Final Report

Long Island Sound Mapping - Phase 2

Prime Award: CDEP 2017-312-54302, Subaward 2(GG013173)
Research Foundation of the SUNY Stony Brook Award: 79509
August 1, 2017 to December 31, 2019

and

Continuing Studies of Acoustic Mapping, Long Island Sound Cable Fund – Seafloor Mapping Phase 2

Prime Award: CDEP CU20-0883, Subaward 2(GG015553)
Research Foundation of the SUNY Stony Brook Award: 89713
July 30, 2020 to December 31, 2022

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June 20, 2021 (draft)
October 18, 2022 (today's date)
October __, 2022 (final)

Introduction

Benthic habitat mapping in Long Island Sound (LIS) has long been identified as a priority need and is essential to improving science-based environmental management and mitigation decisions. Sea floor landscape maps depicting habitat structure and the ecological characteristics associated with those habitats are critical pieces of information which typically integrate information from a variety of sources including acoustic bathymetry and backscatter, sedimentary, geochemical, physical, and biological data. Plans for systematic benthic habitat mapping in Long Island Sound were initiated following the creation of the LIS Cable Fund (a settlement fund that resulted from issues surrounding cable infrastructure in LIS) in 2004. An important step in benthic habitat mapping has been the collection and analysis of high-resolution (multibeam) bathymetric and acoustic backscatter data that show seabed features, sedimentary processes and sediment distribution patterns. Multibeam bathymetric and backscatter data has been collected over a large portion of Long Island Sound as a results of over two decades of charting activities conducted by the National Ocean Survey, a branch of NOAA. This represents a remarkable achievement by NOAA which has resulted in accurate and up-to-date charts of Long Island Sound which are helping to make vessel operations safer in Long Island Sound.

The equipment used to collect multibeam bathymetric and backscatter data has continued to improve and NOAA survey strategies have also evolved as the charting has progressed. As a result, the data collected during earlier NOAA surveys does not have the coverage or spatial resolution in depth or acoustic backscatter that is needed for benthic habitat mapping. Also, complete (100% coverage) multibeam data was not always required in shallower areas for charting purposes although 100% multibeam coverage is desirable for benthic habitat studies. A first step in planning for LIS Cable Fund studies was to evaluate the existing NOAA multibeam coverage and to plan to collect any missing data. In the "Pilot Study" or "Phase 1" area studied by the LIS Cable Fund in central Long Island Sound the existing and planned NOAA mapping data was supplemented by multibeam mapping surveys done primarily by SoMAS, Stony Brook University

As part of the present "Phase 2" study in eastern Long Island Sound our NOAA colleagues assembled the existing and newly collected NOAA multibeam and backscatter data into regional high-resolution coverages. Our NOAA colleagues also identified 30 areas, or survey blocks, in water depths over about 6 meters which did not have the desired 100% multibeam bathymetry and backscatter data (Figure 1). Twenty eight of these blocks were selected for continued study. SoMAS agreed to collect high-resolution bathymetry and backscatter data in 25 of the survey blocks and LISMarc agreed to do the same in three of the survey blocks. In addition, SoMAS also agreed to work in at least one of the areas being surveyed by LISMarc in order to allow for the comparison of survey results.

Methodology

Equipment and Survey Activities

The SoMAS surveys were conducted during two deployments, the first deployment from December, 2017 through March, 2018 (called DM) and the second deployment in June and July, 2018 (called JJ, Figure 2 and Table 1). During our deployments we collected data continuously along track although we ran at full speed and did not collect sound velocity profiles. We collected data during transits in order to identify areas where seabed morphology has changed between the prior NOAA surveys and our study. During our block surveys we collected data at normal survey speeds and track lines extended far enough beyond the boundaries of each block so that there was significant overlap with data surrounding the block. On several occasions where the blocks were close together we conducted one survey that included several blocks, or parts of blocks (Table 1). Due to time constraints not all of the blocks surveyed during our first deployment were completed during that deployment. We completed surveying those blocks during the second deployment and the results of multiple surveys in the same blocks are reported separately. Survey activities in all blocks were completed in 2018.

