Old Ships, New Ships, Red Ships, Blueprints[1]

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Abstract

The Canadian Hydrographic Service (CHS), like other hydrographic offices and organizations worldwide, has much experience in retrofitting multibeam sonars into and onto existing vessels. Some of these vessels are past their predicted lifespan, but will continue in service for some years to come while the replacement vessels are designed, approved, funded and ultimately built. A new experience for the CHS will come in finding a replacement vessel for inshore hydrographic and oceanographic research to accommodate either an existing multibeam sonar (or sonars), or to come with a new sonar as part of the vessel scientific instrumentation.

Herein, a tale of Pacific Region CHS' experiences with shallow and mid-water multibeam sonars on various vessels, the latest saga being the upgrade of our EM1002A mid-water system mounted on a mechanical ram on the CCGS Vector (built in 1967) to a 0.5° x 1.0° EM710 gondola installation with other scientific sonars and navigation equipment. We looked to the experiences of our CHS colleagues on the east coast of Canada, to the Naval Oceanographic Office (NAVOCEANO) and other experts in marine acoustics and underwater design for their advice on what has worked, what has not worked and how CHS might make the most of the potential Vector replacement. The Regional Class Research Vessel (RCRV) being designed and built for the US research fleet holds much promise for this replacement.

Introduction

When faced with a new sonar to install, a review of existing installations, what has worked and what has not worked is a good starting point. Several hydrographic organizations worldwide have recently switched from flush-mounted or pod mounted multibeam sonars to gondola installations with significant successes. Experiences of CHS in Atlantic Region (CCGS Matthew EM710 installation) and NAVOCEANO (TAGS-60 class upgrades to EM710 and EM120) have shown that a gondola installation can greatly improve acoustic performance through better bubble sweep down rejection.

Background

CHS Pacific region had its first experiences in multibeam surveying with the DOLPHIN (Deep Ocean Logging Platform for Hydrography with Integrated Navigation)/EM100 in 1994. In 1996 CHS acquired 3 EM3000 shallow-water multibeam systems, complete with Applied Analytics POS/MV version 1. Each system was installed in 31 foot CHS P-boats (Puffin, Petrel and Penguin) and accepted by CHS Atlantic Region office in Dartmouth (Bedford Institute of Oceanography – BIO). Pacific Region was shipped the launch Puffin with EM3000 serial number 0001! In 1997, the launch Puffin was transferred to CHS Québec Region and a new EM3000 system was purchased and installed in the 41 foot Bertram vessel Revisor. By 2003, the Revisor was showing signs of age, so the system was moved to the 44 foot east coast trawler Otter Bay. In 2006, CHS upgraded 5 EM3000 systems nationally to EM3002, with an associated upgrade of the POS/MV systems to version 4.

[1] With sincere apologies to Dr. Seuss. "One fish, **two fish**, red fish, blue fish" is a children's book released in 1960.

The EM1002A system was purchased in 1999 and installed in the Canadian Coast Guard Ship (CCGS) R. B. Young, which had been in cold lay-up since 1997. In 2002, the system was moved to the CCGS Vector, a much older but program-funded vessel for science in Pacific Region. In March 2008, CHS acquired a 0.5° x 1.0° EM710 which was to replace the EM1002A on the Vector. The following table summarizes this timeline. The figures that follow it show the progression of ships and systems.

Old Ships

Table 1 lists the vessels used for multibeam installations in CHS Pacific Region.

Vessel	Built	System	Installed	Removed
Puffin	?	EM3000, S/No. 1	1996	1997 - sent to CHS Québec Region
Revisor	1972	EM3000	1997	2003 – vessel retired
Otter Bay	1992	EM3000	2003	2006
Otter Bay		EM3002	2006	N/A
R.B. Young	1990	EM1002A	1999	2002 – vessel sold to Alaska State Department of Fish & Wildlife
Vector	1967	EM1002A	2002	2008
Vector		EM710	2009	N/A – replacement planned for 2013

Table 1 - Multibeam vessels in CHS Pacific Region 1996-present

EM3000/2

Puffin

Figure 1 - CSL Puffin EM3000 serial number 0001

Figure 2 - Puffin in-keel fairing of EM3000

Revisor

Figure 3 - CSL Revisor EM3000

Otter Bay

Figure 4 - CCGC Otter Bay EM3000/3002

Figure 5 - Otter Bay along-keel transducer pod (EM3002 is on port forward)

