AUV-derived geographical photomosaics – using multibeam bathymetry to correct image placement

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***Abstract*—A photomosaicking technique was improved by incorporating data from multibeam bathymetry acquired simultaneously with the seafloor images. AUV navigation logs are used to geographically place the images, as has been previously documented. This revision accounts for navigation offset and drift by using multibeam processing tools to refine image placement. The processed bathymetric grid combined with vehicle logs allow for the scaling of image size and illumination to produce more accurate photomosaics.**

Keywords—photomosaicking; seafloor mapping; AUV navigation

I. Introduction

In 2009 the National Institute for Undersea Science and Technology (NIUST) acquired the hovering AUV *Mola Mola*. The first photos were stitched together using software, primitive by today's standards, which matched control points between adjacent images. Without any constraint on geographical positions, the mosaics rapidly warped from real space as more and more images were added. In early 2010, the groundwork was set for a mosaicking solution which relied solely on vehicle navigation logs instead of graphical control points. Due to the substantial systems integration carried out in order for *Mola Mola* to be capable of deep sea mapping missions, successful grid surveys were not completed until late 2012. At which time, three sites from 860m to 1630m were mapped in the Mississippi Canyon region of the Gulf of Mexico.

During these and subsequent photosurveys of the deep Gulf, several observations were made which further prohibited pure graphical techniques. As a limitation of the mission plans and the imaging system itself, the survey suffered from lack of acrosstrack overlap and occasional alongtrack gaps caused by dropped frames. Even recent surveys have little acrosstrack coverage as a compromise to allow greater overall survey coverage. The bottom type in many of the survey areas was largely homogeneous mud separating coral communities, carbonate outcrops, gas hydrates, and even shipwreck remains. Both the gaps between images and the homogeneous terrain result in a lack of control points between images, causing failure of a purely graphical technique.

The solution of using a mosaicking technique based purely on vehicle navigation rather than graphical image content overcame the limitations of ambiguous or nonexistent control points. This solution did, however, couple the high resolution photos to the accuracy of AUV navigation, which can be poor in deep water, even when acoustic position aiding is available. The intent of the method is to correct navigation within a few meters absolute accuracy and produce mosaics that maintain geographical integrity over the entire survey area. This goal has been met, but the technique does have downfalls. Where the purely graphical techniques suffer from geographical distortions on a large scale, they do typically merge neighboring images cleanly with few artifacts. The compromise with the geographical technique is that integrity is maintained on a large scale, but poor matching is made between neighboring images causing harsh edge effects and mosaic artifacts. An ideal approach would require a combination of both methods, however, work still exists for improving the geographical element of the process.

In the initial implementation of the geographical mosaicking technique, uncorrected vehicle logs were used for image placement, and the raw images captured by the imaging system were processed independently [1]. The results were surprisingly good, and a general guide to bottom types and target locations was provided clearly by the early mosaics. A major element of the next revision was to attempt to correct for navigational drift by examining re-imaged areas appearing in both the main survey and its crosslines [2]. In effect, this process was to use graphical control points shared between images appearing several meters apart, and apply a linear drift correction over the entire survey. While the drift of a DVL-aided inertial navigation system is nonlinear, it often exhibits a strong linear trend over the course of a 6-hour survey, so an incremental improvement was made. Continuing to refine this technique seemed to only produce a small gain, however, it indicated the further importance of correcting navigation over the duration of the survey.

Up to this point, the poorly-tuned Imagenex DeltaT multibeam echosounder data had been completely overshadowed by the primary sensor, the camera. Although parameters and procedures had to be varied to produce useful data, the resulting processed multibeam bathymetry allows for correction of navigational drift due to the overlapped sonar swaths. By overlaying image center coordinates atop the resulting bathymetric grid, nadir altitudes of the images could be determined. Having the proper camera altitude then allows for image size scaling and illumination correction. Fig. 1 indicates the revised procedure, in which raw vehicle navigation is input along with DeltaT data into an extensive processing effort using MB-System, resulting in improved navigation and a bathymetric grid. Along with the image logs,