We had initially planned to work in the shallowest areas during the first deployment using the 28-foot R/V Donald W Pritchard and then work in the deeper areas using the 80-foot R/V Seawolf. While the shallow-draft R/V Pritchard is appropriate for daytime use, the R/V Seawolf can operate 24-hours per day which effectively increases the available mapping time. Also, the larger R/V Seawolf experiences less movement when at sea than does the smaller R/V Pritchard, and multibeam data is generally better when the ship is more stable. We were notified that we would not be able to use the R/V Seawolf for our second mapping deployment due to an unanticipated schedule conflict so we used the R/V Pritchard for the second mapping deployment also. During both deployments we used a Kongsberg multibeam system along with an Applanix motion sensor and GPS system, one or more Trimble RTK-capable GNSS receivers (using networked, land-based satellite corrections provided by the UConn ACORN Real Time Network (RTN)), an AML probe for surface-water sound velocity and a profiling AML sound-velocity probe for the water-column sound-velocity profile. Other needed survey equipment included a computer system to operate the multibeam sonar system (including a system to guide the helmsman along the desired survey line) and to log the survey data. The side-scan sonar, used during the first deployment to ensure 100% backscatter coverage, had a separate computer to operate the system and log the survey data. We had not planned to use the side-scan sonar during the second deployment on the R/V Seawolf.

During the first deployment we used the SoMAS Kongsberg EM 3000D multibeam echosounder for bathymetry and backscatter and the SoMAS Edgetech 272TD side-scan sonar for backscatter at a different frequency. A multibeam bathymetric system collects depths across a swath of the seafloor that is perpendicular to the vessel track by sending out a ping and then recording the sound returns at different angles. The travel time and angle information is processed to determine the water depth across the swath. The strength of the returned echo (the acoustic backscatter) is also recorded. The strength of the backscatter can often be related to the nature of the seabed material. The across-track width of the swath is generally a characteristic of the transducer design and the swath width of a single transducer is often about four or five times the water depth. The EM 3000D multibeam system uses two transducers mounted so as to create a wider mapping swath (up to 10 times water depth in the shallowest water and decreasing as the water depth increases) which can reduce survey effort. A side-scan sonar operates like a multibeam system in that the sound returned from a ping is recorded (the acoustic backscatter) across a swath. The angle of the returned sound is not generally known for a side-scan sonar so no depth can be determined; however, the spatial resolution of a side-scan sonar record is often higher than that of a multibeam system so the side-scan can show more detail about the seabed than a multibeam echosounder. The 272TD side-scan sonar was mounted on a pole rather than towed in the traditional fashion. By mounting the side-scan sonar unit on a pole we reduce uncertainty in the position of the sonar system and simplify vessel operations in shallow water settings. However, a pole-mounted side-scan sonar has considerably more motion than a towed sonar since the sonar rolls and pitches along with the boat, and the motion of our side-scan sonar significantly degraded that data. The EM 3000D used sound waves of 300 kHz and the 272TD used sound waves of 100 kHz. The acoustic backscatter depends in part on the wavelength of the sound being used so mapping at multiple frequencies can provide additional insight into the character of the seabed. Many other factors also affect the recorded backscatter, including sound attenuation in the water column, wind and wave conditions and the noise of the ship's engine. The width of the multibeam swath varies with water depth while we used a fixed side-scan sonar swath of 150 meters (75 meters/side, 10 pings/second).

Vessel operations in December and January were hindered by having short days (we can only conduct vessel operations during daylight) and strong winds and high waves made it impossible to work on six possible survey days. We were also hindered by cold weather and our vessel was stuck in the harbor by ice for about eight possible survey days in early January. We did not survey from mid-January to mid-March due to classes and we resumed operations during spring break in March. We did successfully map for 21 days, we completed seven of our assigned survey blocks and we collected data in the shallower parts of four more survey blocks in anticipation of using the R/V Seawolf in deeper water later in the year.

The EM3000 multibeam system has been used at SoMAS since about 1998 and the system was upgraded to dual-head operation in about 2004. The multibeam system utilizes a SUN Solaris Ultra 2 computer system which is now obsolete although we have been able to keep our computer systems and Kongsberg hardware and software operating. The license for the Kongsberg software is on a chip in the Ultra 2 which has a built-in battery. That battery had failed on the computer system we were using, although the computer and software could be started and used by typing in the license code. However, when we started the computer in that fashion the date being used by the computer was consistently incorrect although the time of day was correctly set from the GPS system. The failed chip battery was replaced after our 10th survey day by dissecting the chip and attaching a new battery. The multibeam files that were recorded with the wrong dates were renamed and rewritten with the correct file names and dates (except that the names of the sound-velocity profiles incorporated in the .all files were not updated), and only the rewritten files with the corrected dates have been used in processing.

