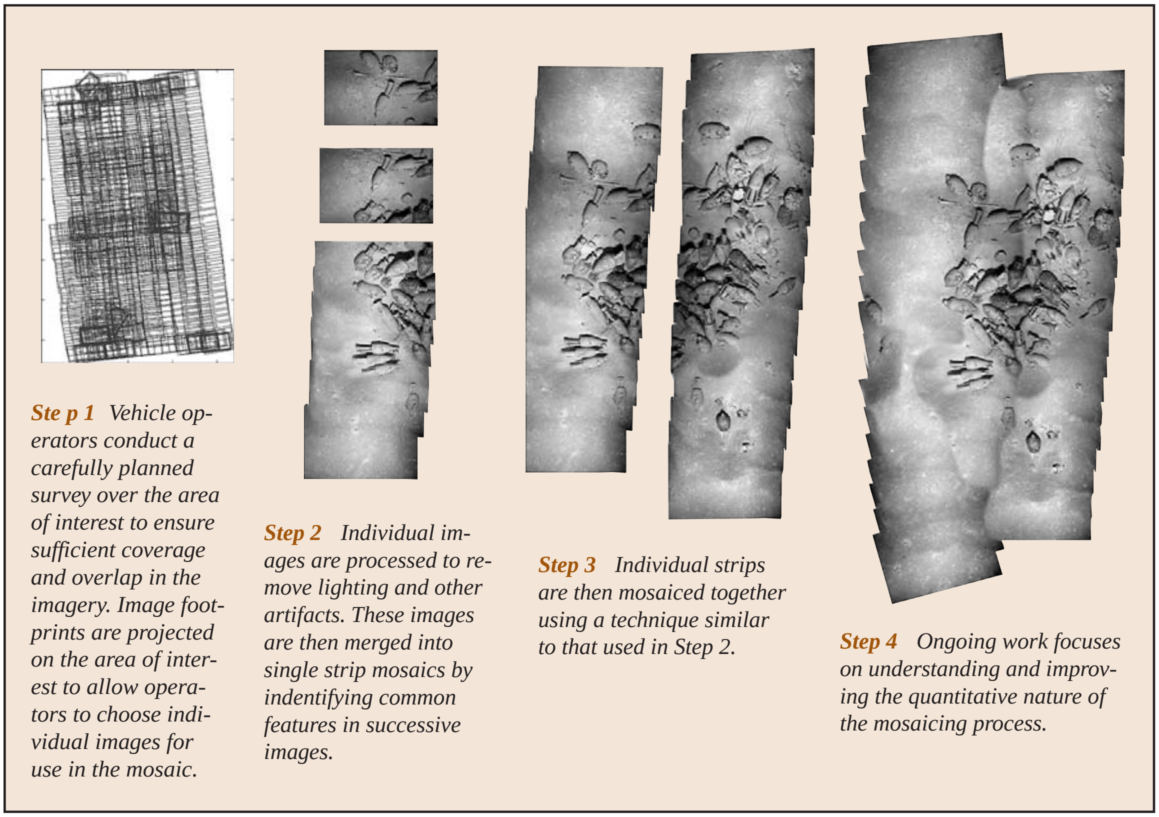
One way of overcoming this effect is by utilizing cameras with high dynamic range. The enhanced dynamic range allows us to separate out the components of color that are a function of attenuation and that vary slowly across the image as opposed to the higher frequency components that are associated with differences in color inherent to the objects being imaged. This process is illustrated in Figure 3 where we can see the effects of our algorithm when applied to imagery collected on a 4th century B.C. shipwreck in the Aegean Sea.

