Optical Survey of Scallop Abundance and Benthic Habitat in the Nantucket Lightship Closed Area, Closed Area I, and the Western Great South Channel

submitted by

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for
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29 April 2010

Original requested funding: Federal $0 Industry $418,608 Total $418,608
Actual funding generated: Federal $0 Industry $351,068 Total $351,068
List of Acronyms

CLA I  Closed Area I, groundfish closure area (1994), located in the Great South Channel
       A portion of this area was reopened to the scallop fishery in 2000 and 2005

CLA II Closed Area II, groundfish closure area (1994), located on Georges Bank
       The southern portion of this area was reopened in 1999, 2000, 2004-6, and 2009

DAS  Days at Sea

DMV  DelMarVa, Delaware Maryland Virginia scallop Access Area

ET  Elephant Trunk scallop Access Area

HABCAM  Habitat Mapping Camera System

HAPC  Habitat Area of Particular Concern

HCAA  Hudson Canyon scallop Access Area

NLSCLA  Nantucket Lightship Closed Area, groundfish closure area (1994)

NEFMC  New England Fishery Management Council

NEFSC  Northeast Fisheries Science Center, Woods Hole

NOAA  National Oceanic and Atmospheric Administration

NOS  National Ocean Service

nm  nautical mile, 1 minute of latitude

NMFS  National Marine Fisheries Service

RSA  Research Set Aside

SMAST  School for Marine Science and Technology, Univ. of Massachusetts, Dartmouth

TAC  Total Allowable Catch

UNOLS  University - National Oceanographic Laboratory System (www.unols.org)

VIMS  Virginia Institute of Marine Science, College of William and Mary

VMS  Vessel Monitoring System

VPR  Video Plankton Recorder

WGSC  Western Great South Channel, an “open area” recently designated an HAPC

WHOI  Woods Hole Oceanographic Institution
1. Abstract
Three cruises to sea scallop resource areas were conducted by F/V Kathy Marie during June and July 2009 using the HABCAM optical imaging system. These cruises were structured to accomplish two primary project objectives:
For the first objective the tracklines of 56 NOAA Fisheries survey dredge tows (R/V Hugh R. Sharp) were replicated using the HABCAM optical system, both in the Mid-Atlantic and Georges Bank portions of the scallop resource area, in order to compare dredge catch rates on various substrate types and in differing current regimes.
Almost all NOAA towpaths were run three times, several 5 times, and a few 7 times to compare the variance between passes.

To accomplish the second objective optical surveys were conducted in three scallop access areas: NLSCLA, Closed Area I, and in the newly designated Western Great South Channel Habitat Area of Particular Concern.
The transects in three areas were conducted using a rectilinear patterns consisting of parallel transects with a spacing of 1 to 3 nm. Images were color processed during the cruises, with manual counts of scallop density obtained both during the cruises and after coming ashore.

Biomass estimates were developed by HabCam Group member Gallager and in spring of 2010 presented to NOAA Fisheries and international scallop scientists at a series of Invertebrate Subcommittee preparatory meetings, culminating with the SARC/SAW 50 meeting in June.
2. Description of the problem addressed

The following three sections (2.1, 2.2, 2.3) have been presented previously in the Final Report of NOAA Award NA08NMF4540668 and are included here for reference. The background, and the conditions of the Atlantic scallop fishery have not appreciably changed in the intervening year. These sections might have been just cited, and/or placed in the Appendix, however both of the those approaches would leave the required format of this report incomplete.

2.1 Background on the management of the U.S. northwest Atlantic scallop resource

Over the last thirty years the annual scallop survey conducted by the NOAA/NMFS/Northeast Fishery Science Center (NEFSC), has served as the only broadscale snapshot of sea scallop (*Placopecten magellanicus*) populations over the U.S. range of the resource in the northwest Atlantic. Strata based on depth and bathymetric features were developed and have proven quite useful in measuring current, and predicting future, landings and trends. However a combination of changes to scallop management strategies has contributed to the necessity of improving our scallop resource assessment methods. Foremost among these changes was the shift from region wide management based on input controls (i.e. fishing effort or Days At Sea or DAS), to area management based on output controls (i.e. Total Allowable Catch or TAC) from specific areas. The situation became more acute as the landings from these relatively small rotationally fished areas with high density scallop populations have proven to be larger than previous annual landings from the entire continental shelf. In these areas, even a small error in the population estimate can lead to either foregone earnings worth millions of dollars, or short term windfall catches followed by depleted stocks. Both results are poor outcomes for commercial fishing businesses.

A more detailed history of the successive developments that have occurred must also include:

1. the institution of large areas closures for the protection of managed groundfish species in 1994: Nantucket Lightship (NLSCLA), Closed Area 1 (CLA I), and Closed Area II (CLA II),
2. the rapid rebound of scallop populations within those areas,
3. the first large closure specifically for scallop growout: Hudson Canyon (HCAA) 1997,
4. the reopening of portions of areas closed in 1994 with specific limits on fishery removals,
5. changes to regulations that required temporary closure of areas with large amounts of small scallops specifically for scallop growout purposes (Scallop Amendment 10),
6. massive reseeding of an area downcurrent from the Hudson Canyon closure requiring establishment of an additional scallop growout closure, Elephant Trunk (ET), and
7. another massive set of small scallop south of the ET area resulting in the establishment of yet another scallop growout area, DelMarVa (DMV).

Related changes within the fishery management regulations include the required use of Vessel Monitoring Systems (VMS) aboard each vessel for tracking Days At Sea (DAS) usage and for accurate vessel location in order to provide enforcement for the scallop growout areas. In addition, implementation of the 2% Research Set Aside (RSA) funding mechanism has allowed participating industry vessels to contribute to projects in diverse areas such as stock assessment, bycatch of flounders and skates, and protected species (e.g. sea turtles) that might interact with the scallop fishing gears. Other efforts include substrate and habitat deliniation, and other modifications to the scallop fishing gears.
There are a number of inherent uncertainties in the annual NOAA Fisheries scallop survey and in the survey method. Primary among them are a limited budget affecting survey vessel time and thus the spatial coverage or scope of the survey, and a highly variable efficiency in the catch rate of the survey dredge. The simple fact is that the survey was developed for broadscale sampling to produce an index and it served us well for that task. However, the current acute problem is developing a cost effective and accurate biomass estimate for the much smaller and more densely populated scallop access areas in order to determine the TAC.

2.2 Background on development and previous use of HABCAM instrument and system
The HABCAM system was designed as a towed instrument to collect both seafloor imagery and other environmental data (i.e., altitude, depth, temperature, pressure, salinity, fluorescence, vessel position, and velocity). HABCAM transmits the data directly to the vessel in real-time to enable on-the-fly changes to the line transect survey route. The original instrument and software were constructed in 2002 by the Woods Hole Oceanographic Institution in cooperative partnership with the commercial fishing industry with funding from the Northeast Consortium of Sea Grant Institutions. Initial images were obtained during March 2003 while towing the instrument from the WHOI R/V Oceanus.

Significant changes were later made to the original vehicle with support from the 2004 Scallop Research Set Aside program within the New England Fishery Management Council (NEFMC). Other changes included the refurbishing and installation of a fiber-optic winch, and construction and installation of an A-frame which have allowed the New Bedford commercial scallop vessel F/V Kathy Marie to efficiently handle all operational requirements for the HABCAM system. Additional funding was obtained from the NEFMC RSA program for the years 2006 and 2007. This significantly increased the capabilities of the system, especially in the areas of image processing and visualization of the rapidly expanding collection of data and data products (HABCAM GROUP 2006, 2008A, 2008B). All data products generated by all projects to date are available via the internet at http://habcam.whoi.edu.

2.3 Background on Closed Area I Access Area and the western Great South Channel HAPC
The rebuilding scallop population within CLA I was first reopened to the scallop fleet in 2000. The area was again reopened in 2005 under the rotational management provisions within Scallop Amendment 10 (Fig. 3) Since that time the area has remained closed to scallop fishing because of NEFMC changes to the area boundaries, the resultant lawsuit from the environmental industries, and the court decision on the matter. Because there have been no fishery removals for the years 2006 to present there has been an unplanned opportunity for continued study of the area without the potentially confounding effects of fishing impacting the results. During this same time the WGSC has remained open to fishing and has been repeatedly recolonized with new year classes of scallop larvae. The southern portion of the area has recently been designated as an HAPC for small cod, however no management actions have been implemented to this time.