We used a leased EM 2040cD multibeam system for our second deployment. This was the current model of our EM 3000D system and it had a faster ping rate and could obtain a wider swath than the EM 3000D at the same water depth. These improvements somewhat compensated for not using the R/V Seawolf and they allowed us to complete our survey assignment in our second deployment while still meeting the survey requirement of obtaining at least five depth points per grid cell and multibeam backscatter. The EM 2040cD was operated at 300 kHz. We did not use the side-scan sonar during the second deployment. We successfully mapped for 12 days although we did lose 7 potential survey days to an engine failure.

Both multibeam systems recorded raw data in the Kongsberg .all format which incorporates datagrams from each piece of equipment used during the survey into one large file, including datagrams from the multibeam echosounder, the motion sensor, GPS navigation systems and sound velocity data. Navigation data was also recorded independently of the multibeam system to allow for additional filtering. The multibeam survey technique requires that the relative positions and orientations of all of the equipment in use be know and that the times at which the different pieces of equipment made a measurement be known so that the different data streams can be combined. We used a land surveyor to measure the relative positions of instruments on the R/V Donald W Pritchard when the boat was out of the water and we performed required calibrations at several times during our survey operations to verify and fine-tune equipment offsets. We had quite good survey results using the EM 3000D system and we successfully collected high-quality bathymetric data even at times when the survey vessel was moving over 1 m vertically with significant roll and pitch although some small small motion artifacts were often observed. We also had quite good survey results with the EM 2040cD system when vessel motions were small, but our data showed some motion artifacts when we experienced significant wave motion. These motion artifacts in part were caused by a small time offset of about 0.005 seconds between the echosounder (depth) and motion data (roll, pitch, heading and heave). This offset was apparently not present when using the EM 3000D system on a Sun computer with the Solaris operating system. The EM 2040cD multibeam system is normally used with a Kongsberg motion sensor while we used a motion sensor from a different manufacturer. The EM 2040cD logs the survey data on a Windows 10 computer and we suspect that the time offset for the motion sensor is due is somehow related to using the non-Kongsberg motion sensor on the Windows 10 computer. We were able to substantially correct for a constant timing error but some residual motion remains in the multibeam depth data.

The data from the pole-mounted Edgetech 272TD side-scan sonar was recorded in xtf format on a Windows computer using Triton-Elics software. The xtf files included side-scan sonar data and navigation data. The time of the side-scan sonar system is synchronized to the time of the multibeam system so that data recorded by the multibeam system (especially water depth, orientation and filtered navigation) can be applied to the side-scan sonar system during data processing.

Data Processing

The multibeam depth data was processed using CARIS HIPS and SIPS, version 10.4 and multibeam backscatter data was processed using the QPS FMGT, version 7.9.5. Programs from the University of New Brunswick SwathEd multibeam processing system were also used in evaluating the multibeam depth and backscatter data and for processing the side-scan sonar data. The multibeam programs processes the Kongsberg .all files so that data from each ping has the proper orientation, position and sound-velocity data, taking into account the offsets between instruments. FMGT also corrects the multibeam backscatter data for beam pattern. The software packages can also be used to edit data from individual sensors and calculate the final water depth after integrating water-level data and the sound-velocity profile data. The side-scan sonar xtf files were processed using SwathEd programs as modified at SoMAS. Processing steps included reformatting the sonar data, integrating navigation, orientation and water-depth with data extracted from the multibeam data files, and correcting the side-scan sonar data for beam pattern.

Satellite Navigation and Water-Level Data

RTK fixes can have nominal horizontal accuracies of 1 cm and vertical accuracies of 2 cm. Successful RTK fixes require an adequate internet or radio connection to receive correction data from a network or base station, a nearby base station or correction network since the accuracy of the fix degrades with distance, an appropriate satellite geometry since fixes can't be calculated if there are not enough satellites or if they are in a row, and strong satellite signals which can be degraded by solar and weather conditions). When all conditions are met then our GPS/GNSS receivers can determine a 3D fix (latitude, longitude and elevation) up to 10 times per second. If all conditions are not met, then our receivers determine a 2D fix (latitude and longitude) using the RTK corrections or possibly WAAS corrections. The quality and mode of each fix is shown in the navigation telegram. While latitudes and longitudes for 2D fixes are not as accurate as for 3D fixes, 2D fixes can be adequate for determining the position of the survey vessel. The navigation fixes determined using the ACORN RTN are in the NAD83 (2011) coordinate system and elevations are referred to the NAD83 ellipsoidal datum. The navigation fixes were filtered to retain the high-quality navigation (latitude, longitude) and elevation (latitude, longitude and elevation) fixes and the high-quality navigation fixes were merged with the multibeam depth data.