III. Photomosaicing

III.1 Photomosaicing Planar Sites

As was alluded to earlier, a composite view of a large area underwater can only be obtained by exploiting the redundancy in multiple overlapping images distributed over the scene through a process known as photomosaicing. Mosaicing assumes that images come from an ideal camera with known camera and lens geometry and that the scene is planar. Although there has been considerable effort in this regard for land-based applications, the constraints on imaging underwater are far different. These assumptions often do not hold in underwater applications since light attenuation and backscatter rule out the traditional land-based approach of acquiring distant, nearly orthographic imagery. Underwater mosaics of scenes exhibiting significant 3D structure usually contain significant distortions. However, for planar sites one can build a reasonable qualitative representation of the objects being imaged.

Typically, vehicle operators conduct a planned survey over the site to ensure sufficient, redundant coverage to allow us to combine, either automatically or manually, individual images into strips that are then assembled into a composite large area mosaic as illustrated in Figure 4.



Step 1 *Vehicle operators conduct a carefully planned survey over the area of interest to ensure sufficient coverage and overlap in the imagery. Image footprints are projected on the area of interest to allow operators to choose individual images for use in the mosaic.*

Step 2 *Individual images are processed to remove lighting and other artifacts. These images are then merged into single strip mosaics by indentifying common features in successive images.*

Step 3 *Individual strips are then mosaiced together using a technique similar to that used in Step 2.*

Step 4 *Ongoing work focuses on understanding and improving the quantitative nature of the mosaicing process.*

Figure 4. The Process of Photomosaicing

An example photomosaic of the so-called Skerki D shipwreck(Ballard, McCann et al. 2000) is shown in Figure 5. Composed of over 180 images collected over four individual tracklines this mosaic provides a high level perspective of the entire site is physically impossible to obtain any other way. Note the use of image equalization techniques that have minimized the effects of different tracklines while preserving the variations in shading attributable to the depressions in which some of the amphorae are situated.

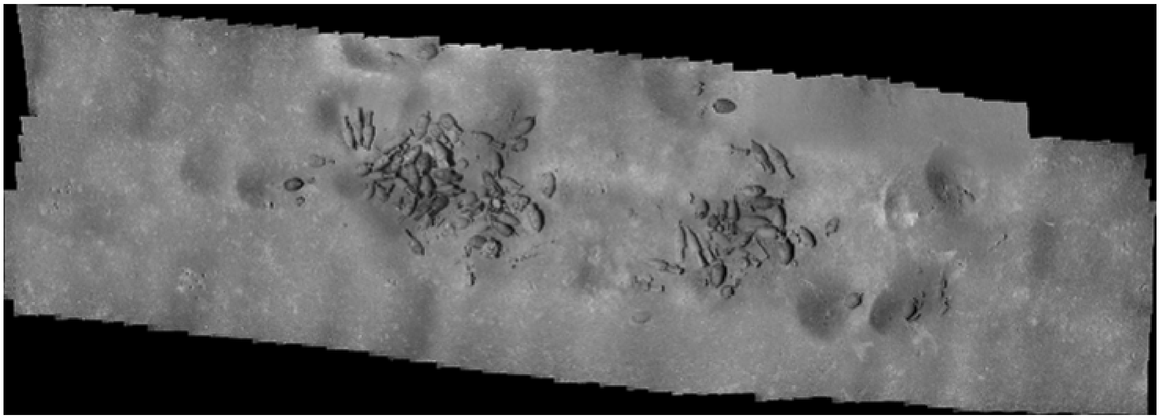


Figure 5. A 180 image mosaic of the Skerki D shipwreck constructed from high dynamic range imagery collected by the Jason ROV. This site is relatively flat so that the photomosaic provides a reasonable overall perspective of the site.

III.2 Photomosaicing Non-planar Sites

If we consider large sites with non-planar geometries where there is significant relief as measured with respect to the field of view, mosaics can become highly distorted. A good example is seen in Figure 6, where we have tried to mosaic together three different passes over the "Tanit" Phoenician shipwreck(Ballard, Stager et al. 2002) located off of the coast of Israel.