The WGSC HAPC has long been of significant economic importance to New England fishing communities as well, with estimates of current fishery landings from the area valued at $80 to 100 million annually for all species combined (NEFMC). Note the near continuous effort by the scallop fleet in the area as shown on the plots of Vessel Monitoring System (VMS) data below.
2.4 Project goals and objectives
There were three primary goals for this project:

1. conduct 56 comparative scallop survey tows with the R/V Hugh R. Sharp during the 2009 annual NEFSC scallop survey. Of primary concern was determining relative dredge efficiencies and variability in both the Mid-Atlantic and Georges Bank scallop resource areas.
2. document scallop resource conditions in Closed Area I scallop Access Area, an area that has not been open for fishing in recent years, and within the Western Great South Channel Habitat Area of Particular Concern (WGSC HAPC), between Closed Area I and Nantucket Shoals. An additional task was added to the revised proposal to have all four survey groups (NOAA Fisheries, University of Massachusetts School for Marine Science and Technology (SMAST), Virginia Institute of Marine Science (VIMS), College of William and Mary, and the HABCAM group) conduct surveys within the Nantucket Lightship Closed Area, in order to compare methods and biomass estimate results during a common survey time period.

3. continue to document substrate characteristics in the recently designated WGSC HAPC area, using both HABCAM. This effort greatly expands on previous efforts to describe the substrate in this very important area to both the scallop and cod fisheries using both the HABCAM optical system and the AST ProSAS synthetic aperture sonar system. Data from the combination of instruments is intended to provide both optical and acoustic information from the same area, in order to compare and visually calibrate the sonar return for the substrates in the area, i.e. sands, gravels, cobbles, and/or boulders.

2.5 Expected products
The workplan presented in the project proposal was designed to generate three products:

1. A scallop biomass estimate for the CLA I scallop Access Area which is scheduled to reopen in 2011, including areas beyond the current boundaries;

2. a scallop biomass estimate for the recently designated WGSC HAPC to document scallop abundance and fine scale substrate composition and type in the transect areas; and

3. a scallop biomass estimate for the Nantucket Lightship scallop Access Area. This survey was added as an additional element to the original proposal in order to compare results from all four biomass survey methods.

4. Comparative results and dredge efficiency estimates from 50 comparative tows with the R/V Hugh R. Sharp;

3. Approach and methods
Two cruises were conducted by the New Bedford scallop vessel F/V Kathy Marie during summer 2009. In the first cruise, to NLSCLA, a single 348 nm transect in the shape of a quadrilateral spiral (to conform with the area boundaries) with 1 to 3 nm spacing was made in order to produce the most amount of data in the shortest amount of time.

The comparison tows were accomplished during a separate cruise with three HABCAM Group members (Gallager, York, Taylor) aboard R/V Hugh R. Sharp on the Georges Bank leg of the annual NOAA Fisheries scallop survey. Manual counts of scallop and managed demersal species (flounders, cod, monkfish) were made by examining every 10th image in order to give a “first look” at comparison tow data were made during the cruise. In areas identified as having the higher target species counts the images were examined at higher frequency.

In the second cruise aboard F/V Kathy Marie 665 nm of parallel transects were conducted in Closed Area I (267 nm) and in the WGSC HAPC (398 nm). All transects in both areas were made with a nominal 1 nm spacing going northerly and southerly, directly into or away from the strong prevailing current. The sole exception to this approach was a small area (~6 nm²) in the...
SW corner of Closed Area I where very high densities of scallop were located in the troughs of 5-10 meter barcan sandwaves running east and west.

In the WGSC HAPC initial transects were made at a 3 nm spacing in order to identify areas with recent scallop settlement. These identified areas were then run with a 1 nm spacing in order to more accurately document variability and extent.

4. Results and discussion

Optical transects were conducted by F/V Kathy Marie in the NLSCLA, Closed Area I, and WGSC HAPC to accomplish the three of the four project goals. Overall almost 4,000,000 square meters of high resolution (~1mm pixel size) optical imagery were collected in these areas. 56 comparative tows were made during the third leg of the annual NOAA Fisheries scallop survey in the Georges Bank area.

4.1 Cruise 1: F/V Kathy Marie, Nantucket Lightship Closed Area, 4 – 11 June 2009.
In this cruise 348 nm of optical transects with 1 to 3 nm spacing were conducted in the NLSCLA in the form of a quadrilateral spiral. This typical “Search and Rescue, Man Overboard approach was seen in previous trials to efficiently cover the most amount of area in the shortest amount of time (HABCAM GROUP 2008). Initially every 10th image was examined manually and along track variability and patch size documented. Kriging of transect data using two cell sizes, the smaller one more accurately reflecting patch size, yielded a harvestable biomass estimate of approximately 7 - 8,000 metric tonnes for the area, with the smaller cell size producing the higher estimate. This amount was squarely in the middle of the estimates (4,000 to 10,000mt) produced by the other scallop survey methods used by NOAA Fisheries, VIMS, and SMAST.
See Appendix III for .pdf slide presentation of the methods and results.

Over 200 comparison tows between the dredge and optical methods had been conducted previous to this effort using the R/V Albatross IV, R/V Hugh R. Sharp, and F/V Kathy Marie. In this 2009 cruise, three members of the HABCAM team, Gallager, York, and Taylor, accompanied the scallop survey crew on the R/V Hugh R. Sharp on the third leg of the NOAA Fisheries 2009 scallop survey. Both dredge optical transects were conducted at 56 of the preselected survey stations in order to demonstrate the practicality of deploying the camera from the (chartered) NOAA survey vessel, to continue the calibration of dredge and optical survey methods, and to remove the possibility of any vessel effects.
Stations were conducted beginning in the southern portion of the Great South Channel, and the cruise proceeded east on Georges Bank in a counterclockwise direction to survey the Southeast Part, the Canadian scallop grounds, then back westerly along the Northern Edge, and finally the northern portion of the Great South Channel.

4.3 Cruise 3: F/V Kathy Marie, Closed Area I, 6 – 16 July 2009.

**Background**
Closed Area I was originally closed to all fishing gears capable of capturing groundfish stocks in 1994. A middle portion of the area was subsequently seasonally reopened to the scallop fishery in 2000 after a NMFS sponsored cooperative research survey conducted in 1999 demonstrated significant scallop resources and few groundfish. After a Joint Advisory Panel meeting in 2002 the location of various groundfish and scallop area boundaries were identified and later slightly adjusted by Framework action to better protect juvenile groundfish and to provide more complete access to traditional scallop fishing grounds and settlement areas. A subsequent court case was decided in favor of the environmental lobby position that such changes were too important to be decided by the NEFMC Framework process, and the area has remained closed to the scallop fishery since that time, 2005 (see Table 1 for VMS plots of the scallop fishery over time).


**Scallop resources and substrate characterization in the Great South Channel HAPC**

**Background**
Reports had come in from the commercial scallop fishing fleet of a large set of juvenile scallop in the area, with these reports later verified by the 2007 and 2008 NOAA Fisheries survey. Given the unknown management measures to be applied by the NEFMC Habitat Committee of this newly designated HAPC with its well known long term historical importance to the scallop and...
cod fisheries, and given that all other HAPCs for juvenile cod are effectively closed to the scallop fishery, this project was designed to perform a systematic fine scale survey of the area, with specific focus on substrate.

**Substrate**
Gravel pavements have been suggested (Valentine, Auster, Lindholm) as essential to the growth and survival of newly settled demersal species and specifically for cod, *Gadus Morhua*. In 2007 the Applied Signal Technology, Inc. (AST) synthetic aperture sonar system (ProSAS Surveyor) had been used to conduct experimental trials of about 30 kilometers length aboard F/V Kathy Marie using a developmental testbed prototype of their technology. In 2008 more extensive fieldwork was performed in this area and several others (Closed Area I, Northern Edge HAPC, SBNMS) as a subcontract within NOAA Award NA08NMF4540668. In total the AST sidescan arrays were towed over a trackline of ~129 nm (238 km) in the WGSC HAPC looking out 100 -135 meters to each side.