Our survey results are reported in the NAD83 (2011) horizontal coordinate system and the NAVD 88 vertical datum (North Atlantic Vertical Datum 1988). NAVD 88 is the official vertical datum of the United States and is an approximation of mean sea level. Water depth on navigation charts is generally referenced to Mean Lower Low Water (MLLW) rather than NAVD 88 because users of those charts want to know about the shallowest likely depth in an area and that depth occurs at low tide. Users of the data reported here should be aware that water depths reported with respect to NAVD 88 will seem to be deeper than water depths reported with respect to MLLW, and this is one of several reasons why **<u>OUR DEPTH DATA SHOULD NOT BE USED FOR NAVIGATION</u>**. Depth data can be converted from one vertical datum to another (e.g., from NAVD 88 to MLLW) using VDatum, an online and down-loadable utility provided by NOAA (https://www.vdatum.noaa.gov).

Elevations in NAVD 88 can be determined by subtracting the geoidal height from the ellipsoidal height. The ellipsoidal height is reported by the GPS/GNSS fix and the geoidal height at the navigation point is determined using the NGS/NOAA web site https://www.ngs.noaa.gov/cgi-bin/GEOID_STUFF/geoid12A_prompt1.prl. We verified our elevation measurements in NAVD 88 by comparing elevations we measured while our boat was at the dock in the Ragged Rock Marina, Old Saybrook CT, to water-level measurements at a gauge we installed in the marina and with the NAVD 88 water-level recorded every 5 minutes by USGS at the nearby station at Old Lyme, CT (USGS 01194796).

The precision 1-second latitude, longitude and elevation fixes were used to determine water-level relative to the NAVD 88 datum along the ship track and thus to reference the measured sea-floor elevation to NAVD 88. The high-quality GPS/GNSS elevation fixes were averaged into six-minute intervals to determine the equivalent of a six-minute tidal curve at the position of the vessel during the survey. In the absence of precise elevation data, NOAA generally calculates water-level at the vessel location during a survey by scaling water-level measurements at a nearby NOAA water-level station and applying a time delay. The scaling factor and the time delay are determined based on NOAA's tidal zonation map (https://noaa.maps.arcgis.com/home/item.html?id=21d7b399e6fa42e18a72ee30be9aa5c9). Our GPS/GNSS-based water-level record compared favorably to the offset and scaled water-level measurements made by NOAA at the New London, CT water-level gauge (8461490) and any gaps in the elevation record were filled with values consistent with the offset and scaled NOAA tidal record.

Sound Velocity Profiles

The vertical sound velocity profile in the water column needs to be known to correct for the bending of sound rays in the water column which occurs when sound velocity varies in the water column. Use of an incorrect sound velocity profile can create significant depth errors, especially at the outer edges of the swath. Sound velocity can vary spatially and temporally because of things like currents, tidal water movements, flow over topography, varying amounts of fresh-water input (especially off rivers), vertical mixing due to winds or waves and the development of internal waves on density interfaces in the water column.

Much of our survey activity occurred at or near the mouth of the Connecticut River which is the major source of fresh water to Long Island Sound. Fresh water discharge to LIS is largest during ebbing tides when water is drawn from the Connecticut River estuary and river and smallest during flooding tides when LIS water is drawn into the estuary. There is considerable mixing in LIS off the river mouth and in the Connecticut River estuary which creates significant lateral and temporal local variability in sound velocity values and water column structure. The Connecticut River discharge generally moves eastward in LIS along with the general circulation although details of the water motion depend on tidal currents and winds. There are additional complications to the sound velocity structure near the Thames River at New London but fresh-water discharge from the Thames River is significantly smaller than that from the Connecticut River.