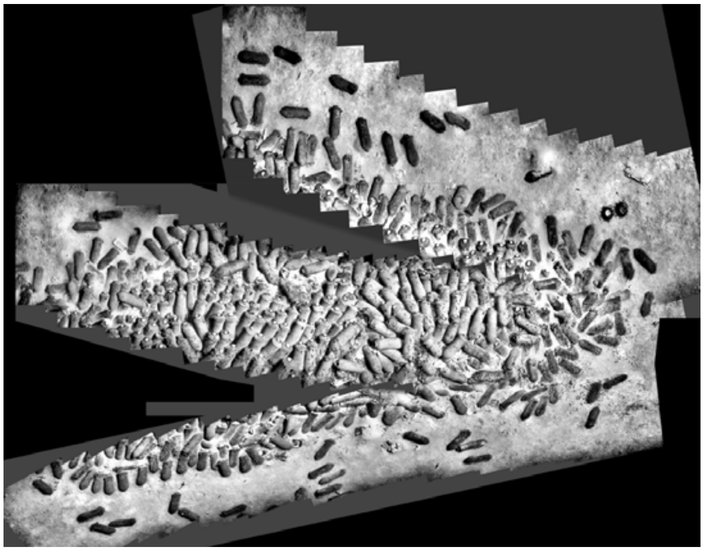


Figure 6. The effects of terrain on photomosaicking. Differences in depth of the order of a meter, compared to the four meter altitude from which this imagery was obtained, result in distortions of the individual strips. The problem is essentially of representing a three dimensional unstructured surface on a two dimensional plane.

For this site physical oceanographic or possibly ship impact effects have scoured out a depression around the wreck so that the difference in height from the central portion of the wreck to the depression is greater than one meter. This difference in altitude is comparable to the 4m altitude that the Jason ROV was flying while acquiring this imagery. Thus if consider three overlapping passes over the wreck (Figure 6) the pass over the centre is relatively undistorted as all the amphorae within the imagery lie at roughly the same depth. The two passes on either side however, span the central mound as well as the depression around the site. As we would expect from the geometry illustrated in Figure 7, each of these passes gets skewed away from the amphorae pile as successive images are added to the strip. Also, as expected the amphorae which have spilled over into the depression appear much bigger than those in the central pile even though they are all the same size.