The area of the WGSC HAPC is about 700 nm$^2$ or 9 10 minute “squares”. Thus, neglecting the few areas where the sonar transects crossed each other (and were useful for calibration purposes), the total imaged area using the AST sidescan was about 17 nm$^2$ (61 km$^2$) or about 20% of one 10 minute square, or about 2% of the entire area. Approximately 10% of the area on the far western Nantucket Shoals side is in places quite shallow (< 10 fathom) with sand ridges, wrecks, and underlying ledge, and thus difficult to survey safely with a 100’ class vessel and problematical with any towed vehicle such as the FOCUS-2, as the sonar arrays need to be below the vessel wake.

In 2008 HABCAM was towed in the WGSC HAPC area and collected 142 nautical miles (263km) of optical data imaging an area of approximately 0.08 nm$^2$ (0.263 km$^2$) or ~0.01%. Previous efforts had imaged only small discrete areas.

**HABCAM 2009 optical survey of WGSC HAPC**
In this 2009 effort almost 400 nm of parallel optical transects were conducted, first with a systematic 3 nm spacing, then followed up with a 1 nm spacing where recent scallop settlement was noted. As in the other areas, initially every 10th image was examined, scallop and managed groundfish counts recorded along with a categorization of substrate composition. Areas that exhibited higher densities were examined at higher image frequency.

The majority of bottom seen in the imagery within the area may be categorized as sand with less than 10% of imaged areas gravels with a grain size greater than ~6mm (~1/4”). Rocks and boulders were imaged but at very low frequency (<.001%) however sonar images in the central area near the BB navigation buoy revealed that boulders (.25 to 5m max diameter, but usually 1-2m) seemed to be distributed with 20-100 meter spacing, something not evident in the optical imagery because of the narrow (~1 m) field of view.

All processed optical imagery and associated data are available on the project website at [http://habcam.whoi.edu](http://habcam.whoi.edu).

**4.5 Contribution to management**
Work accomplished during this project contributes to management in several ways. It has:

1. added to the body of knowledge concerning the efficiency of NOAA survey dredge in various scallop resource areas, useful in calibrating the optical survey method to historical time series in preparation to NOAA Fisheries operating their own optical system;
2. provided scallop count and biomass estimates in NLSCLA, CLA I, and WGSC HAPC; and

3. continued to provide internet access to all of the optical and much of the acoustic imagery collected to date, the latter in areas where generally there is no existing or publically accessible backscatter data.

4. Results from the NLSCLA survey (item 2 above) were presented and reviewed by the Invertebrate SubCommittee at the NEFSC during the weeks of February 8th to 12th, March 15th to 19th, and April 26th to 30th 2010. These meetings have been conducted in preparation for the scallop Stock Assessment Review Committee (SARC 50) held in early June at the NEFSC.

The HABCAM derived biomass estimating method used rectilinear parallel and crossing transects with spacing between 1 and 3 nm documenting along track patchiness. Kriging of the linear transect data between transects using the alongtrack patchiness, the optically derived shell height data, and the NOAA Fisheries shell height/meat weight ratio produced both total and exploitable biomass estimates that fell directly in the middle of the estimates derived by the other survey methods used. Estimates of variance of the data based on transect spacing were also derived and presented (Gallager).

5. Participating organizations and individuals
The HABCAM GROUP is a partnership with individuals from the Woods Hole Oceanographic Institution (Gallager, Howland, York, Lerner), Arnie’s Fisheries, Inc. (Rosonina, DeMello), and independent researchers (Vine, Taylor, Bolles). Additional individuals contributed greatly in at-sea data collection and shoreside data processing tasks (Keating, Tyler and many others).

6. Acknowledgements
The Northeast Consortium provided funding for initial camera and vehicle development in 2002. Particular recognition is given to Jonathan Howland, Lane Abrams, Andy Girard, Scott Gallager of the Woods Hole Oceanographic Institution for their contributions to instrument and vehicle design, construction, and testing.

NEFMC/NMFS Scallop RSA program grant (NOAA Award NA05NMF4540009) for funding further camera system development in 2005. This funding allowed the system to become fully functional and included major vehicle modifications, installation of a fiber optic winch and A-frame.

NMFS Advanced Technology Working Group, Deborah Hart P.I., for providing additional funding for software development specifically focused on color correction and segmentation of targets, a computer for data processing, and a dedicated server.

NEFMC/NEFSC Scallop RSA program grant (NOAA Award NA06NMF4540264) for funding to conduct survey transects in 2006. This funding also allowed for further system development, integration of software improvements, and progress in comparing survey designs.

NEFMC/NEFSC Scallop RSA program grant (NOAA Award NA07NMF4540030) for funding to conduct survey transects in 2007. This funding also supported additional sea time for imagery collection, further development and integration of software improvements.

NEFMC/NEFSC Scallop RSA program grant (NOAA Award NA07NMF4540668) for funding to conduct survey transects in 2008. This funding also supported additional sea time for imagery collection, further development and integration of software improvements.
SBNMS for a contract to collect imagery of an archeological resource on Stellwagen Bank.

NOAA/NOS Integrated Ocean Observing System IOOS program funding (FY 2007-2009) which allowed repeated visits to many of the same areas where scallop transects have been conducted in order to document changes in benthic community structure over time.

Special thanks are due to Arnold DeMello, owner of the F/V Kathy Marie, Captain Paul Rosonina, and the rest of the crew for being willing to modify their fishing schedule and make the vessel available for the science cruises. In particular, Antonio Melo, the engineer, must be singled out for making necessary changes and repairs to equipment on the fly, while making it seem as if it is all in a day’s work.

7. Presentations
Invertebrate SubCommittee, NEFSC, Woods Hole, MA, 8-12 February 2010
Invertebrate SubCommittee, NEFSC, Woods Hole, MA, 15-19 March 2010
Invertebrate SubCommittee, NEFSC, Woods Hole, MA, 26-30 April 2010
Stock Assessment Workshop, (SARC 50), NEFSC, Woods Hole, MA, 1-4 June 2010

All Powerpoints, posters, reports, and other publications are on the website at URL http://www.habcam.whoi.edu

8. References
http://www.fao.org/docrep/006/y5029e/y5029e0c.htm


9. Appendix (attached separately)
9.1 Appendix I - NLSCLA Survey - Report to Invertebrate SubCommittee (Gallager).
2009 RSA Objectives

1. Relative dredge efficiency and variability in multiple scallop resource areas
   50 tows, joint ship operations with R/V Hugh Sharp

2. Intensive survey of Closed Area I and Western Great South Channel

3. Scallop resource conditions in Nantucket Lightship Closed Area Access Area
   - Compare survey designs- time, cost, accuracy- grid, spiral
   - Scallop abundance and biomass as a function of shell size
   - Total abundance and biomass
   - Estimate exploitable biomass
   - Assess patchiness as a function of size
**Methods**

Merge synoptically acquired optical and acoustic benthic data with water column data

- 175 kHz AST Synthetic Aperture Side scan VPR, CTD, Fluorometer on Focus vehicle
- Stereo optical imaging
- Kongsberg EM3002 300 kHz multibeam

Machine vision
digital stereo video cameras

Benthos Altimeter

RDI 1200 kHz ADCP

Strobe x4

2 Imagenix side scan sonars Teledyne Benthos C3D side scan sonar

HABCM
Habitat Mapping Camera System
Stereo 2 Mpixel system

Fiber optic tow cable

0.68 inch fiber optic tow cable

1m Field of View
5 – 10 frames per second
>50% overlap @ 5kts
Comparison between dredge and continuous imaging surveys

Standard dredge survey
- 15 min tow @ 3.8 kts = 4,500 m²
- 24 tows/24h period, on average
- = 106,704 m²/day

Conduct continuous imaging survey
- 5 images/s @ 5 kts
- 2700 m²/15 min tow
- 259,200 m²/day
- ~2.5X greater ground coverage

50% overlap to allow object registration for mosaicing

~1 Terabyte / day

Comparison between dredge and continuous imaging surveys

NLSCA Area: 334 nm²
Trackline length: 348 nm
Images Collected: 1,235,251
Images Processed: 123,000
Area Covered: 0.187 nm²
% Area Covered: 0.54%
Time to collect data: 70h, 2.9 days
Time to process data: 7 days x 2 = 14 man days
Survey Efficiency: 334/20 = 17 nm²/day
Biomass (g MW/m²) = \exp(a + b \log(SH) + c \log(depth))

\begin{align*}
a &= -8.62 \\
b &= 2.95 \\
c &= -0.51
\end{align*}
Biomass (g MW/m²) = \exp(a + b \log(SH) + c \log(depth))

a = -8.62  b = 2.95  c = -0.51

Total abundance of all scallops gridded at 3km scale
Total abundance of all scallops gridded at 300m scale

Exploitable abundance of scallops gridded at 3km scale
Exploitable abundance of scallops gridded at 300m scale

Exploitable biomass of scallops gridded at 3km scale
Exploitable biomass of scallops gridded at 300m scale

Variance map
Distribution of Q1: the residuals between observed and predicted values.