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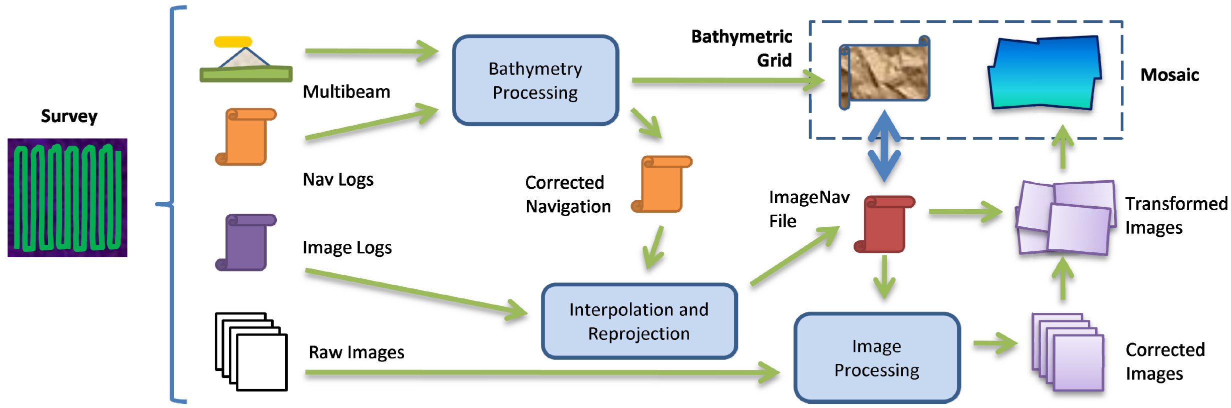

Fig. 1 Geographical mosaicking process diagram

these can be used to generate an "imageNav" file containing all camera geometry and geography. This file aids the image processing step, and from it, the necessary inputs for the mosaic generation step are produced.

II. Acquisition

From the time the first photosurveys were completed, many changes have been made to elements of the acquisition process, including vehicle software, mission behavior, and general operational procedures. These revisions each came from observations made during processing between cruises, and sometimes during cruises. Any errors or deficiencies in this step will plague all subsequent processing efforts.

A. The Mola Mola AUV

Mola Mola is a SeaBED class AUV [3] consisting of a positively buoyant upper pod and negatively buoyant lower pod separated by vertical struts. This distribution of buoyancy and mass allows it to resist pitch and roll forces. Along with its two horizontal thrusters and single vertical thruster, this arrangement allows it to function as a slow moving, near-seafloor photographic platform. It was acquired by NIUST, which is a partnership between the University of Mississippi and the University of Southern Mississippi, to work alongside their larger and faster *Eagle Ray* AUV. The two have been utilized on joint missions in which *Mola Mola* is deployed to survey areas of interest located during an initial *Eagle Ray* overview.

An AVT Manta industrial camera with an 8mm Schneider Optics lens is the centerpiece of the imaging system. It is assembled in a DeepSea Power & Light flat-port housing and connected to the main electronics housing using a power-over-gigabit-Ethernet protocol. A pair of DeepSea Power & Light LED arrays synchronized with the camera are located fore and aft on the lower pod, with the camera just starboard of the centrally-mounted thruster. The DeltaT multibeam echosounder is located forward in the lower pod, while the IxBlue Phins (an inertial navigation system) and Doppler velocity log (DVL) are located in the rear of the lower pod. This distribution is shown in Fig. 2.

The Phins is the hub of the navigation system, with all navigation sources supplied directly to it or relayed through the control computer [4]. External position aiding is provided to the Phins by transmitting navigation offsets to the vehicle through acoustic telemetry, or by the vehicle interrogating acoustic beacons placed on the seafloor. In addition to the formatted output from the Phins for general vehicle navigation, a second auxiliary position output is used to log latitude and longitude to 8 decimal places rather than 6 in the originally selected feed. This additional precision makes a significant difference in the relative positioning of images and multibeam pings.

Mission duration is roughly 6 hours, although the vehicle is currently undergoing a battery refit to a set of pressure tolerant modules purchased from SWE in 2014. Addition of a descent weight mechanism was necessary prior to the successful photosurveys to improve efficiency and to reduce the duration of free-inertial drift that occurs when the vehicle is in the water column with only sporadic acoustic updates. Expendable descent weights are used on all but the shallowest dives.

B. Survey Mission

The typical survey mission covers roughly 60m by 60m at a survey altitude of 3m. Line spacing was recently reduced to 1.8m from 2.0m in order to improve mosaic quality while marginally increasing overall survey duration. A recent survey is shown in Fig. 3. The tight survey proceeds slowly with *Mola Mola* traveling at 0.2m/s. The vehicle control routines have been modified such that this speed is further reduced as a function of altitude error from the nominal 3m. Two crosslines are appended to the grid pattern. Early surveys had both crossing the center of the north-south survey from east to west; these were the first and last lines of the survey. In recent missions, the crosslines have been shifted such that one crosses the northern half of the survey while the other crosses the southern half. The intent was to be able to assess the drift of each survey line relative to the two crosslines during bathymetric processing, but so far no survey has had sufficient features visible at both crossings to make such a determination.