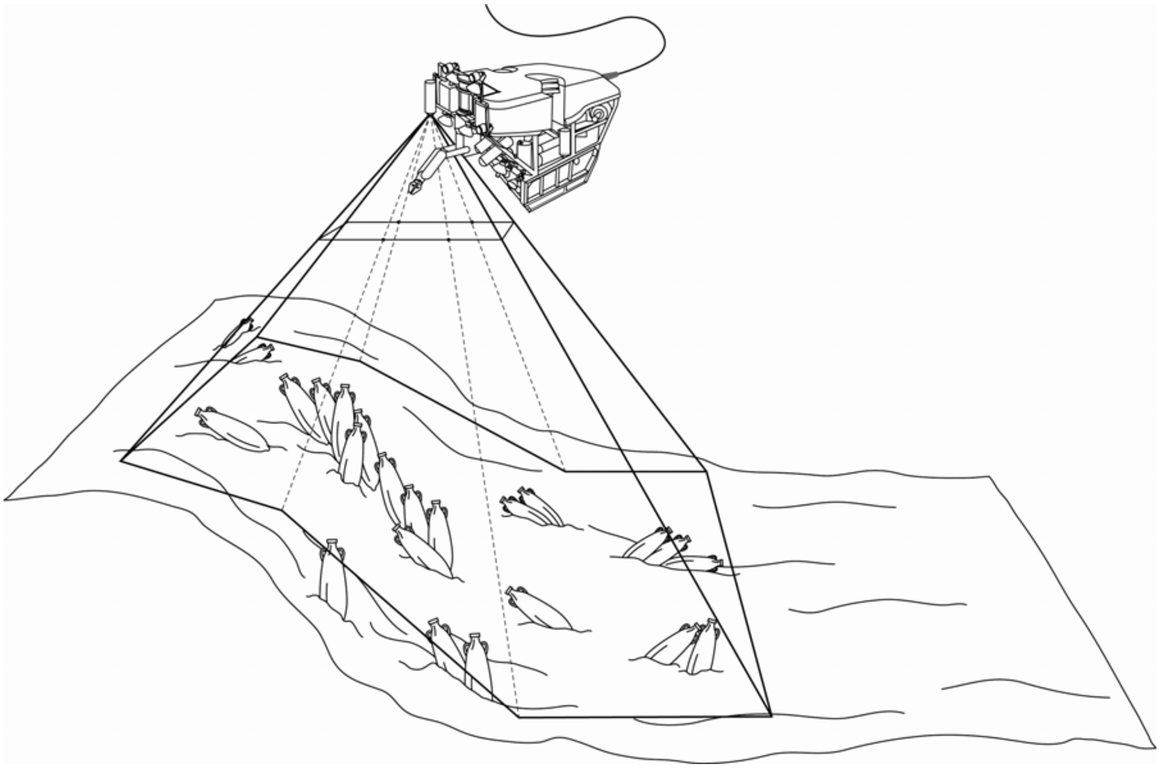


Figure 7. The geometry of image formation in an unstructured terrain. Equal sections in the image plane do not represent equal areas on the seafloor. Projective transformations do not accurately capture the image-to-image geometry. This can lead to significant distortions as shown in Figure 6.

Essentially the problem is of projecting a three dimensional unstructured terrain on a two dimensional planar surface. Several possible solutions suggest themselves. The overlapping imagery could be utilized to obtain a three dimensional image reconstruction of the site under consideration as outlined in the next section. We could also utilize other sensor data to correct or compensate for the distortions.

In this case an alternate method was utilized which produced reasonable results. We surveyed the wreck from a much higher altitude to minimize the effects of perspective distortion. The imagery acquired was of quite poor resolution due to backscatter effects but was easy to mosaic as shown in Figure 8(top). The individual strips could then be overlaid over this mosaic which served as an undistorted basemap for the individual strip mosaics distorted by the effects of terrain to form a consistent high resolution mosaic of the site even in the face of significant terrain as shown in Figure 8(bottom).