EM1002A

R.B. Young

Figure 6 - CCGS R.B. Young EM1002A

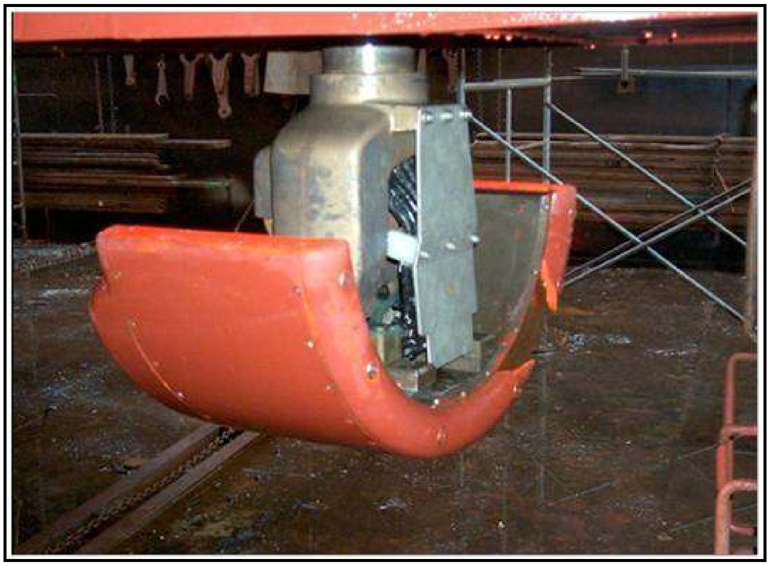

Figure 7 - R.B Young/EM1002A transducer damage from semi-submerged debris (logs)

Vector

Figure 8 - CCGS Vector EM1002A/EM710 (0.5x1.0)

Figure 9 - Vector/EM1002A transducer protection grids (cow catcher)

Figure 10 - Vector EM1002A installation on ram (Note studs for cow catcher)

The remainder of this paper is devoted to a discussion of the Vector upgrade from EM1002A on a ram to a gondola-mounted EM710 (0.5°x1.0°) and the possibilities for the Vector's replacement.

New Ships

Vector Replacement considerations

The consensus of the Vector science user's committee, at a meeting held in May 2007 to discuss the replacement vessel, was that we need a clone of it (see Table 2). While it does work well for the existing science programs that use it, the Vector replacement would have to meet all safety and vessel requirements of the day it is built. This includes the necessity to have all accommodations above the water line which could result in a somewhat larger vessel and commensurate increase in costs to build, crew and run. Acoustic quietness (meeting ICES noise standards) was felt by the committee to be a key requirement, although there was a concern about the increase in costs that may be required to build a ship that meets these standards.

Length	39.7 m
Breadth	9.5 m
Draft	3.5 m
Power	1 Caterpillar 3208 geared diesel, controllable pitch propeller, bow thruster
Gross Tonnage	515 grt
Range	3500 nm
Endurance	20 days
Speed	10 kts (cruising)

Table 2 - CCGS Vector vessel specifications

While Science will be the primary task of the Vector replacement, as a Coast Guard ship it will also have to respond to search and rescue (SAR) calls, so it will need to be crewed not only for 24/7 operations, but also to be able to respond to SAR call outs. It will need a Rigid-Hull Inflatable Boat (RHIB) aboard for this purpose. There will be an expectation that crew and science staff of a certain rank or level is entitled to a single cabin. The Vector has berths for up to 8 science staff and a crew of 13, including 5 officers. She has several large water tanks, but no on-board water making capability, thus restricting her endurance.

There are other health and safety requirements for ship's crew. At least 6 hours sleep is mandated for bridge crew, which might restrict operation of low frequency (audible) sonars, station keeping (requiring thruster operation) or winch operations (requiring hydraulics) to something less than 24 hours a day. CCG vessels are crewed on a lay day system where two crews alternate 28 days on and 28 days off. The Vector's operational profile for a year is 10-2-1, or 10 months operational, 2 months in refit and 1 month out of service. This results in a maximum available ship time of 280 days per year. Ship certifications, safety audits, crew changes, replenishing fuel, water and food, change-over between science programs, etc. all contribute to a reduction in available vessel days for at-sea science. There are 254 available vessel days for Vector in 2009. In 2008 there were 255 days of program usage planned.