Sound velocity casts are taken by lowering a probe through the water column. The profiles were examined immediately after collection and edited if necessary to remove any bad data. Sound velocity profiles with closely-spaced measurements in the vertical need to be subsampled to use with the data acquisition software. The Kongsberg software filters the sound velocity profile but keeps a sufficient number of points to properly calculate ray bending. Standard survey protocol which we followed is to collect sound-velocity casts at least every four hours but more often if anomalies are observed on the bathymetric swath. We attempted to collect closely-space sound-velocity profiles during deployment 1 by using a system that can collect a velocity profile while the ship is underway. However, the system proved to be unwieldy on our small survey vessel and sound velocity profiles could only be collected when the vessel was stopped.

A total of 172 sound velocity profiles were collected during the study, 112 during deployment 1 (DM) and 60 during deployment 2 (JJ). CARIS HIPS and SIPS can recalculate water depths based on the sound velocity profiles collected during the survey. However, sound velocity structure in the water column often changes more quickly than can be captured with periodic sound velocity profiles so some later sound-velocity corrections, done using tools within CARIS HIPS and SIPS, are often required. Internal waves can create small-scale lateral variability in sound velocity structure which can create depth anomalies which are most pronounced at the outer portions of the swaths. These kinds of anomalies were generally removed by editing the depth data.

Results

Map Creation and Production

CARIS HIPS and SIPS, FMGT and SwathEd programs were used to create the map products using the NAD83 (2011) coordinate system (UTM Zone 18 N) and the NAVD 88 vertical datum (Figures 3 to 5). As noted previously the defined survey blocks were quite close together in some areas. In some of those cases data collected during one ship survey included several defined survey blocks while in other cases data from adjacent blocks has significant overlap (see notes in Table 1). Some of the survey blocks were large enough to require data collection during both deployments (i.e., survey blocks 12, 13, 14 and 18), and data collected during different deployments overlapped considerably and were reported separately due to the use of different equipment in the two deployments. The data in survey 13_JJ consists mostly of single tracks that cover the same area mapped in 13_DM in order to evaluate temporal variability. Survey data reported from a portion of block 11 (survey 11_Cal_JJ) is reported separately from the other data in survey 11_JJ. Survey 11_Cal_JJ was one of our calibration areas so there are many overlapping lines in the survey. The area is of potential interest because it includes a relatively flat area (dimensions of 250 m x 500 m) at a depth of 26 m which has a sharp edge where it intersects a steep slope (with slopes over 30 degrees) that that extends to water depths of 50 m over a horizontal distance of about 250 m. Possibly this unusual geometry is related to the underlying geological structure at the site.

We collected and reported multibeam data collected in parts of two of the survey blocks mapped by LISMarc, survey blocks 24 and 25, in order to facilitate the comparison of depth and backscatter data collected by the two sets of surveys. Our data collected in block 24 (survey area 24_NL-Light_JJ) was in the vicinity of the New London Ledge Lighthouse and our data collected in the southernmost portion of survey block 25 is reported in our survey that also covered the small survey blocks 26 and 27 (survey area 25-26-27_JJ).

A short survey was also conducted at a water depth from about 50 to 60 m where prior NOAA multibeam data showed the existence of barchan sand dunes. This kind of crescentic sand dune which opens in the direction of travel is often found in desert areas and underwater where there is some sand over a harder substrate and the unidirectional wind or water flow has swept the sand into one or more barchan dunes. We were interested to learn if currents in the area had been strong enough to cause the barchan sand dunes to move, and how far they had moved, since the prior NOAA multibeam survey.

Overall, maps were produced for 26 survey areas as GIS-compatible GeoTIFF grids wiht appropriate metadata using SoMAS data (Table 1). Nine survey areas used data collected during the DM deployment and 17 survey areas used data collected during the JJ deployment. Bathymetry maps were created using CARIS HIPS and SIPS, hillshade bathymetry maps were created using CARIS HIPS and SIPS, multibeam backscatter maps (QPS FMGT) and side-scan sonar backscatter maps were created using SwathEd (DM only). The grid size was 1m x 1m except for the Barchans survey (water depth about 50-60 m) where the depth grid size was 2m x 2m.

The files with the survey map data are named following the recommended naming schema which is <Org/Group>_<Theme Area>_<Collection Year>_<BasicDatasetDescription>. For these files the Group is SoMAS, the Theme Area is PhysEnv and the collection year is 2018. The BasicDatasetDescription is a combination of the survey area name (e.g., 01-02-03_JJ) and the data type (i.e., Bathymetry, Hillshade, MB_Backscatter or SS_Backscatter).