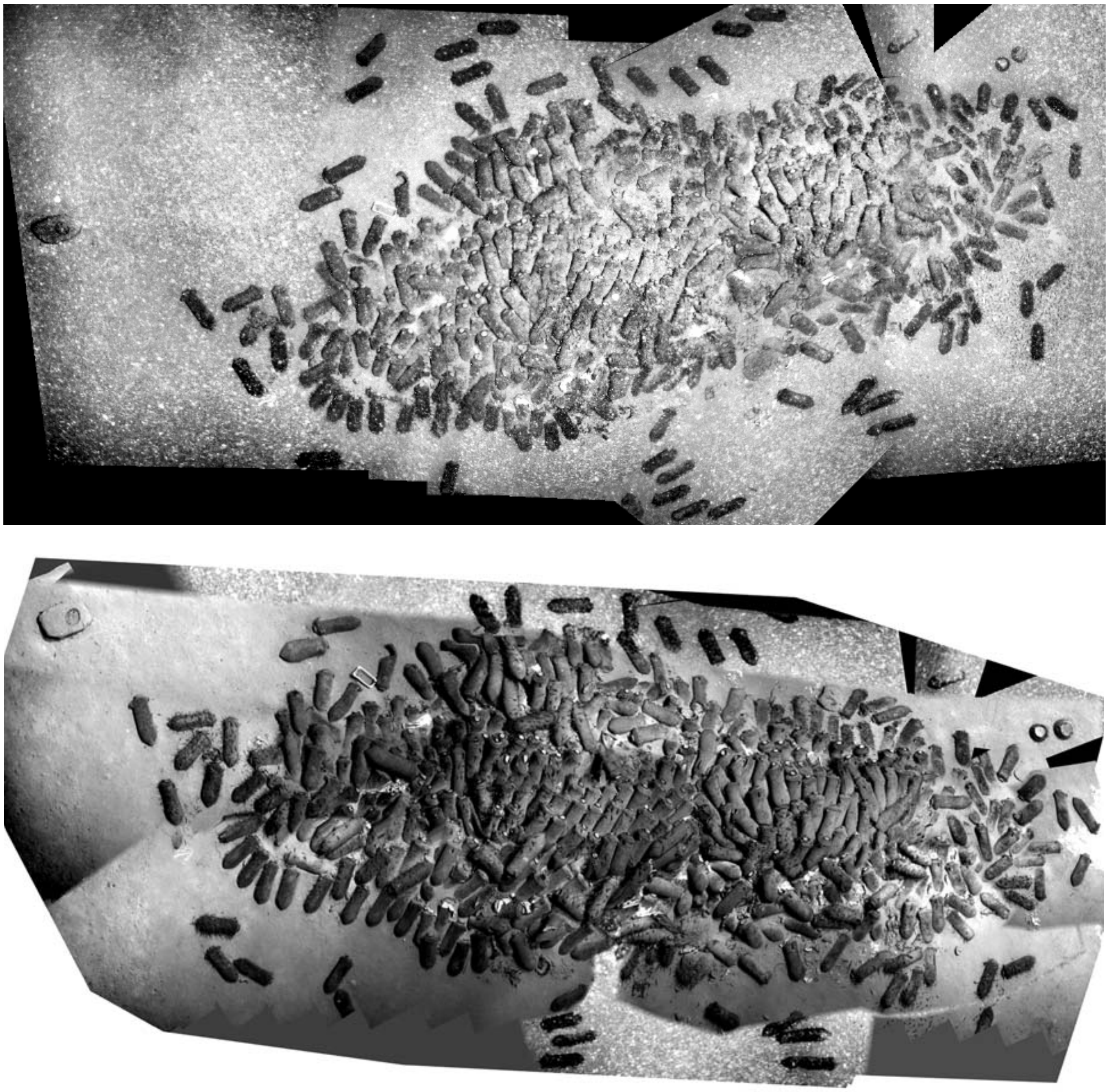


Figure 8. A high altitude pass over the wreck results in imagery that is relatively distortion free and easy to mosaic although it is marred by significant backscatter. This can however be used as a basemap to compensate for distortions in the low altitude strips to build a high resolution mosaic of the site.

IV. Three Dimensional Structure from Motion or Stereo Photomosaics

In contrast to mosaicing, the information from multiple underwater views can be used to extract structure and motion estimates using ideas from structure from motion (SFM) and photogrammetry.