As of the date of writing this paper, no Statement Of Requirements (SOR) had been produced or approved for Vector's replacement. According to the Capital Project Summary Note (CPSN) requesting funding approval for the replacement vessel, design work should have been at the mid-way point with a completion in May 2009. The design lifespan for the replacement vessel is up to 30 years. The Vector is now 42 years old. Whenever the design work does get on track, science users will continue to push for a fuel-efficient vessel that can be run effectively by a minimum of crew and has an optimized science capability.

Regional Class Research Vessel

The proposed Regional Class Research Vessel (RCRV), being designed under supervision of the US Navy for the UNOLS research fleet is one model for the Vector replacement that holds some promise. Vessel specifications are given in Table 3. Original plans were to build three vessels by 2013 at a total cost of $91M USD. As of October 2008, cost estimates for each vessel had escalated to between $50M and $60M USD when fully outfitted. The capital plan for Vector replacement [Steven, 2006] identified less than $20M CAD and a planned replacement date of 2013. The list below details the proposed capabilities of the RCRV. While the specifications and capabilities of the RCRV would seem to be ideal for Science, it may be more ship than we can afford.

The RCRV will be a modern mono-hull research ship capable of integrated, interdisciplinary, oceanographic research in areas from shallow coastal bays and estuaries out to deeper water [GlobalSecurity.org, 2006]. The ships shall be capable of performing the following tasks:

a. Sampling and data collection of surface, mid-water and sea floor parameters using modern scientific instrumentation.
b. Launch, towing, and recovery of scientific packages, both tethered and autonomous.
c. Handling, monitoring and servicing of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs).
d. Deployment and recovery of autonomous air vehicles (AAVs) and balloons.
e. Deployment and recovery of moorings.
f. Deployment and recovery of boats (appropriate for vessel size).
g. Deployment and recovery of free-floating instruments.
h. Shipboard data processing and sample analyses in modern, well-equipped scientific laboratories.
i. Precise navigation and station keeping and track-line manoeuvring to support deep sea and coastal operations.
j. Long periods of operation (up to 30 days) on-station or at low speeds.

Length overall	42.7 – 50.3 metres
Draft	3.7 metres maximum navigational
Propulsion	Integrated diesel electric propulsion plant capable of continuous speed control to ½ rev/minute throughout the entire operating speed range
Speed	Maximum speed of at least 12 knots and a sustained speed of 10 to 11 knots in calm seas at full load. Some science operating profiles will require continuous underway survey or towing operations at speeds from 0 knots up to the normal cruising speed. The design shall consider the impacts on engine operation, maintenance and emissions, exhaust gas ingestion, water making capability, and other factors when on-station or moving at slow speeds for extended periods.
Range	5,400 to 6,500 nautical mile range at sustained speed in calm water.
Endurance	At least 21 days. A surge capacity for an occasional 30 days endurance is desirable.
Availability	Operate and meet scientific requirements continuously (24 hours per day, 7 days per week) during a 30 day at-sea deployment without sustaining a system failure that cannot be corrected at sea or that degrades scientific capabilities.
Towing	The ship shall be capable of towing scientific packages with up to 10,000 pounds of towing load at 6 knots and 20,000 pounds of towing load at 4 knots. The ship shall be capable of performing towing operations continuously during an entire cruise (up to 30 days).
Berthing Accommodations	Permanent berthing accommodations and toilet/showers shall be provided as follows: ➢ 14 single staterooms with toilet/shower facilities shared between pairs of single staterooms. ➢ 8 to 10 double staterooms with toilet/shower facilities shared between pairs of double staterooms.
Laboratories	A suite of modern, well-equipped laboratories including Main Lab, Wet/Hydro Lab, Computer Lab, and Staging Bay. The Main Lab, Wet/Hydro Lab and Staging Bay shall be located adjacent to each other and the Working Deck. It is desirable that the Computer Lab also be located adjacent to the other labs.

Table 3 - Specifications of the RCRV

Red Ships

Canadian Coast Guard and other issues

Just because a sonar installation design has the desired characteristics for good data quality does not necessarily imply that that design will prove acceptable to those who own and run the ship, or will be easy for the shipyard who wins the bid for vessel upgrades to be able to build it as designed. Any changes to a CCG ship require approvals through the configuration change request (CCR) process, which can take over a year as we found out.

The dry docking schedule for the Vector for maintenance and recertifications is twice in a five year period. A dry docking was scheduled for late December 2008; the next dry docking not planned until 2011. If we couldn't make the plan work for the first period, it was possible that we would have brand new sonars sitting on the shelf for another two years.