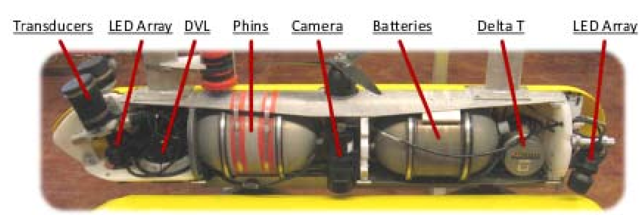

Fig. 2 Systems of the lower pod

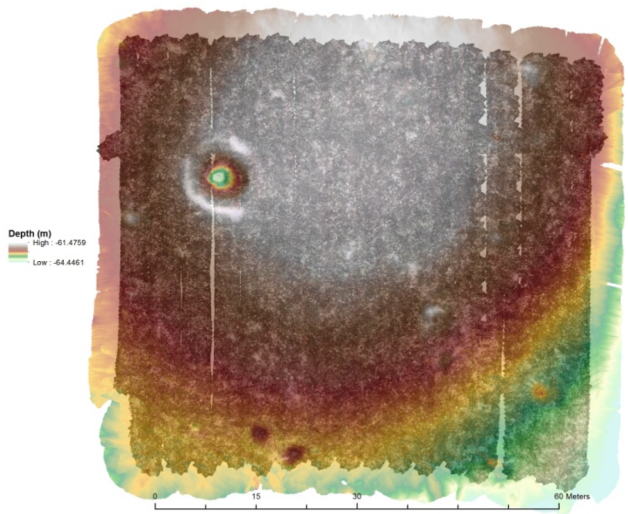

Fig. 3 Recent survey with overview of mosaic and bathymetry

After the on-deck Phins alignment procedure is completed, *Mola Mola* is disconnected from the hardwired Ethernet connection and charger umbilical and prepped for launch, while continuing to receive GPS input. It is then crane launched, typically with a descent weight tethered to an electromagnet latch. During descent, and throughout the mission, the vehicle is tracked by a TrackLink 5000HA ultra-short baseline (USBL) system. If this position is stable and reasonable, based on qualitative intuition of the pilot, navigation updates are transmitted to the vehicle during each uplink opportunity of the communications cycle. In an effort to reduce acoustic interference during the most recent missions, the cycle has been slowed to only allow a position update every 1.5 minutes.

When the vehicle nears the seafloor, it drops its weight and powers down to 3m altitude before performing a calibration square to ensure the Phins has reached a stable state. The vehicle then begins a lead-in to the first crossline, during which it is receptive of position updates from the surface or aiding from acoustic beacons, if deployed. During the mission, the vehicle simply follows the grid pattern. Because the sway component of motion is not actuated on this AUV, heading is adjusted to compensate for currents. During several recent surveys in which no measurement of bottom currents was available, headings of 70 to 80 degrees off the course were noted as the vehicle fought against a cross-current. The vehicle seems to have a significant oscillation when running down current, and both of these behaviors cause pronounced artifacts in both the multibeam and image data.

Assuming no anomalies occur, the acquisition phase is complete after the second crossline. The vehicle makes a very slow ascent, and is recovered by crane, involving a collection of various poles and hooks. Offload of the over 20GB for roughly 4 hours on survey is done through the hardwired gigabit Ethernet connection, and initial quality-control assessments are conducted.

III. Navigation Correction

Between the last GPS signal received at the surface and the start point of the survey, the vehicle accumulates significant error. Acoustic aiding is applied in an attempt to correct for this error, but USBL error is typically greater than 10m at depth, and even navigation beacons, if used, have imprecise positions. These sources all contribute to a static error present at the beginning of a survey.

During the survey itself, a nonlinear error builds. Datasheet values indicate an ideal circular error probability (CEP 50%) of 0.1% of the distance traveled. *Mola Mola* typically exhibits a significantly greater error, at least 5 times that, perhaps due to the lack of rigid structure between the DVL mount and the Phins. A unified framework between the two critical navigational components has been proposed, but its design would be a drastic change to the original structure of the vehicle.

Last are the small scale errors that make a difference when processing data with millimeter-range resolution. The size of each image is already well below the absolute error of the system, but limitations in precision cause difficulties in relative positioning of adjacent images as well. Utilizing a higher-precision position feed from the Phins helps greatly, but at this resolution, more precision is welcome. At this scale, only graphical alignments could correct the position. For the prior two types of error, static offset and survey drift, significant corrections can be derived from careful examination of the multibeam data.