Predictions are statistically valid at the 99.9% percentile.

Double kriging: observed and predicted values.
### Scallop Abundance

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### Scallop Biomass

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- **NLSCA Area:** 334 nm²
- **Trackline length:** 348 nm
- **Images Collected:** 1,500,000
- **Images Processed:** 150,000
- **Area Covered:** 0.043733 nm²
- **% Area Covered:** 0.44%
- **Time to collect data:** 70h, 2.9 days
- **Time to process data:** 7 days x 2 = 14 man days
- **Survey Efficiency:** 334/20 = 17 nm²/day
Summary of HabCam Activities Related to the NMFS/NEFSC Sea Scallop Survey of the Nantucket Lightship Closed Area and Yellowtail Flounder Observations in 2009

The HabCam Group
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Richard Taylor\textsubscript{2,3}, Norman Vine\textsubscript{2}
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Karen Bolles\textsubscript{3,4}
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(2) Advanced Habitat Imaging Consortium,
(3) Arnie’s Fisheries, New Bedford, MA
(4) Ocean Explorium, New Bedford MA

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  Joint tows
  Relationship between substrate, scallops and yellowtail

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  Edge effects-border rules
  Camera calibration model
  Scallop abundance
  Shell height measurements
Introduction
Here we report on use of the HabCam camera system to conduct sea scallop surveys on Georges Bank, joint scallop survey work and dredge calibration with NOAA vessels, and an analysis of inherent errors in camera calibration, scallop abundance estimates, and shell height measurements.

Operational Capabilities and description of hardware and software
Onboard sensors include a high resolution machine vision GigE color camera, four xenon strobes, side scan sonar, CTD with temperature, salinity, chlorophyll, turbidity, and pH, and a variety of engineering sensors including vehicle roll, pitch, and heading (Fig. 1). All sensors are networked subsea and data telemetered via a GigE network to the surface in real-time where they are time stamped for recording and processing. The HabCam imaging system is “flown” 1.5 to 3 meters off bottom while being towed at 4 to 5 knots (~2.5 m/sec), thus a track approximately 100 nautical miles is imaged each 24 hour day while at sea. Optical imagery is collected at a width of approximately 1 to 1.25 meters (total ~200,000 m$^2$/24 hr day). Images (1280x1024 pixels, 16 Bit) are acquired at 5-6 Hz providing a minimum of 50% overlap between images. Images are processed in real-time on the ship by color correcting raw 16 bit tiff images and converting them to 24 bit jpegs (Fig 2). Figure 2 represents a combination of existing data structures and what we envision as fully queriable database.

![Figure 1. The HabCam vehicle is towed on 0.68” fiber optic cable ~1.5-3 m from the bottom. The camera provides a field of view of 0.5-2 m$^2$. Four strobes flash synchronously with each image. Ancillary sensors include side scan acoustics, CTD, chlorophyll fluorometer, and CDOM fluorometer.](image)

A comparison between operational capabilities of the NMFS dredge and HabCam show the following statistics: the standard survey 8’ wide dredge makes approximately 24, 15 min tows at 3.8 kts per day covering about 4,500 m$^2$ per tow and 106,704 m$^2$/day. Continuous operations with HabCam towing at 5 kts and producing 5 images per second with 50% overlap covers 259,200 m$^2$/day, nearly 2.5 times the area covered by the dredge.
We have implemented two forms of image informatics (i.e., extracting information from images): manual and automated classification. Manual classification proceeds by having one or more operators reviewing image by image, or a subset of images, and identifying and measuring every target observable through a GUI with point and click functionality. This allows about 60 to 200 images per hour per operator to be quantified depending on image complexity and number of individual species being identified. Currently, there are more than 460 taxa or taxonomic groups ranging in size between \( \sim 1 \text{ mm} \) to 2 m in our image library. While taxonomic definitions used in image analysis are based on epibenthic organisms, a variety of infauna can typically be observed and quantified such as the siphons of bivalves, turbularian worms, burrowing shrimp, and some vertebrates (e.g., tilefish and their burrows).

In addition, the operator evaluates the substrate type in each image and categorizes it into one of 43 groups ranging from silt, sand, gravel, shell, cobble, boulder, and a variety of combinations. Development of approaches for automated classification of targets and substrate is proceeding using the manually classified images as training sets for the supervised classification software. However, the species richness and habitat complexity along the Northeast Continental Shelf is
sufficiently high that automated approaches cannot, as yet, capture the true nature of the environment.

For the purpose of the scallop surveys reported here, images were classified manually by several technicians who characterized substrate into the categories noted above and measured all scallops and groundfish, including yellowtail flounder. To speed the analysis, every 10th image was processed. Rationale for this strategy is discussed in the following sections.

Scallop Survey Results
2009 Nantucket Lightship Closed Area (NLSCA)
Overview
The objectives were to estimate scallop abundance and derived biomass as a function of shell size in NLSCA. A secondary objective was to estimate the distribution and abundance of yellowtail flounder in relation to substrate. A modified spiral was conducted starting 1.3 nm outside the boundary of the closed area to allow interpolation of the final abundances without boundary influences (Fig. 3). The spiral was conducted around the border then continued at an interval of 2.6 nm. Following completion of this coarse spiral, the vessel steamed to the northeastern corner and began a finer grid extending from the northern edge to the center of the closed area. This finer grid began at an interval of 2.6 nm but compressed to 1.3 nm as the vessel approached the western-most section of the closed area. This was to provide higher resolution in the area to the northwest where prior knowledge indicated dense scallop abundance. The area of NLSCA is 334 nm². Total trackline length was 348 nm with 1,235,251 images collected. A total of 123,000 images were processed for a total area covered of 0.187 nm². Total area sampled by HabCam was 0.57% of the NLSCA. The survey required 72 hours of continuous towing and approximately 27 man days to process the data, assuming 12 hour shifts.
To assess multi-scale patchiness and to determine how many images should be processed, a preliminary transect from east to west 2 nm in length was processed by manually counting and measuring every other image to effect complete coverage. This provided information for calculating the appropriate image decimation or downsampling rate for processing the remainder of the spiral and for calculating a patchiness index for use in setting appropriate interpolation scales.

Along track scallop abundance ranged between 0 and 23 scallops/m² (Fig. 4). It appeared that aggregations of scallops at densities between 5 and 20 /m² occurred in clumps at a spatial scale of 400m. Therefore, a Nearest Neighbor–k analysis was performed to establish the dominant spatial scales of patchiness. The Neighbor-k showed strong patchiness ranging from 400 to 900m and again at 3000m (Fig. 5).

Figure 4. Scallop abundance in the northern section of the NLSCA survey along a 4.5 km (2 nm) track. Every other image was classified manually to establish a baseline for downsampling and patchiness. Note the very patchy distribution ranging from 0 to >20 scallops per m².

Figure 5. Ripley’s Neighbor-k analysis of 1 dimensional patchiness of scallop distribution along the track sampled by every other image. Spatial scale is on the x axis while the residual between observed and predicted nearest neighbor distance under randomness (1000 Monte Carlo simulations) is on the y axis. The first mode indicating a characteristic patch size is located at 700-900 m, and a second at 3.2 km. Both modes are well above the red line under randomness indicating these patch dimensions to be statistically significant at the 95% confidence level.
Data from this track processed at every other image was downsampled by extracting abundances and the CV at intervals ranging from every 4<sup>th</sup>, 8<sup>th</sup>, 10<sup>th</sup>, 12<sup>th</sup> etc. out to every 500<sup>th</sup> image. The mean and CV remained stable up to a downsample level of every 10<sup>th</sup> image. Therefore, the remaining spiral was processed at a decimation rate of every 10<sup>th</sup> image (Fig. 6).