Refits are under the purview of CCG Fleet Engineering, but CCG Fleet Human Resources also has a stake in any changes made to the ship. Ship's crew may be accustomed and comfortable with pods and blisters for sonars under the ship. They are less comfortable with a gondola suspended by struts below the hull, even if designed by a marine architect to withstand severe impacts from submerged obstacles. They may be even less willing to accept a gondola design if it isn't pretty – fleet personnel viewed the CCGS Matthew gondola pictures and were ready to reject any gondola design outright without even seeing the final designs from ManTech Advanced Systems International (acoustic consultants) and BMT Fleet Engineering (naval architects). Even though the initial design of a wing-shaped gondola, modelled after the NAVOCEANO TAGS-60 class design (scaled down in x, y and z to fit the EM710 and 3x3 sub-bottom profiler array), was accepted by the required CCG personnel, modifications were later proposed to the design by other CCG personnel.

Initially, there were concerns by CCG Fleet personnel about the increase in vessel draft. These concerns were addressed by demonstrating that the increase in draft was only a few cm beyond the EM1002A draft when fully deployed on the mechanical ram. In addition, removal of the EM1002A and ram from the ship would eliminate the need for regular commercial dives for each hydrographic survey to install, remove and inspect the "cow catcher" – transducer protection grids.

The gondola design was modified twice by BMT due to changes in personnel and a lack of communications regarding designs and decisions made from one project engineer to the next. A finite element stress analysis was conducted on one of the designs to determine required internal changes to the ship to support the new gondola structure and to specify the materials and specifications for the structure of the gondola itself. The initial wing design, supported by one forward and two aft outer struts eventually became a much simpler design (I liken its shape to a handheld windshield ice scraper) with only a single tapered centre strut. Initial plans to have all cables go through the starboard wing strut in order to use the existing (from the EM1002A) hull penetration were abandoned in favour of a narrower gondola with a larger opening for running cables through the centre strut.

BMT also performed simulations to determine the effects of the gondola on vessel performance [Campbell, 2008]. A reduction in top speed of 0.5 knots was forecast and an increase in fuel consumption of up to 10% was also predicted. This deterioration is largely due to the increase in cross sectional area that the gondola presents to water flowing past the hull.

On the plus side, it was forecast that the addition of the gondola may have a damping effect on vessel roll, to a lesser degree pitch and possibly create a keel effect that would make line keeping easier, although minimum turning radius might suffer as a result. Removal of the EM1002 and ram was forecast to allow the return of a potable water tank to its original size. It was also hoped that the crew (cook's) cabin could be put back to the way it existed prior to the EM1002 installation in 2002, although some space would still be required for EM710 cable runs.

A later decision to move four Science transducers (12, 38, 120 and 200 kHz) from an existing blister into the gondola also promised to provide a small reduction in drag by removal of the blister and restoring original hull shape. A dual axis electromagnetic speed log (Skipper EML 224) was also designed into the new gondola at the request of CCG vessel electronics. Other navigation sonars were left in their existing installations due to concerns that gondola failure would leave the vessel with limited or no sonar navigation capabilities. It was also felt that moving the sonars to the gondola would result in improved sonar performance due to better bubble sweep down rejection performance.

Other considerations for moving the 3.5 kHz array included a Health Canada [2008] report on noise levels in accommodation areas – it was felt that the gondola installation could reduce noise levels – and a desire to improve its performance – 9 new transducers were purchased and configured in a 3x3 array to decrease beamwidth and improve bottom penetration. While the Health Canada [ibid.] report noted that sound pressure levels measured in crew accommodations did not exceed the Government of Canada Treasury Board baseline of 87 dB rms, nor did they exceed the Marine Occupational Safety and Health Regulations baseline of 75dB rms, the report did recommend several options for reducing nuisance noise (that which falls below legislated limits). The options provided include: administrative controls, personal hearing protection and/or engineering controls – the gondola option being considered an option of the latter type.

Fisheries Science personnel expressed a desire to upgrade the fisheries sonars (38, 120 and 200) to split-beam sonars for better species recognition. Unfortunately, upgraded transducers were not available at the time of installation so the existing sonars were used, with some minor improvements to sections of deteriorated cabling. The gondola was designed so that these sonars could be upgraded at the next dry docking in 2011, although running new cabling could present a significant challenge to this upgrade.