A. *Multibeam Bathymetry Processing*

The MB-System package is used to process the bathymetric data from the DeltaT multibeam echosounder. The first step is to convert the navigation from the raw vehicle logs into the MBPRONAV (.nve) format used by MB-System. After entering known sensor offsets, the navigation can be merged with the multibeam pings. This step allows the individual soundings to be viewed in 3D space for cleaning. The most significant noise source is the acoustic communication, which disrupts the bottom detection of the sonar for several seconds at a time. The communication period has been lengthened as a compromise to increase the multibeam quality, but this change results in a greater delay between position updates when the vehicle navigation is being corrected using USBL positioning. So far, any attempts at automated cleaning have resulted in additional effort since not only are many bad soundings left unchanged, but many good soundings are flagged as bad.

Once an initial thorough cleaning is performed, drift correction can be applied using the process *mbnavadjust* [5]. This interactive graphical utility is used to determine offsets between crossing and overlapping swaths of soundings. By determining spatial offsets between a distinctive bathymetric feature imaged at two points in time, a tie point is made. After several tie points are determined, a nonlinear drift model is computed. A before and after image is shown in Fig. 4. A ghost image of the large depression in the northwest is visible. This is due to the northern crossline having an error several meters to the northwest. After running this procedure, the drift is resolved, with accuracy approaching that of the multibeam resolution, yet still at least an order of magnitude greater than

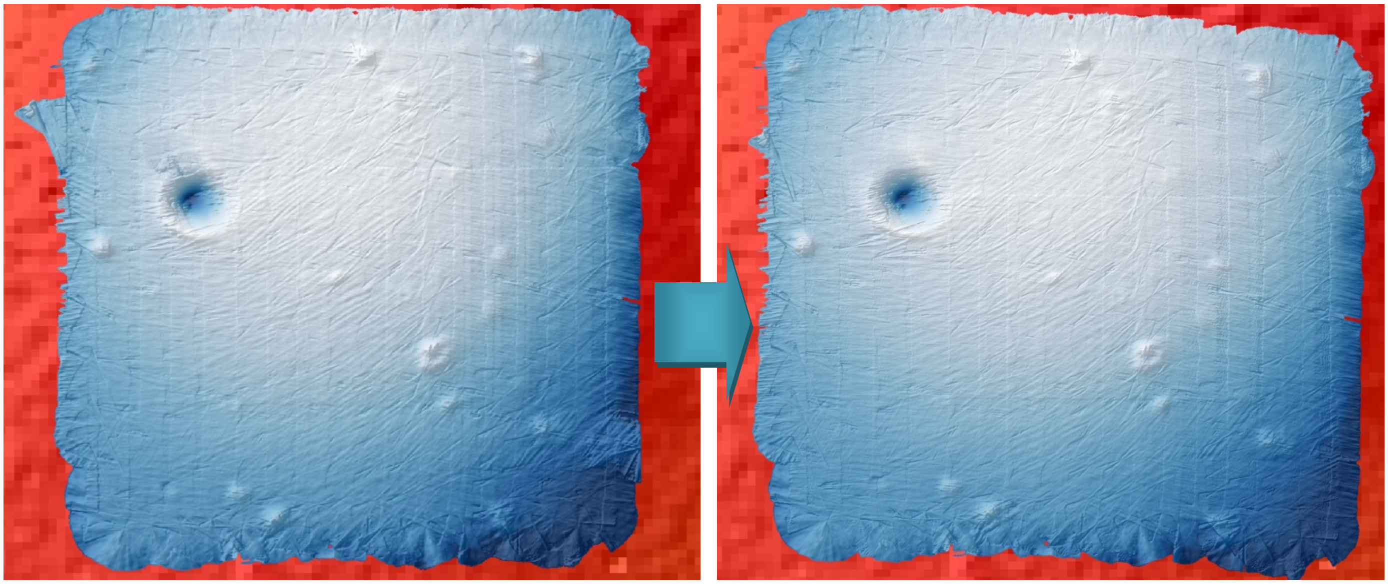

Fig. 4 Drift correction using mbnavadjust

the image resolution. Regardless, this can be viewed as a significant improvement to relative navigation quality, and the navigation can be easily exported from the resulting MB-System files.