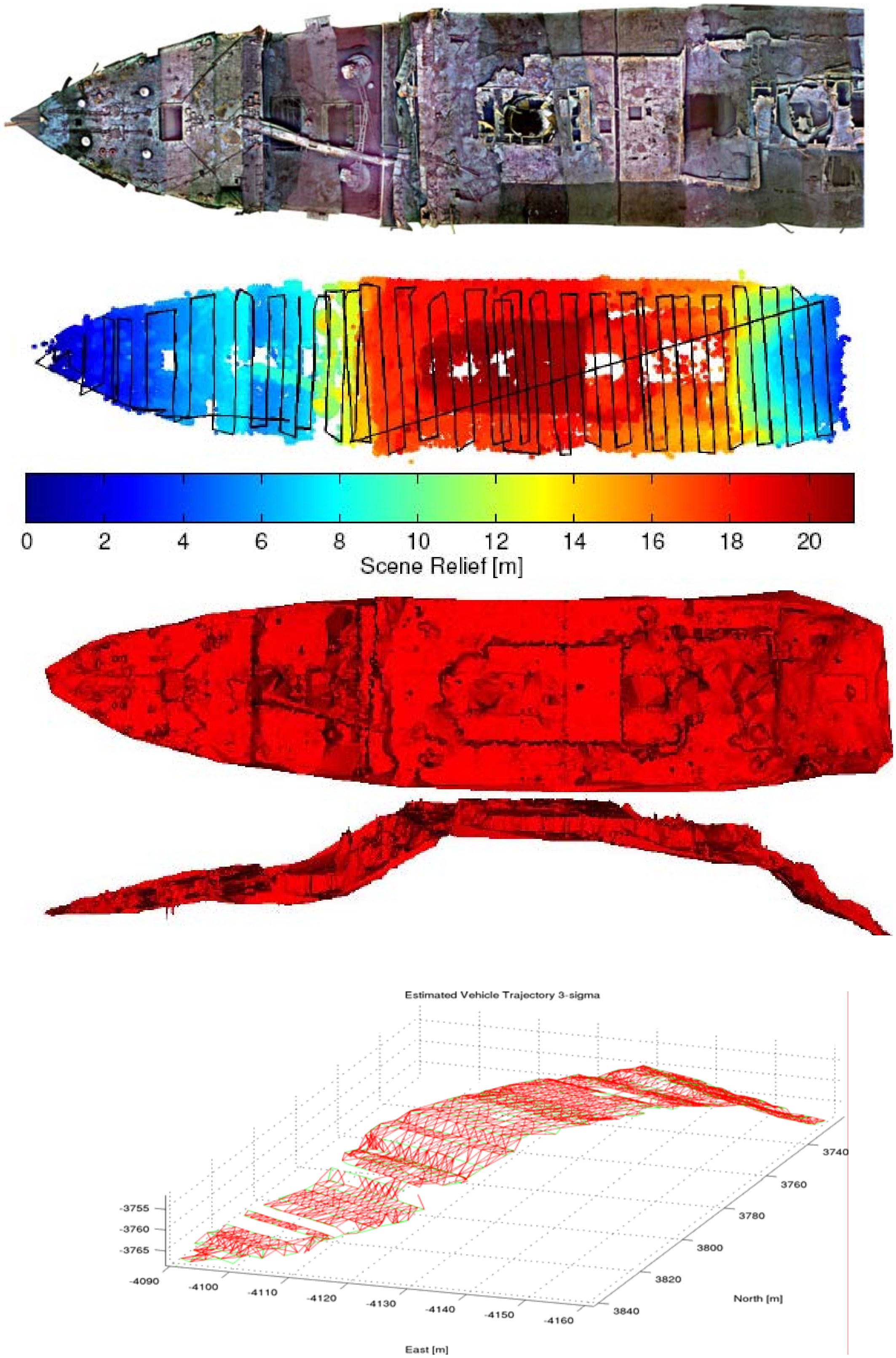


Figure 9. (top) A photomosaic of part of the wreck of the RMS Titanic. (middle) Different views of the 3D image reconstruction derived from the same set of imagery and (bottom) the camera state estimates simultaneously derived from the imagery. In comparison to the photomosaic we can make quantitative statements about the accuracy of our reconstruction and use it for mensuration on the site of interest.

The basic idea behind these algorithms is to utilize geometric constraints between successive images to allow us to simultaneously estimate the three dimensional structure of the underlying scene as well as the precise position of the camera for each image. By concatenating pairs of such relationships and then optimizing the results over the entire set of images one can obtain highly constrained three dimensional structure and camera (vehicle) poses over large sites underwater. In contrast to photomosaics such reconstructions are quantitative and can thus be utilized for direct measurements of artifacts and for quantifying the spatial relationships between objects.

V Conclusions

In this tutorial we have tried to examine the issues associated with high resolution imaging underwater of large sites with optical sensors. While some of these technologies are relatively mature a number of the techniques presented in this tutorial are still the subject of active research efforts in the imaging community. In addition, it must be pointed out that optical imaging is often used in combination with other sensing modalities including acoustics and lasers. There is also considerable work in related areas of GIS systems, and computer visualization that may be germane to the archaeologist interested in high resolution imaging of sites underwater.

VI References

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