12,902 scallop shell heights were counted and measured using MIP (Manual Identification Program developed by AD York), which allows users to quickly point and click on scallops to extract measurements and select substrate type from a menu. The shell height distribution was strongly bimodal with modes at 53 and 125 mm (Fig. 7). A third, less prominent mode was located at 142 mm.

The scallop density from every 10<sup>th</sup> image plotted as color coded dots for all scallops showed highest aggregations in the central upper third and in the central eastern region of the closed area (Fig. 8a). Scallops were sparse in the northwestern corner and southern regions. A similar plot for just those scallops with shell height between 20 and 65mm showed that small scallops were most abundant in the east central region of the closed area (Fig. 8b).

The raw scallop density per image was interpolated into rectangular grids at two scales using ordinary kriging: 3350x2217m and 335x221m. First, a semi-variogram was constructed to evaluate autocorrelation of the data. For the coarse and fine scales, the mean for each grid cell was color coded (Fig. 9a,b). Total abundance, mean, and variance for each grid cell were calculated. An overall CV was calculated by bootstrapping the standard error divided by the mean for each grid cell. As data were collected and kriged beyond the location of the closed area boundary, results were clipped to lie within the boundary.
Figure 8. Raw abundance (#/m²) estimates on a per image basis for all scallops regardless of shell height. Each dot represents a single image with the abundance indicated by color. Where no dots exist, no scallops were observed. a) All Scallops (#/m²). b) Scallops with shell height less than 60mm.
Figure 9. a) Kriged scallop densities at a scale of 3350x2217 m. Mean densities represented by color referenced to the color bar on the right. b) Kriged scallop densities at a scale of 335x221 m showing considerable patchiness at this fine scale.
The highest mean value was 4 and 6 scallops/m² for the coarse and fine scale grids, respectively. Total abundance within the closed area boundary was calculated by summing each of the grid cells that fell within the boundary. Those cells that were partially within the boundary were evaluated by including only the proportion of the cell falling within the boundary. Total scallops in the coarse and fine scale grids were 174,966,666 and 197,545,580 scallops, respectively. The discrepancy in total abundance between grid scales probably lies in the fact that the scallops were patchy at scales of 400-900m as shown from the Nearest Neighbor-k analysis. The courser grid scale smoothes high density patch values over a larger area than the higher resolution grid. The finer grid, therefore, is providing a more representative view of the scallop distribution and also the most accurate total count. Overall mean was 0.187 scallops/m² with a CV of 0.04. Variance per cell ranged between 0.5 where sampling density was greatest to over 0.7 where sample density was low (Fig. 10).

Biomass per scallop was calculated from a mixed-effects model for shell height, meat weight, and depth:

\[
\text{Biomass (g MW/m}^2\text{)} = \exp(a+b \log(SH) + c \log(\text{depth in m})
\]

Where \(a = -8.62\), \(b = 2.95\), and \(c = -0.51\) (D. Hart, per com).

Mean biomass per scallop was 32.9 gMW. The basic pattern of distribution followed that of scallop abundance with high value areas in the northern central region and in the central eastern region (Fig. 11). Biomass kriged at the fine scale for all scallops produced a total of 6,782 MT (Fig. 12).

It was desirable to observe the density of scallops in relation to depth and substrate type. Depth from the ships echosounder was linearly interpolated onto a uniform grid and colored as a function of depth (Fig. 13a). Sand waves in the northern central region and a trough in the central eastern region are notable. When scallop density was plotted as a color map over the
Figure 11. Dot plot of scallop biomass for all scallops regardless of shell height.

Figure 12. Kriged biomass estimates completed at the fine scale for all scallops regardless of shell height.
interpolated depth, it was clear that greatest densities were at the eastern base of the sand waves and just eastward of the trough, but not in the trough (Fig. 13b).

Figure 13. a). Depth from the ship’s sonar interpolated to a uniform grid. b) Depth with overlaid scallop abundance on the same color scale as in Fig. 12. Z axis is exaggerated.
Substrate was categorized into three numeric bins of dominant substrate: (2) sand, (3) gravel, and (4) shell. Dominant substrate categories include mixed substrate types, for example, “gravel” contains mixed substrate images such as gravel/sand and gravel/shell. Interpolation of these substrate categories across the NLSCA grid showed the entire area to be mostly sand (Fig. 14a,b). The greatest accumulation of sand/shell hash corresponded to areas of high scallop densities. The region to the central eastern side of the trough had notable sections of gravel, which is also where scallops were most abundant, particularly scallops less than 60mm in height. The combination of all three variables, scallop density, depth, and substrate (Fig. 15) provides a

Figure 14. a) Dominant substrate binned numerically into three categories (2) sand, (3) gravel, (4) shell. b) Sand dominated pie chart of substrate in NLSCA.
visualization of how scallop distribution is affected by these variables.
As an alternative method for calculating total population abundance without kriging or interpolating, one may simply use the overall mean multiplied by the total area. Our results using this approach is 0.187 scallops/m² x 1,142,280,000 m² = 213,606,360 scallops with a CV of 0.034.

Yellowtail flounder observed in NLSCA and other regions during our survey were generally sparse (Fig. 16). In NLSCA, 124 observations were made with the densest concentration in the central region. This region was also characterized by being mostly sand with patches of gravel. The most abundant aggregations of yellowtail were observed in the Southeast Part of CLAI and on the Canadian side with densities exceeding 0.14 fish/m². In some cases two or three fish were observed in a single image. Images from CLAI show yellowtail to be found on mostly sandy bottom with shell hash and occasionally on gravel.

Figure 15. Depth overlaid with scallop abundance and substrate. Note location of invasive tunicate *Didemnum vexillum* in relation to high scallop densities.
An interesting relationship between scallop and yellowtail density was observed on the Canadian side of the Northern Edge. Data for yellowtail and scallops for the same trackline are plotted alongside each other in Figure 17. Note that yellowtail appeared to be at highest densities where the abundance of scallops is low. This seemingly inverse relationship only holds for this trackline at that point in time and is probably related more to substrate, food supply, reproduction, or environmental variables, than a true relationship between scallops and yellowtail.

Figure 16. (top) Observations of yellowtail flounder in CLAI, WGSC, NLSCA, CLAII and on the Canadian side of the Northeast Peak. Each red dot represents an individual sighting. (bottom) Example of three yellowtail in a single image, taken in NLSCA.
Figure 17. Yellowtail flounder and scallop densities observed along a 1.7 nm long trackline on the Canadian side of the Northern Edge. Each place mark represents data binned at 50 m intervals.
**Joint Ship Operations**

Since 2007, The HabCam Group has been collaborating with the NMFS in their annual scallop surveys by conducting joint tows. These joint tows were designed to compare scallop abundances and size estimates from the standard federal dredge survey with those derived from HabCam imagery. Data will be presented here for 2008 and 2009.

In June and July 2008, The F/V Kathy Marie ‘shadowed’ the R/V Sharp on 113 total tows with 44 in the Elephant Trunk, 35 in CLAI, 8 in CLAI HAPC, 9 in NLSCA, and 17 in WGSC (Fig. 18). HabCam made at least three passes at over 50% of the NMFS stations, and in a few cases made up to seven. These multiple passes were designed to assess the variability of scallop density along each track and between multiple passes. Images from all passes were processed at a downsample rate of every 10th image. This translates into processing about 1 m² every 5 m.

Within hours of conducting a dredge tow, the beginning and end points for the tow were communicated at sea via radio from the Sharp to the Kathy Marie. This allowed the captain of the Kathy Marie to line the vessel up on the dredge tow and follow a straight line from one end to the other. Because the absolute position of neither the dredge nor the HabCam vehicle was precisely known, our best efforts were to make multiple passes that coincided within about 50m of the dredge tow line and between each pass of HabCam. As an example, data for seven passes along the dredge tow for one station in Elephant Trunk (91) shows within and between variability of scallop densities observed by HabCam (Fig. 19). Although Pass 6 appears to be an outlier, results of a one-way ANOVA suggest that there is no significant difference between all 7 passes (p<0.001).

HabCam estimates of scallop abundance were consistently greater than those for the dredge. Mean shell height measurements were similar between dredge and HabCam (Fig. 20), but as will be discussed in the section under error analysis, the tails of the frequency distribution for HabCam are higher than those for the dredge indicating some inherent error in the measurement.