Typically, *Mola Mola* missions are conducted in an area that has already been mapped at lower resolution by another AUV such as *Eagle Ray*, or even ship multibeam in the case of some relatively shallow recent dives on Pulley Ridge off the southern Gulf Coast of Florida. Usually this bathymetric basemap has a resolution of 1m or higher. In previous work, attempts were made with limited success to align mosaics to the basemap by trying to correlate visual and bathymetric features. Using the high-resolution bathymetry acquired by *Mola Mola* is easier to match with the basemap, although the absolute positional accuracy is still limited by the quality of the base survey.

B. *Image Placement*

When using the corrected navigation derived from bathymetric processing, only the final mosaic needs to be created; however, the following figures show intermediate steps to highlight the improvements offered by each step. In Fig. 5, the effect of the drift correction performed by mbnavadjust is indicated. The area north of the depression noted in Fig. 4 is shown in detail before and after the correction. Note that due to the drift error of the navigation system, acrosstrack overlap was lost between several lines.

The static shift is one of the most important corrections geographically; however, it has no visual effect associated with the images unless one examines the mosaic with respect to the basemap bathymetry. This particular survey at Pulley Ridge already had a static error of 6m when compared to the 1m basemap. Survey depth was around 62m, and in the clear

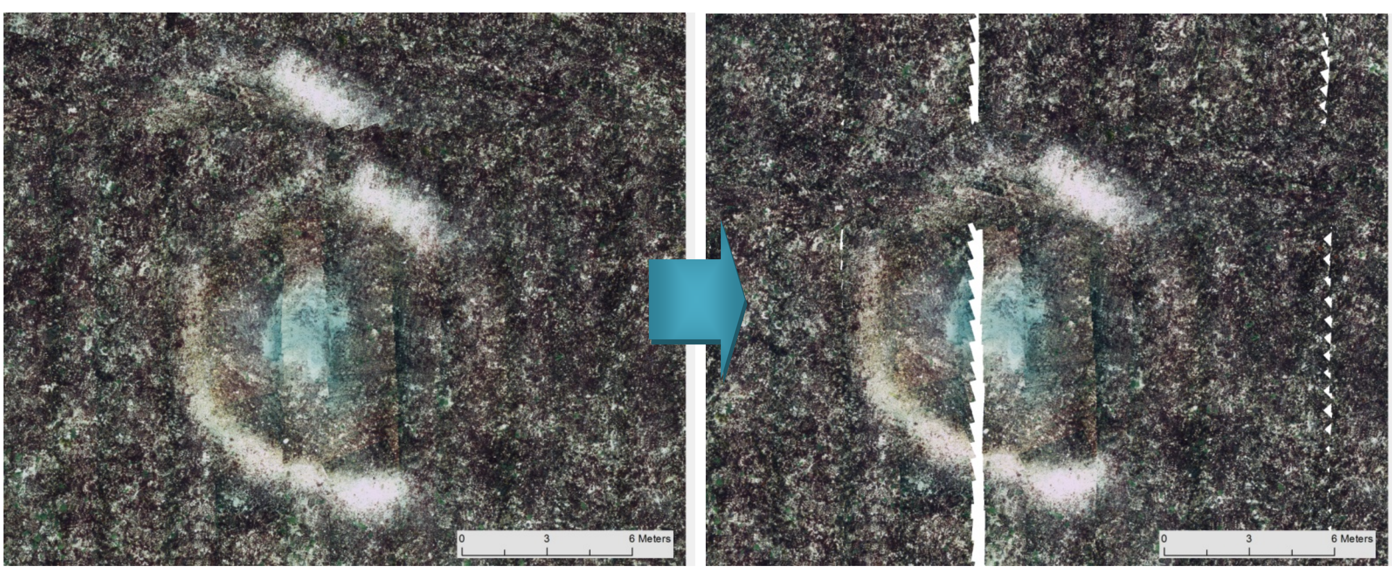

Fig. 5 Drift correction applied to image placement

water, the 1.2MHz DVL could receive pings off the bottom at an altitude around 35m. This corresponds to only 2 minutes of free inertial drift during the powered descent (without any acoustic aiding used on these shallow dives). While this survey has a fairly small absolute error, this is not typically the case in deeper dives, even with acoustic aiding.

One correction that will be discussed further in the next section is based on altitude. The bathymetric grid output from MB-System can be processed along with image locations to obtain scale corrections for each image. By computing the altitude of the camera over the bathymetry, the image can be expanded or reduced relative to nominal. A limitation of the process is that the image is assumed to be planar, which only holds true on flat bathymetry where the vehicle maintains constant altitude with ease. Still, this correction does a decent job of correcting gross exaggerations that occur when the AUV suddenly goes over the edge of a depression or travels over a mound, with the former shown in Fig. 6. Note that significant deviations from nominal imaging altitude are common since the DVL which serves as the altitude source for the vehicle control system is over half a meter behind the camera.