Blueprints

The EM710 was acquired by the end of March 2008. At that time, it was hoped, perhaps somewhat naively or optimistically, that all plans, approvals, funding and contracts could be in place by the scheduled dry-docking for Vector in December 2008. In early April 2008, the previously submitted configuration change request (CCR – a CCG requirement for any major vessel modifications) for an EM710 (1x1) submitted in November 2007, was resubmitted for approval of an EM710 (0.5x1). The Kongsberg-supplied 1x1 configuration pod design was supplied as supporting documentation. The vision for the installation was to keep as near to the hull location and depth of the existing EM1002A (which was known to perform well even in moderate to heavy sea states).

The first of several user consultation meetings occurred in mid-April 2008. At that time, the plan to proceed with installation was announced to the Science users and to CCG. The initial CCG estimate was between $80K and $150K CAD. Approval of the CCR was required before any further discussions could proceed. No particular concerns were raised. A follow-up meeting was held with CCG in mid-May, where responsibilities and timelines were identified.

In mid-June, an extraordinary meeting of the vessel user's committee was held to make a presentation on the proposed installation so that client and stakeholder concerns could be aired and subsequently addressed. By this time, the CCG cost estimate had increased to $150-200K. Only approval-in-principle for the CCR had been received. Concerns raised at this meeting included reduced vessel speed and increased draft. CCG Marine Engineering felt that moving the transducers to a pod or gondola centred on the keel (EM1002A was offset several metres to starboard) would not be possible by December due to the many approvals required for new hull penetrations. A review of bubble sweep-down effects and modern gondola design for optimum performance was given. CHS identified potential positive benefits of the EM710 and gondola installation as:

- Improved depth capability (twice that of the EM1002A)
- Better acoustic backscatter
- Greater spatial resolution (nearly 10 times the EM1002A)
- New capability to record water column (volume) backscatter
- Improvements in vessel stability (roll damping and keel-assisted line keeping)
- Recovery of a potable water tank that was reduced in 2002
- Recovery of cook's cabin space that was taken over in 2002
- EM1002 ram would be made available to another vessel, the CCGS John P. Tully, for science transducers currently suffering from bubble sweep-down issues.

CCG was identified as the lead on overall project management, mechanical removal, construction and installation of hardware. CHS was identified as the lead on acoustic analysis and recommendations, wiring and integration, removal of the EM1002A electronics. Items on the critical path were identified as:

- Approval of CCR - CCG (June 18 – actual approval granted June 20)
- Direction from CCG Fleet/Operations to Marine Engineering - CCG (June 18 – actual approval from CCG Operations received July 31)
- Advice on acoustic design and performance from Mantech Advanced Systems International - CHS (July 14)
- Specifications for installation (August 18)
- Obtain funding ($150-200K) for installation - CHS (August 22)
- Gondola/blister design & construction
- Specifications to Public Works and Government Services Canada for contracting (September 8)
- Specifications posted, vessel viewing (October 7)
- Bids close, award contract (November 1)
- Gondola/blister construction complete (November 28)
- Shipyard work period (6 weeks: December 2008-January 2009)
- IOS work period (1 week: January 2009)
- Sea-acceptance testing (1 week: April 2009)

Another project review meeting was held July 15, 2008 – the day after Mantech Advanced Systems International visited the Vector. After some discussion, the design that met with the greatest degree of approval was a centre-line mounted gondola (scaled TAGS-60 design) using the existing through-hull penetration aligned to a starboard strut for running all cables.

A final project review meeting was held July 24, 2008. Final decisions were made about what sensors would go into the gondola and discussions were held regarding predicted vessel performance, funding envelopes and requirements for strengthening of hull and gondola.

By early September, BMT Fleet Technology Limited had been contracted to produce the gondola design.

Gondola Evolution

From an acoustic performance standpoint, the gondola is considered by far the best. This is directly associated with bubble sweep down rejection performance. A gondola has been demonstrated in the past on other research vessels to provide a very good acoustic background as well. Based on these specific issues, Mantech Advanced Systems International recommended [Gates, 2008] a gondola as the preferred method of installing the EM 710.