In June 2009, in addition to shadowing the Sharp with the Kathy Marie during Legs 1 and 2 of the annual scallop survey, HabCam was towed from the A-frame of the Sharp as part of routine dredge operations on Leg 3. This project was designed to support image collection and processing, scallop and groundfish identification and enumeration, and comparison of HabCam data with that obtained by standard dredge tows during Leg 3 of the 2009 NMFS Scallop Survey. Because of sea state and time considerations, HabCam was towed at and between 23 stations. HabCam collected a total of 787,832 images with a footprint of about 1 m² each. By area, 85,572 images were collected in CLAI, 216,809 images in CLAI, 183,070 images on the Canadian side of the Northern Edge of Georges Bank, and 302,381 images between stations. The objectives of this project were to: 1) process all images from cruise HS_20090623 for color correction and conversion to jpeg; 2) manually count and measure all scallops and fish in images along each track and characterize substrate; 3) plot vessel tracks, images, and data products in Google Earth for ease of visualization; 4) establish a training set of images manually processed for use with an automated target classifier and compare results with manual classification, and 5) compare HabCam data with dredge survey data to obtain a dredge efficiency for both scallops and yellowtail flounder, where applicable. A final report has been filed with the NOAA CINAR office and Russell Brown at the NEFSC.
Figure 18. 44 Joint tows between R/V Sharp and HabCam on the F/V Kathy Marie in the (a) Elephant Trunk, (b) CLAI, (c) CLAI HAPC, (d) NLSCA, and (e) WGSC. Red lines are dredge tows, blue lines are HabCam tracklines.
Figure 19. (a) Federal dredge station 91 in ET with 1 nm tow shown in red. Seven passes by HabCam shown in blue. Multiple passes of HabCam were within 50m of each other. (b) Mean +/- SE of scallop abundance (#/m$^2$) from each of the seven passes at station 91.

Figure 20. Data from four joint stations illustrating the relationship between dredge and HabCam data. In each of the boxes shell height frequency distributions, mean abundance, and position along track for the dredge and HabCam are compared.
As each image represents about 1 m² and there is approximately 50% overlap, an area of about 242,000 m² was imaged. In an area on the Canadian side called the ‘seed box’, the density of small (50-60 mm) scallops was extremely high, upwards of 50 to 90 scallops per image (e.g. Fig. 21).

Shell height measurements from HabCam showed a strongly skewed distribution to the left with a mode of 55 mm and a mean of 79 mm (Fig. 22), indicating that this area was dominated by two year old scallops with relatively few older individuals.

Along track abundance of scallops at Station 404 ranged from 0 to well over 60/m² (Fig. 23). A Neighbor –k analysis of scallop distributions along the track in Fig. 4 showed that patchiness was significant at several spatial scales from 600 to 1000m (Fig. 24).

Yellowtail flounder were sparse but most abundant in the Southeast Part of CLAI and on the Canadian side of the Northern Edge (Fig. 25). Images show yellowtail to be found on mostly sandy bottom with shell hash and occasionally on gravel (Fig. 26).

There are numerous reasons why dredge efficiency can be highly variable: for example, tow direction in relation to tidal currents, substrate composition, wire out, tow speed, tow duration. To compare scallop abundances estimated by the NMFS dredge and HabCam, plots were generated by region and by substrate and include data for both 2008 and 2009 (Fig. 27). Georges Bank includes NLSCA, WGSC, CLAI and CLAII. Mid Atlantic Bight includes Elephant Trunk, DelMarVa, and Hudson Canyon. Regression slopes were 0.34 for Georges and 0.46 for Mid Atlantic Bight. When the data are broken out by substrate regardless of region, the regression slope for sand was 0.35, for sand plus other substrate types such as shell hash it was 0.40, and on gravel it was 0.35. Therefore, no immediately apparent systematic bias existed as a function of substrate.

Bland-Altman plots are used to assess the correspondence between two forms of measurement for the same data and are constructed by plotting the difference between the two data sets against the mean. For these data, it was necessary to normalize the residuals for the sum of both dredge and HabCam samples. Mean residual for all data for 2008 and 2009 was 0.37 (Fig. 28), which is consistent with the regression analyses presented in Figure 27. The residuals are normally distributed between the limits of agreement suggesting that while there is a strong systematic bias, neither measurement approach is affected by abundance of scallops being measured.
Figure 21. The HabCam Manual Identification Program (MIP) while processing an image collected on the Canadian side near station 404 where 90 scallops were counted and measured in a single image.

Figure 22. Frequency distribution of scallop shell heights from HabCam images at Station 401 in the seed box.

Figure 23. Along track abundance of scallops at Station 401 in the 'seed box' on the Canadian side. Mean abundance was 16 scallops/m².
Figure 24. Neighbor-k analysis of the distribution of scallops at Station 404. Note significant modes at 600 and 1000m.

Figure 25. Georges Bank and tracklines of the R/V Hugh Sharp Leg 3 of the NMFS scallop survey (orange) and the regions where HabCam was deployed and collecting images (purple). Red dots and yellow stars are yellowtail flounder sightings.
Figure 26. Composite of example images of yellowtail flounder from Georges Bank.
Figure 27. Regressions of dredge survey estimates against HabCam estimates of scallop densities for both Years 2008 and 2009. Each point represents a single 1nm tow in the Georges Bank (a) or Mid Atlantic Bight (b) areas. Data broken out by substrate type in sand (c), sand plus shell hash (d), and gravel (e). The one to one correspondence line is plotted in black.
Figure 28. Bland-Altman plot of the residuals for all joint tows in 2008 and 2009. The y axis represents (Dredge-HabCam)/(Dredge+HabCam) and the x axis is the mean of the two observations. The mean difference and the limits of agreement are also plotted.
Assessment of Real and Potential Errors Associated with HabCam Image Data

Sources of error to be assessed:

Border rules for measuring and counting scallops

Engineering Error
- Calibration of Field of View (FOV), complete camera model for intrinsic parameters, estimation of in-water, focal length, principle point, and pixel error
- Incorporation of extrinsic parameters for each image into calculation of FOV (area swept)- roll, pitch, heading, altitude

Human Error
- Analysis of measurement error both between individuals and within individuals using Intra Class Correlation

Imaging Error
- Scallop shells not orthogonal to camera axis

Total Measurement Error
- Analysis of shell height measurement error relative to NMFS dredge survey in NLSCA Errors in interpolation of 1D data into 2D
- Kriging correlograms and variograms
- Variance within and between gridded cells
- Non-model based assessment of biomass

HabCam Border Rules
The purpose of the HabCam rules for border effects is to reduce undercounting or overcounting due to animals being on the edge of images. The desired outcome is to count scallops on the edge of images exactly half the time. To achieve this, the following rules, which result in counting only scallops that have their centroid in the image, are followed (Fig. 29):

Primary Rule: Count all organisms that are more than half way in the image.
Secondary Rule: If the organism is exactly half way in the image, count only the organisms that are half way in the top and right sides. This process is identical to that described for counting blood cells on a Spears-Levy Hemacytometer and eliminates the need for altering the field of view (FOV) on an image to account for image basis.
Figure 29.

a) Four cases (represented as white squares) are shown in a 1 m² area to demonstrate HabCam border rules. Circles represent scallops. Stars represent scallops which would be counted in each of the 4 images.

b) A HabCam image with scallops labeled “Yes” or “No” designating whether they would be measured using border rules.
**Calibration of Field of View (FOV)**

Calibration of an optical system must include a complete camera model for intrinsic parameters, estimation of in-water focal length, principle point, and pixel error, followed by image correction by employing extrinsic parameters collected for each image.

The intrinsic parameters for the HabCam camera were calculated using images of a 1m² target marked off at 10cm intervals in a 4 m deep seawater tank. The HabCam vehicle was positioned above the target at various altitudes (1-3m), roll, and pitch (0 and 20 degrees). Twenty eight images representing a range of positions were used for calibration of the camera with the Calibration Toolbox in Matlab.