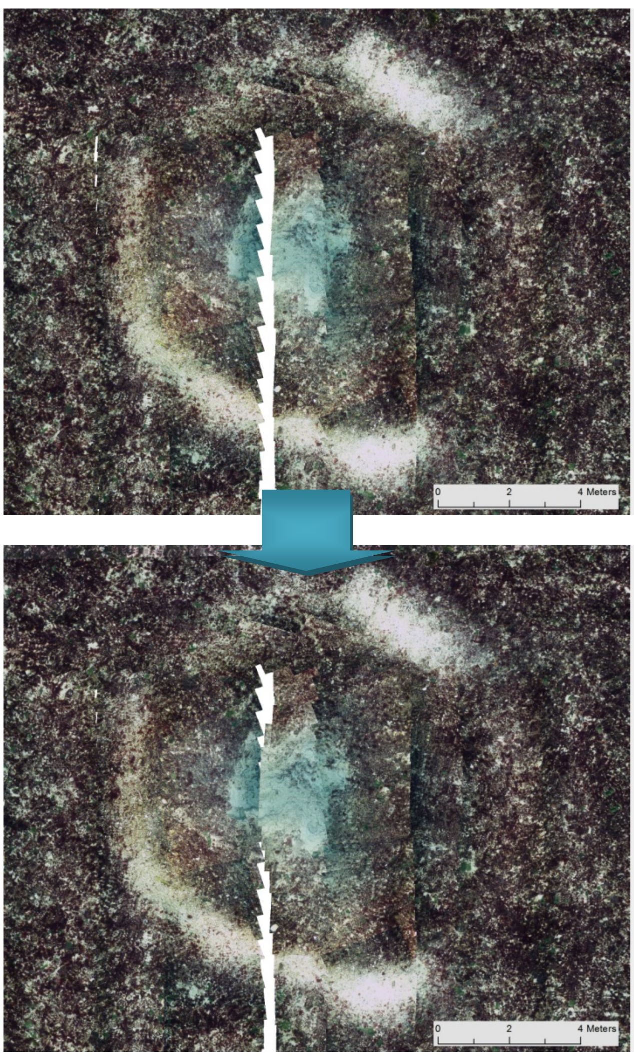

Fig. 6 Altitude correction applied to image placement

IV. Image Processing

Raw sensor data from the AVT camera is stored as a graymap image, in which each pixel represents either a red, green, or blue intensity. The first process uses a program delivered with the vehicle that has been modified to perform a uniform color correction over a set of images. This utility generates the color image from the raw data and then scales each color band separately to correct for differing light absorption encountered at the nominal survey altitude. Since the camera is set in a manual configuration, its gain, exposure length, and white balance are uniform for the whole survey. The lens itself has a fixed focal length, and the focus and aperture are dialed in on land.

After the color image is generated and initially balanced, the program stores each image in standard JPEG format. Each image is nominally 2.3m by 1.7m at survey altitude, with a pixel resolution of 1936 by 1458. Because of the lighting and optical geometry of the imaging system itself, the images generally suffer from a pronounced vignette effect, in which the edges are much darker than the center. This effect and its correction are shown in Fig. 7. A uniform vignette removal setting was found during qualitative testing of the images in Adobe Photoshop. This correction is applied in a batch process, along with a second batch process in the GNU Image Manipulation Program (GIMP) to remove an outline artifact generated by the initial utility.

For the last image correction, attention turns once again to the results of the multibeam processing. These outputs are the bathymetric grid and the corrected navigation. A Matlab script was written to interpolate the corrected navigation for the timestamp of each image. Using the Matlab Mapping Toolbox, the positions were projected to UTM for the convenience of the meter-based coordinates. The navigation was then translated to reflect the camera positions, and parameters for each image were output to the imageNav table. Using GIS software this table can be imported, and the position of each image can be displayed atop the bathymetry raster. The ArcGIS “extract multi values to points” tool is utilized to determine the bathymetric depth at each image point. These values are then used to calculate the nadir altitude between the camera and the image center on the seafloor.