NOAA Map Compilation

Our NOAA colleagues had access to our CARIS HIPS and SIPS project files, our fieldsheets and our raw survey files and they integrated our survey data with existing NOAA survey results to create maps of multibeam depth and backscatter for the entire Phase 2 study area. The results of their compilation are described in the report from NOAA and the data compilations are available at NCEI (https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:167531) Version 1 of the data set is for the multibeam compilation done prior to the most recent multibeam data sets (data at https://www.nodc.noaa.gov/archive/arc0113/0167531/1.1/data/0-data/) while version 2 includes the multibeam data sets (data at https://www.nodc.noaa.gov/archive/arc0113/0167531/2.2/data/0-data/NCCOS-LIS-PhaseII-Mapping_ArchiveDataPackage/Data/). The vertical datum for the NOAA depth compilation was MLLW.

Data Archiving

Data files used in creating these maps along with the map results will be archived at MGDS (https://www.ldeo.columbia.edu/research/marine-geology-geophysics/mgds-geomapapp), NCEI (https://www.ncei.noaa.gov/) and at _Cable Fund Data Archive_.

Raw data and project data files

Raw data files: EM3000D multibeam, EM2040cD multibeam, EdgeTech 272TD side-scan sonar

Note: EM3000D files re-written with correct date, and 272TD files re-written with sonar position, altitude and orientation.

CARIS HIPS and SIPS project files, including fieldsheets

Question, want GSF format files instead?

CARIS vessel files (CARIS and text/xml format)

Survey mapping results

GIS GeoTIFF files for SoMAS map series (87 maps)

Auxiliary data

Sound-velocity profiles for multibeam surveys in CARIS format

Water level along track for multibeam surveys

This report

Metadata for contributed data and files

Discussion

While the prior NOAA mapping in LIS has shown many details about the morphology and character of the seafloor sediments, our new Phase 2 mapping has provided new details in many mostly nearshore areas where detailed mapping did not exist. Other investigators in the Phase 2 project are collecting complementary data sets on the character of the seabed and on the biota, including grab samples, sediment cores, seismic profiles, bottom photographs and ROV transects. Previous studies of the area have also collected similar important data sets. The new bathymetric and backscatter data will be one more piece of information about the seabed that will help to define benthic habitats. While the main focus of our task was to collect the new bathymetric data, it's possible to provide some initial observations based on this new data

Sand waves and Estuarine Flow at 15_DM

Example mapping results for survey area 15_DM show the kinds of information provided by this new mapping data set. Survey area 15_DM is located immediately east of the mouth of the Connecticut River (Figure 6). The area includes a broad, east-west depression that lies between the shoreline and an offshore ridge or bar that parallels the Connecticut coastline. The nautical chart of the area is based on the depth data collected prior to our recent bathymetric mapping so we expect there to be a basic agreement between the chart and our new bathymetric data. According to navigational charts of the Connecticut River the deepest channel of the Connecticut River turns east where it enters LIS and roughly aligns with the 15_DM trough. The Saybrook Outer Bar extends southeast from Lynde Point on the west side of the Connecticut River and tidal and river flows cross this bar. The Saybrook Outer Bar Channel allows safe navigation between the Connecticut River and Long Island Sound. Flow patterns are complex in this area and change with tide, river discharge, weather and other factors.

The bathymetry from 15_DM (Figure 7) shows the broad depression reaching depths over 14 m and then shoaling eastward to a sedimentary sill at about 10 deep before deepening eastward into a second depression over 15 m deep. The hillshade for 15_DM (Figure 8) shows several possible rock outcrops in the trough and apparently erosive lineations on the north flank of the trough east of the sill. These outcrops seem to be buried in the region of the sill although they are present in the shallower waters of the north flank of the trough. Rocks are present again west of the sill although the northern end of Hatchett Reef seems to have been buried. Many of the rock outcrops in deeper water (more than maybe 10 m deep) have sediment tails on their west sides suggesting net water flow towards the west.

There are two fields of sand waves along the south flank of the trough. The waves of the eastern wave field have heights of about one meter and wavelengths about 40 m in water depths of about 6 to 8 m. The waves in this field are asymmetric with steep slopes on their western slopes indicating a net water flow towards the west. The waves in the western field are smaller with heights of about 0.25 m and wavelengths about 15 m in water depths of about 5 to 7 m (we did not map the shallow limit of these waves). The waves are slightly asymmetric towards the east suggesting strong tidal flows but a weak net water flow to the east.