**Intrinsic parameters**

(based on 28 images of target at different altitudes and orientations)

- **Focal Length:** \( f_c = [ 2773.25504, 2764.28859 ] \pm [ 7.18117, 7.13362 ] \)
- **Principal point:** \( c_c = [ 778.19667, 509.00401 ] \pm [ 4.13012, 3.80811 ] \)
- **Skew:** \( \alpha_c = [ 0.00000 ] \pm [ 0.00000 ] \Rightarrow \) angle of pixel axes = 90.00000 ± 0.00000 degrees
- **Distortion:** \( k_c = [ -0.31591, 0.14388, 0.00070, 0.00138, 0.00000 ] \pm [ 0.00702, 0.02649, 0.00038, 0.00056, 0.00000 ] \)
- **Pixel error:** \( e_r = [ 0.53035, 0.50489 ] \)

The numerical errors are approximately three times the standard deviations

- Intrinsic pixel error = +/- 1.59 pixels
- Resolution range \( f \) (FOV): 0.37 – 0.89 mm/pixel
- Intrinsic real-world error : 0.58 – 1.41 mm

These values provide error bounds on the resolution and accuracy of the camera system in water. Plots of the relative errors show that the camera CCD chip, lens and housing window are slightly out of alignment in both radial and tangential attitudes (Fig. 30). The pixel resolution is a function of FOV, which in turn is a function of altitude off the bottom. In calibrated screen measurement space, the overall measurement error is between 0.58 and 1.41 mm.
Figure 30. Radial, tangential, and complete distortion model for the HabCam camera.
Distortion in each image is first corrected using the intrinsic parameters given above (Fig. 31).

\[ \mathbf{K}_K = [f_c(1) \alpha_c f_c(1) c_c(1); 0 f_c(2) c_c(2) ; 0 0 1]; \]

Where the KK matrix is the uncorrected image matrix.

\[ r_{2\text{ extreme}} = (nx^2/(4*f_c(1)^2) + ny^2/(4*f_c(2)^2)); \]

\[ \text{dist\_amount} = 1; (1+k_c(1)*r_{2\text{ extreme}} + k_c(2)*r_{2\text{ extreme}}^2); \]

\[ f_c\_new = \text{dist\_amount} \times f_c; \]

\[ \mathbf{K}_K\_\text{new} = [f_c\_new(1) \alpha_c f_c\_new(1) c_c(1); 0 f_c\_new(2) c_c(2) ; 0 0 1]; \]

\[ \mathbf{K}_K\_\text{new} \] is the corrected image matrix.

\[ \mathbf{I}_2 = \text{rect} (\mathbf{I}, \mathbf{eye}(3), f_c, c_c, k_c, \mathbf{K}_K\_\text{new}); \]

Where \( \mathbf{I} \) is the distorted image and \( \mathbf{I}_2 \) is the undistorted image.
Extrinsic parameters relate to the combination of intrinsic parameters plus the orientation of the camera relative to the image plane. The calibration matrix is built up from the 28 views indicated in Figure 32.

Figure 32.

a) Camera centric views of 28 orientations and altitudes to build extrinsic parameter list.

b) World centric views of 28 orientations and altitudes.
Calculation of extrinsic parameters

Cross over points in the calibration chart are automatically detected and their locations in pixel space extracted before calculation of extrinsic parameters (Fig. 33).

The extrinsic parameters are encoded in the form of a rotation matrix \( (Rc_{ext}) \) and a translation vector \( (Te_{ext}) \). The rotation vector \( omc_{ext} \) is related to the rotation matrix \( (Rc_{ext}) \) through the Rodrigues formula: \( Rc_{ext} = rodrigues(omc_{ext}) \).

Let \( P \) be a point space of coordinate vector \( XX = [X;Y;Z] \) in the grid reference frame \((O,X,Y,Z)\). Let \( XX_c = [X_c;Y_c;Z_c] \) be the coordinate vector of \( P \) in the camera reference frame \((O_c,X_c,Y_c,Z_c)\). Then \( XX \) and \( XX_c \) are related to each other through the following rigid motion equation:

\[
XX_c = Rc_{ext} \ast XX + Te_{ext}
\]

In addition to the rigid motion transformation parameters, the coordinates of the grid points in the grid reference frame are also stored in the matrix \( X_{ext} \).

Each image taken by HabCam has its own unique set of extrinsic parameters.

Extrinsic parameters for an example image:

Translation vector:
\[
Te_{ext} = [ -225.840216 \quad -130.369514 \quad 608.628548 ]
\]

Rotation vector:
\[
omic_{ext} = [ -2.148393 \quad -2.284790 \quad -0.123388 ]
\]

Rotation matrix:
\[
Rc_{ext} = [ -0.062925 \quad 0.996680 \quad 0.051672 \\
0.996448 \quad 0.059838 \quad 0.059254 \\
0.055966 \quad 0.055217 \quad -0.996905 ]
\]

Reprojection Pixel Error: \( err = [ 2.00116 \quad 1.26492 ] \)

Extrinsic pixel error = +/- 2 pixels
Resolution range (FOV): 0.37 – 0.89 mm/pixel

The extrinsic real-world error becomes: 1.11 – 1.78 mm (under best optical conditions)
Pixel error in X and Y can be visualized as a scatter plot and frequency distribution (Fig. 34). Note that 99% of values are less than 2.2 pixels.

Figure 33. Extrinsic parameters for image 24 above, as an example.

Figure 34. (a) Scatter plot of pixel error around the origin. (b) Frequency distribution of pixel error along x axis.
Frequency distributions of pitch, roll, altitude, and image area (FOV) for the NLSCA 2009 survey based on 129,289 images are shown in Figure 35. The mean pitch was -5.24 degrees indicating that, on average, the nose of the vehicle pointed down slightly. Downward pitch is part of the system design and tends to stabilize the vehicle while underway. Mean roll was -0.97 with very little variation indicating the vehicle is quite stable, laterally. Altitude measurement varied from <1 to 4.5 m off the bottom with a mean of 1.87m. Images below 1 m were out of focus and removed from the image database. Images taken higher than 3 m were typically not sufficiently clear, due to turbidity, to be useful and were also not used. Taking roll and pitch into account using the extrinsic equations present above, the FOV ranged from 0.2 to >4m² with a mean of 0.72 m². 95% of the calculations for FOV fell between 0.4 and 1.5 m². Figure 36 shows a comparison between FOV calculated with and without the use of roll and pitch, i.e., directly from the altitude, only. Incorporation of roll and pitch into the geometric projection of the FOV has an effect of broadening and smoothing the frequency distribution of values without changing the mean.

Figure 35. Frequency distributions of pitch, roll, altitude, and image area (FOV) for the NLSCA 2009 survey.
Analysis of measurement error both between individuals and within individuals.

It was desired to estimate the level of error associated with the manual screen measurement of scallops both within a given technician and between technicians. The former would provide insight into measurement repeatability and the latter into systematic bias between individuals.

To accomplish this, we assigned four identical 4.2 nm long image transects containing 4,432 images from Western Great South Channel to six individuals (raters) (Fig. 37). Raters measured scallops using MIP under the same measurement rules as would be used under normal conditions (edge effects, height vs width, etc).
Western Great South Channel Transect (~4 nm)

Rater 1
Rater 2
Rater 3
Rater 4

281 scallops x 4 raters x 4 passes = 4,496 measurements

Figure 37. Inter Class Correlation analysis of scallop shell height measurements. Four individuals measured scallops from one transect four times.
Table 1. Summary statistics in pixels. N = 277 for each run. A total of 4,432 scallops were measured. KLB, ADY, PK, and DPF are initials of the four raters.