An altitude correction was already shown to affect image placement in Fig. 6, and the altitude is used again to adjust the brightness and contrast of images. A script was produced to iterate through all the entries of the imageNav file and to brighten or darken images based on their difference from nominal altitude. The shell script called upon a script of GIMP commands to perform the image file opening, brightness and contrast adjustment, and file save. An example of this correction in the vicinity of a brine seep at Mississippi Canyon block 798 is shown in Fig. 8. Although the image scaling by altitude seemed to work decently in most places, the image intensity adjustment was only a limited success. It improved some isolated areas while causing a distracting pattern of excessive adjustment overall. Some tuning of the parameters may help, but the problem might also involve more general limitations of the technique.

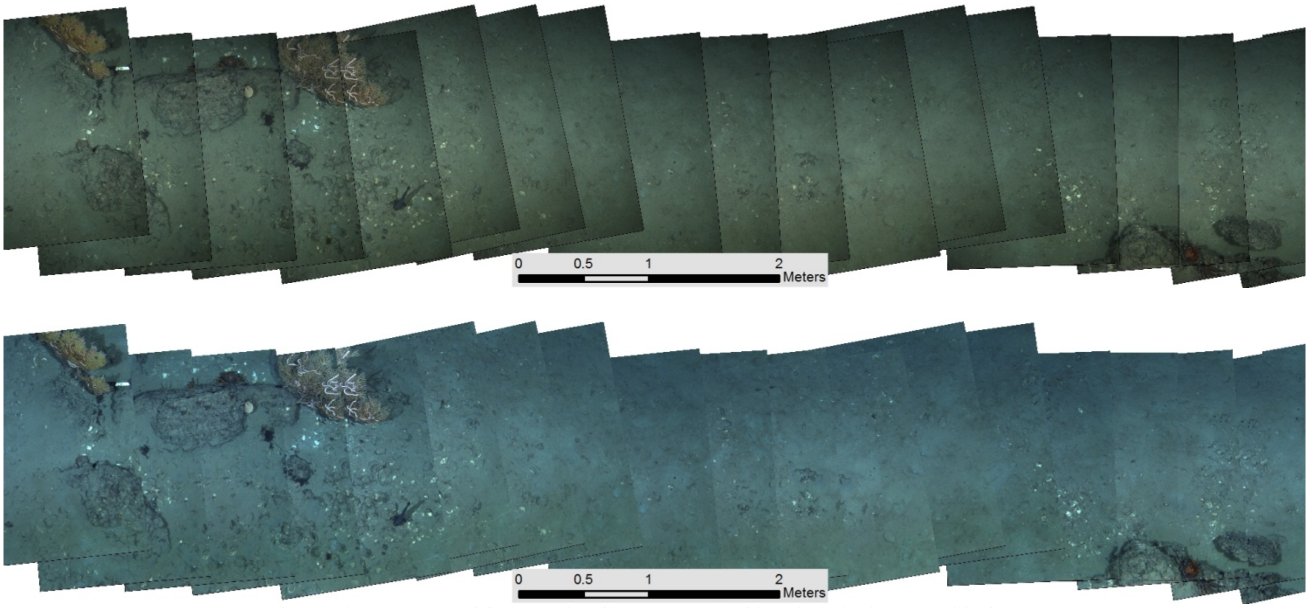

Fig. 7 Vignette removal from a strip of images acquired in Mississippi Canyon block 118