The backscatter patterns for the multibeam and side-scan sonar (Figures 9 and 10) show lower backscatter (darker color) on the southern flank of the trough consistent with sand waves in the area. Sand can have a low backscatter because there are generally few shells in sandy areas and the sand surface can reflect sound like a mirror so little sound returns to the sonar instrument. Backscatter is much higher (brighter color) to the east which may suggest shells on the seabed. Fine-grained sediments with a coarse component can have high backscatter because shells or gravel can reflect sound back towards the transducer while fine-grained sediments with no shell tends to absorb the sound and thus can have low backscatter. Samples are required to verify any interpretation of backscatter patterns but the backscatter data can be used to extend observations at stations to larger areas. Backscatter intensity along the northwest portion of the trough is intermediate, perhaps suggesting some coarser material on the sediment surface in that area especially since these areas of higher backscatter are sometimes associated with outcrops.

Sand waves can form when sand-sized sediment are moved by strong currents and as a result they are generally a useful indicator of both sandy sediments and strong currents. By their very nature sand waves create an unstable seabed so a wide variety of bottom-dwelling organisms may not be present in areas of sand waves. Both of the two sand-wave patches described here were also imaged by multibeam tracks run during NOAA survey H12013 in 2009. Comparing profiles over the same waves in 2009 and in 2018 (Figure 11) shows that sand waves are present in the same areas in both years but individual sand waves have moved and they can't be directly compared. If currents were only unidirectional then we'd expect the sand waves to move along the seabed. However, it's likely that the sand waves could stay in the same place if there was a tidal component of the flow. Tidal flows often have a rotary component so that strong flows can flow in a number of directions over a tidal cycle.

The asymmetric larger (eastern) sand waves suggests a net westward flow consistent a dominant flood current (into the Connecticut River) at about 6 to 8 m water depth, although there is likely a tidal component to the flow. This net upriver (flood) flow is also consistent with sediment tails behind obstacles in deeper water. The weaker asymmetry of the smaller (western) sand waves suggests a weak net eastward flow consistent with a dominant ebb current (out of the Connecticut Rover) at a depth of less than about 7 m. Such a flow pattern (deeper waters having average flow direction into the estuary and shallow waters having average flow directions out of the estuary) is the expected estuarine circulation pattern.

Barchan Dunes in Barchans_JJ

As noted previously, barchan dunes have been observed on NOAA multibeam data in water depths of 50 to 60 m from a portion of Long Island Sound near a disposal area that had been used for clean materials. A short survey conducted in this area did show barchan dunes (Figure 12) which had heights of about 1.5 to 2 m, widths of about 50 m and crestal lengths of about 50 to 200 m. The axes of the dunes are aligned roughly north-south with the horns of the crescents opening towards the west. This orientation is consistent with bedform movement towards the west by a unidirectional current. The positions of barchan dunes on our data from July, 2018 were compared with the positions of the same barchan dunes on the data collected on NOAA survey W00405 done in September-October 2015 and the dunes were observed to have moved from about 50 to 90 m which is a rate of 19 to 34 m/yr. It is likely that the movement occurs only during a portion of the flood tide when current speeds are high enough to move sand-size sediment, but perhaps not during every flood tide. The movement of these sand waves again demonstrates that sand waves indicate the presence of an unstable and mobile sandy seafloor.

Conclusions

Overall we had good survey results and successfully completed surveys in 25 of the blocks that NOAA identified as needing 100% multibeam coverage. We also collected multibeam data in four other areas of interest, including in two survey blocks where the LISMarc consortium collected acoustic data. Depth data collected by our 28-foot survey vessel showed some motion-related artifacts when the survey vessel was being rapidly moved by waves, and the artifacts were more noticeable during our second (JJ) deployment than during our first (DM) deployment. The artifacts are in part due to a small timing offset between the echosounder and the motion sensor during the JJ deployment, but we also note that our small (28-foot) survey vessel experienced considerably more motion than a larger vessel would have experienced for the same wave conditions. Many of the prior NOAA multibeam surveys in LIS were collected by the NOAA Ship Thomas Jefferson which has a length of 208 feet. Such a large vessel would be quite a stable platform for multibeam survey operations.