<table>
<thead>
<tr>
<th>rater</th>
<th>KLB</th>
<th>run1</th>
<th>run2</th>
<th>run3</th>
<th>run4</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>132.41</td>
<td>132.21</td>
<td>132.58</td>
<td>132.28</td>
<td>132</td>
</tr>
<tr>
<td>STD</td>
<td></td>
<td>31.61</td>
<td>31.61</td>
<td>31.44</td>
<td>31.69</td>
<td></td>
</tr>
<tr>
<td>SE</td>
<td></td>
<td>1.89</td>
<td>1.91</td>
<td>1.88</td>
<td>1.9</td>
<td></td>
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</tbody>
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<table>
<thead>
<tr>
<th>rater</th>
<th>ADY</th>
<th>run1</th>
<th>run2</th>
<th>run3</th>
<th>run4</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>128.48</td>
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<td>128.41</td>
<td>128.75</td>
<td>128</td>
</tr>
<tr>
<td>STD</td>
<td></td>
<td>31.42</td>
<td>31.55</td>
<td>31.44</td>
<td>31.78</td>
<td></td>
</tr>
<tr>
<td>SE</td>
<td></td>
<td>1.88</td>
<td>1.89</td>
<td>1.88</td>
<td>1.9</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>rater</th>
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<th>run1</th>
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<th>run3</th>
<th>run4</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>135.57</td>
<td>135.88</td>
<td>134.95</td>
<td>134.28</td>
<td>135</td>
</tr>
<tr>
<td>STD</td>
<td></td>
<td>31.86</td>
<td>31.94</td>
<td>31.81</td>
<td>31.63</td>
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<tr>
<td>SE</td>
<td></td>
<td>1.91</td>
<td>1.91</td>
<td>1.91</td>
<td>1.9</td>
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</tbody>
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<table>
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<th>run1</th>
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<th>run3</th>
<th>run4</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>128.36</td>
<td>127.39</td>
<td>127.48</td>
<td>127.56</td>
<td>127</td>
</tr>
<tr>
<td>STD</td>
<td></td>
<td>31.74</td>
<td>31.63</td>
<td>31.45</td>
<td>31.57</td>
<td></td>
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<tr>
<td>SE</td>
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<td>1.9</td>
<td>1.9</td>
<td>1.89</td>
<td>1.89</td>
<td></td>
</tr>
</tbody>
</table>

In most cases, mean within rater measurements were either accurate to the same number of pixels or within one pixel suggesting that within rater variability was extremely low (Table 1). Between rater variability was greater than within rater variability with mean values of 132, 128, 135, 127, providing a range of 135 to 127, or 8 pixels. Given the resolution range for varying FOV presented above (i.e., 0.37 – 0.89 mm/pixel), an error of 8 pixels represents a real-world error of 3.0 to 7.1 mm.
Inter and intra-Class correlations were analyzed using ICC, Intra Class Correlation analysis (McGraw and Wong, 1996). A two-way mixed effect model

\[ X_{ij} = u + r_i + c_i = r_{ij} + e_{ij} \]

\( u \): population mean, \( r \): row effects, \( c \): column effects, \( e \): residual effects

was used to test the hypotheses that there is no difference between scallop measurements made by the same rater four times, and that there is no difference between individual raters.

**ICC Type C-1: Tests the degree of consistency among measurements**

\[ r = \frac{(MSR - MSE)}{(MSR + (k-1)*MSE)}; \]
\[ F = \frac{(MSR/MSE)*(1-r0)/(1+(k-1)*r0)}; \]
\[ df1 = n - 1; \]
\[ df2 = (n-1)*(k-1); \]
\[ p = 1-fcdf(F, df1, df2); \]

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>143.5</td>
<td>3</td>
<td>47.8</td>
<td>6.23</td>
<td>0.0003</td>
</tr>
<tr>
<td>Group</td>
<td>40170.4</td>
<td>3</td>
<td>13390.1</td>
<td>3.36</td>
<td>0.0182</td>
</tr>
<tr>
<td>Interaction</td>
<td>490.6</td>
<td>9</td>
<td>54.4</td>
<td>7.01</td>
<td>0</td>
</tr>
<tr>
<td>Subjects (matching)</td>
<td>4398738.9</td>
<td>1104</td>
<td>3984.4</td>
<td>522.79</td>
<td>0</td>
</tr>
<tr>
<td>Error</td>
<td>25241.8</td>
<td>3312</td>
<td>7.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4464775.2</td>
<td>4431</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( r = 0.9842 \)

\( LB = 0.9827 \)

\( UB = 0.9857 \)

\( p = 0 \)
ICC Type A-1: Test the degree of absolute agreement among measurements.

\[
r = \frac{(\text{MSR} - \text{MSE})}{(\text{MSR} + (k-1)\text{MSE} + k(\text{MSC} - \text{MSE})/n)};
\]

\[
a = \frac{(k*r0)}{(n*(1-r0))};
\]

\[
b = 1 + (k*r0*(n-1))/(n*(1-r0));
\]

\[
F = \frac{\text{MSR}}{(a*\text{MSC} + b*\text{MSE})};
\]

\[
df1 = n - 1;
\]

\[
df2 = \frac{(a*\text{MSC} + b*\text{MSE})^2}{(a*\text{MSC})^2/(k-1) + (b*\text{MSE})^2/((n-1)*(k-1))};
\]

\[
p = 1 - \text{fcdf}(F, df1, df2);
\]

\[
r = 0.9796
\]

\[
\text{LB} = 0.9695
\]

\[
\text{UB} = 0.9856
\]

\[
p = 0
\]

Summary

There is no difference in measurements made by the same individual raters or between individual raters.

Analysis of shell height measurement error

Shell height measurements from HabCam images taken during the 2009 Nantucket Lightship survey were compared with shell height measurements made from 12 dredge tows on 2009 Leg 2 of the R/V Hugh Sharp during normal survey operations. The HabCam survey was conducted in early June 2009 while the NMFS survey was conducted in mid July, 2009.

Frequency distribution for shell height measurements for HabCam and NMFS dredge survey show surprising similarity in overall pattern (Fig. 38). Since the NMFS survey was conducted about five weeks following the HabCam survey, the shift in mode of the NMFS data for small scallops can be accounted for by growth. The tails of the distribution for HabCam data are spread out more than for the NMFS data suggesting a source of measurement error. There is no indication of selectivity by either sampling approach.
Figure 38. Shell height size frequency distributions for NMFS (black) and HabCam (red) measurements in the NLSCA. HabCam surveyed in early June while NMFS surveyed in mid July. Note a shift to the right of the mode for small scallops in NMFS data relative to that for HabCam probably due to growth.
Shell heights made from HabCam and NMFS dredge survey were analyzed using the approach described by Jacobson et al. 2010). Accuracy (RMSE, root mean square error), bias (HabCam-Dredge), and precision (STD) were calculated.

HabCam measurements were positively biased relative to NMFS data by 3.7%. Percentage square root of the mean square error was 3.70%. Both NMFS and HabCam distributions were negatively skewed and more peaked relative to normal distributions.

<table>
<thead>
<tr>
<th>stat</th>
<th>NMFS</th>
<th>HabCam</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>4,178</td>
<td>13,576</td>
</tr>
<tr>
<td>bias</td>
<td>NA</td>
<td>3.8</td>
</tr>
<tr>
<td>min</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>max</td>
<td>170</td>
<td>180</td>
</tr>
<tr>
<td>avg</td>
<td>106.4</td>
<td>110.3</td>
</tr>
<tr>
<td>%bias</td>
<td>NA</td>
<td>3.70%</td>
</tr>
<tr>
<td>STD</td>
<td>33.4</td>
<td>32.2</td>
</tr>
<tr>
<td>CV</td>
<td>31.4</td>
<td>27.90%</td>
</tr>
<tr>
<td>RMSE</td>
<td>NA</td>
<td>3.8</td>
</tr>
<tr>
<td>% RMSE</td>
<td>NA</td>
<td>3.70%</td>
</tr>
<tr>
<td>skewness (g1)</td>
<td>-0.59</td>
<td>-0.66</td>
</tr>
<tr>
<td>kurtosis (g2)</td>
<td>2.41</td>
<td>2.98</td>
</tr>
</tbody>
</table>

Summary of error analysis
Measurement error can come from a number of sources including intrinsic error in camera calibration, extrinsic error due to camera orientation and altitude relative to geometric projection on the image plane, and errors associated with human operators measuring scallops on the computer screen. Given the resolution range for varying FOV presented above (i.e., 0.37 – 0.89 mm/pixel), a real world for each source may identified.

<table>
<thead>
<tr>
<th>Source</th>
<th>+/- mm error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>0.58 – 1.41</td>
</tr>
<tr>
<td>Extrinsic</td>
<td>1.11 – 1.78</td>
</tr>
<tr>
<td>Within operator</td>
<td>0.5</td>
</tr>
<tr>
<td>Between operator</td>
<td>3.0 – 7.1</td>
</tr>
</tbody>
</table>
Clearly, the magnitude of between operator error dominates the overall potential for measurement error. However, once this source of variability is identified and characterized for each individual measure scallops, a correction factor could be applied for each individual to normalize the results. In addition, automated counting and sizing of scallops and other targets is improving and will eventually be used in conjunction with manual measurements to produce more accurate results.