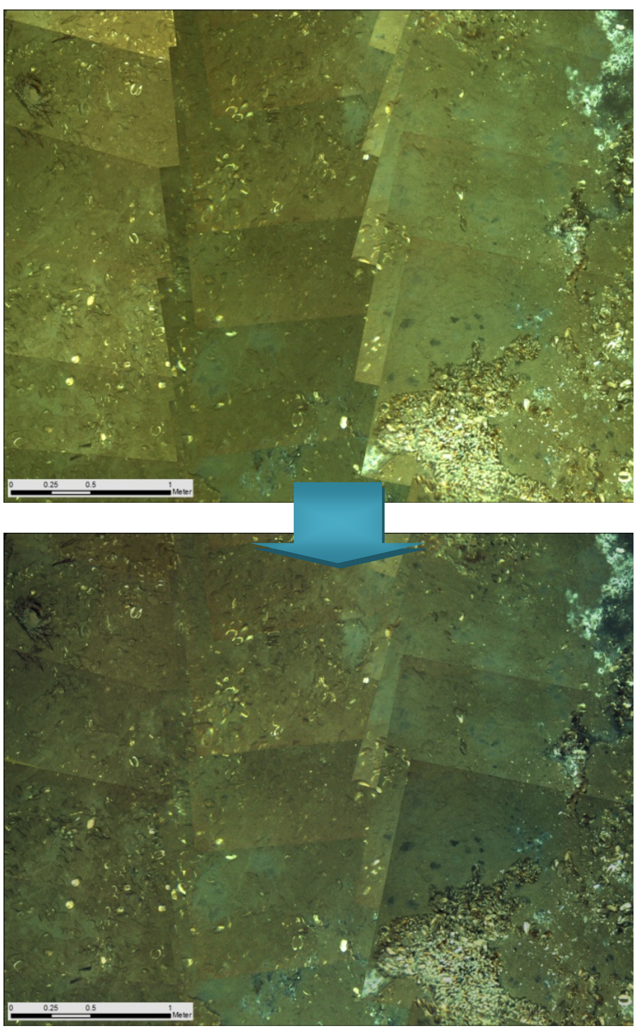

Fig. 8 Illumination balance by altitude

For all manipulations, images are handled as flat planar tiles. This oversimplification is evident when attempting to correct image size and intensity by altitude, since in many cases the images are taken on a slope or a complex bathymetric structure. More advanced techniques consider ranges to individual pixels of an image rather than treating an entire image as a uniform plane [6].

V. Mosaic Generation

In order to tag the positioning information with each image, a worldfile (.jgw) is created to accompany each .jpg file. This file combines all the corrections detailed above as parameters of an affine transform, which translates the images to the corrected location, rotates them to the logged heading, and scales them to the approximated size. In previous versions of the technique, a program translated the vehicle navigation directly into worldfiles. The new version adds flexibility by creating the intermediate imageNav file which can be modified by external tools and used as an input for routines such as the illumination correction program. It also provides the option to use navigation that has been processed in various methods, as long as it is exported in a suitable format. The key functions of the worldfile generation program are to parse the imageNav file, offset the position reference to the upper left image corner (which is the origin of image space), compute the affine transform parameters, and output them in a standard ordering.

Once the worldfiles are created, the individual images can be loaded into a GIS package as a mosaic dataset. For this project, ArcGIS and QGIS have been used for various tasks. Once the mosaic dataset is created, several options are available which control how the mosaic itself is formed from the images. Previously maximum, minimum, and blending operators have been utilized, but they frequently hide important mosaic content while smoothing the overall appearance. Currently, the images are simply stacked, with later images placed atop earlier ones in order to form a single raster layer.

A typical 60m square mosaic is composed of 2700-3500 images depending on mission settings. The mosaic dataset automatically adapts a pixel size just under 1mm, which is the resolution of an image when taken slightly below nominal survey altitude. Working with isolated mosaics is not a challenge with modern storage media, although a cruise consisting of around 10 mosaics or a series of tests producing several intermediate iterations of a sample mosaic can begin to occupy a significant amount of memory. GeoTIFF exports of 4mm, 2mm, and 1mm resolution are approximately 1.8GB, 7GB, and 28GB respectively. For now, exports between 2mm and 5mm have been used for distribution. These mosaic exports have produced acceptable overviews, especially when accompanied with the original images, which can be linked to a mosaic via the imageNav overview.

During the mosaicking process, the results of navigation and color adjustments become evident. Sometimes the crosslines are treated as separate mosaic layers in order to assess the effects of a particular navigation correction attempt. The illumination differences in adjacent survey passes can be seen in mosaic form, whereas they are not clearly observed when examining individual images. At this stage, the need for further improvements is also noted. One change would be to flag an image that has poor illumination quality or excessive roll or pitch, for example, and such an image would be placed lower in the stack or eliminated altogether. A second improvement would be to create a mosaic operator that emphasizes the centers of images, since using the "first" or "last" options causes the edges of images to be emphasized instead, and this is where distortion is greatest. Third, graphical methods may be employed to correct image matching as a small-scale navigation correction. This technique has been implemented in some mosaicking software [7], but it has not been explored for this study. An option to achieve this correction would be to merge graphically-derived tie points into the mbnavadjust drift model, integrating the correction into both the bathymetry and the mosaic.

VI. SUMMARY

The mosaicking technique in its current form has proven successful in representing the results of an AUV-derived photosurvey while maintaining the geographical integrity of the individual seafloor photos. By using corrected navigation and grids obtained by processing the multibeam bathymetry, the overall data quality has improved over previous versions of the technique. Other improvements were made through software and procedural changes in the acquisition phase, which came about from the shortcomings in previous mosaicking attempts.

Limitations of the current procedure have also been noted, in hopes that they may be corrected in the next iteration. As improvements are made, many of the steps detailed in the previous sections can be streamlined and automated, while others, such as cleaning of multibeam data, will continue to be time consuming.

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