Sand waves are commonly observed in our survey areas and they are also common on the NOAA survey data collected in the Phase 2 area. While the sand wave examples in 15_DM appear associated with river and tidal flows and the barchan dunes in Barchans_JJ appear to be associated with flood tides, high water waves can also work to resuspend sediments that can be sculpted by tidal currents. Thus sand wave fields can be altered during wind events such as storms which can generate high waves. Sand waves show that bottom currents are at least periodically strong enough to transport sand-size material and thus that the bed is likely to be unsuitable for benthic organisms that create stable burrows or attach to hard substrates. Sand waves can move across the seabed where there are local sand sources and nearly unidirectional strong flows. Tidal motions tend to create fields of sand waves that are in the same area for long time periods although sand is moving across the sand waves on a tidal timescale.

It is expected that this new survey data and the improved regional water depth and backscatter compilations that include this data will enhance our overall understanding of the benthic habitat in eastern Long Island Sound and provide an improved basis for the management of submarine cables, pipelines and other infrastructure in the area.

Acknowledgements

Funding for this study was provided by the Long Island Sound Seafloor Mapping Fund administered cooperatively by the EPA Long Island Sound Study and the Connecticut Department of Energy and Environmental Protection (DEEP). This funding came through two subawards from the Prime Recipient The Trustees of Columbia University in the City of New York: "Long Island Sound Mapping - Phase 2", Prime Award: CDEP 2017-312-54302, Subaward No. 2(GG013173), August 1, 2017 to December 31, 2019 (RF Award 79509) and "Continuing Studies of Acoustic Mapping, Long Island Sound Cable Fund – Seafloor Mapping Phase 2", Prime Award: CDEP CU20-0883, Subaward No. 2(GG015553), July 30, 2020 to December 31, 2022 (RF Award 89713). The multibeam data was collected by the SoMAS Research Vessel R/V Donald W Pritchard and the efforts of boat captains David Bowman, Brian Gagliardi, Andrew Brosnas and Ralph Curd are gratefully appreciated and acknowledged. The boat was docked at no charge at the Ragged Rock Marina, Old Saybrook, CT and at the University of Connecticut, Avery Point, CT the during the study.

Figure Captions

Figure 1. A total of 30 survey blocks in the Phase 2 study area which had water depths over about 6 m were identified as areas where additional multibeam depth and backscatter data was needed.

Figure 2. SoMAS, Stony Brook University, completely mapped 25 of the survey blocks, collected data in two survey blocks to facilitate comparisons between SoMAS and LISMarc mapping data, and reported mapping results from two other areas of interest in a total of 26 survey areas in the Phase 2 study area.

Figure 3. SoMAS multibeam depth data plotted in the Phase 2 study area.

Figure 4. SoMAS multibeam backscatter data plotted in the Phase 2 study area.

Figure 5. SoMAS side-scan sonar backscatter data plotted in the Phase 2 study area. The side-scan sonar was only used during the December-March (DM) deployment.

Figure 6. Location of survey area 15_DM immediately east of the mouth of the Connecticut River.

Figure 7. Survey area 15_DM multibeam bathymetry showing color-coded depth and 1 m contours.

Figure 8. Survey area 15_DM hillshade of multibeam bathymetry showing smaller-scale relief including areas with lineated erosional character, sand waves and possible rock outcrops.

Figure 9. Survey area 15_DM multibeam backscatter. Areas where more sound is scattered back towards the transducer are lighter in color and areas where less sound is scattered back towards the transducer are darker in color.

Figure 10. Survey area 15_DM side-scan sonar backscatter. Areas where more sound is scattered back towards the transducer are lighter in color and areas where less sound is scattered back towards the transducer are darker in color.

Figure 11. Profiles across two sand wave fields in survey area 15_DM. Upper: The larger sand waves in the eastern wave field are asymmetric towards the west suggesting a dominant westward (flood) current flow. Lower: The smaller sand waves in the western wave field are only slightly asymmetric towards the east suggesting a dominant eastward (ebb) current flow

although there is also apparently a significant tidal flow. The vertical exaggeration of the upper and lower plots are both about 100x.

Figure 12. Left: Hillshade images of barchan sand dunes in survey area Barchans_JJ in October 2015 and July 2018. Right: Bathymetric profiles across the barchan dunes. The barchan dunes imaged have migrated about 50 m towards the west southwest during the 2 years, 8 months between surveys which gives an average migration rate of about 50 m/y for these particular sand waves. Migration rates ranged from 19 to 34 m/yr for the barchan dunes that were identified. The vertical exaggeration of the upper and lower plots are both about 50x.