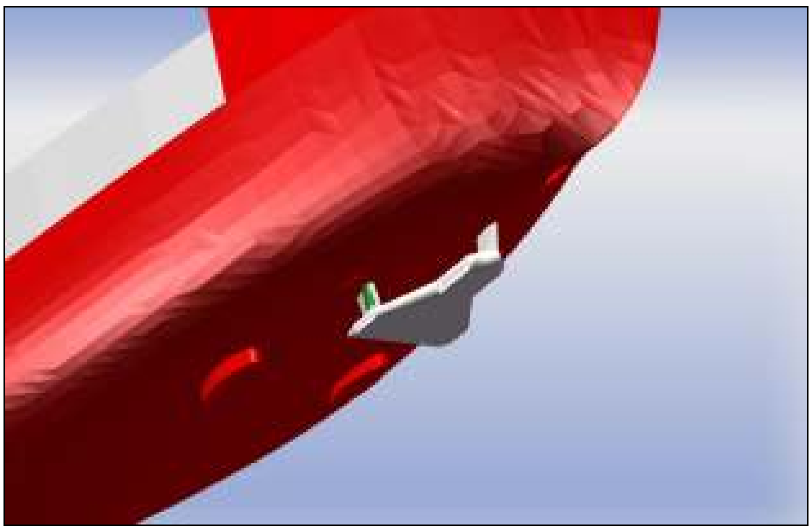

Figure 11 - Mantech gondola design (modified) shown on Vector hull with existing sonar blisters

Existing sonars in the Vector included the EM1002A on a mechanical ram through the hull (located at the aft starboard gondola strut in Figure 11), the science/fisheries transducers (12, 38, 120 and 200 kHz) located in the port blister and geoscience sub-bottom profiler (SBP) array (2x3 3.5 kHz) located in an oil-filled box inside the hull. The port blister contains navigation sonars that were to remain there and not be moved into the gondola for navigation safety reasons. Removal of existing blister and EM1002 fairing, by relocating all science transducers to the new gondola was hoped to improve vessel performance marginally over just the addition of a new multibeam gondola. In addition, it was hoped that by moving the SBP array to the gondola, rather than firing directly through the hull would reduce nuisance noise in the crew accommodation area.

Initially, the engineering firm hired to the design and simulation work (BMT Fleet Technology Limited) was given the Kongsberg Maritime design for an EM710 blister in $1^o x 2^o$ and $1^o x 1^o$ configurations. Due to a CCG requirement to use the existing EM1002A hull penetration, this blister (or gondola) was to be mounted off the central axis of the vessel. CHS and Mantech had a performance requirement, based on built-in self tests of the EM1002A for bubble noise, for the transducers to be located at the same draft as the bottom of the EM1002A transducer when fully deployed on the ram (0.89 m below the hull). Adopting a blister with this height and width would have resulted in significant powering and resistance issues.

Mantech recommended a scaled down (in x and y, but only in z to the point where sufficient height was still available to accommodate transducers and cables without excessive bending) wing-shaped gondola design based on the successful NAVOCEANO TAGS-60 refits. BIST tests on the EM1002A determined that the maximum depth of the gondola need not be any greater than the fully-deployed depth of the EM1002A transducer (89 cm below the hull). Because of the requirement to use the EM1002A hull penetration, this gondola had to be larger (in x and y) than needed to accommodate the transducers only in order for the starboard strut to align and be used as the conduit for all transducer cables. This resulted in decreased vessel performance predictions. Fortunately, as the date for vessel drydocking approached a decision to use an on-keel hull penetration for all cable runs was made and the width of the gondola was allowed to decrease. With a smaller cross-sectional area, powering and resistance issues were predicted to improve.

Figure 12 - BMT gondola design 2, as modified by Allied shipyard with additional CCG input

Despite the recommendation from CHS and its acoustic consultant (Mantech Engineering Ltd.), BMT Fleet Technology Limited ultimately delivered a design that was quite different than the delta wing design provided by Mantech. This was due in large part to a seemingly ongoing turnover of marine engineering staff at BMT, who did not pass on all the project details to their successor. However, after a review of the design, Mantech's conclusion was: "I suspect it will work, just not quite as hydrodynamic. I suspect it will provide adequate bubble sweep down rejection, however." Mantech did suggest that the design be modified to adopt rounded edges and an elliptical leading edge. Despite these suggestions and a modification in the design supplied by BMT to the shipyard, fabrication issues resulted in a much simpler design without the elliptical leading edge (Figure 12). CCG requested the addition of a leading strut (left side of Figure 12) to assist with debris deflection (principally submerged logs in the Vector's area of operations).

The final evolutions of the gondola involved monitoring its performance. Two low-light pan/tiltable underwater cameras were added to the topside of the gondola (one on the starboard side forward and one on the port side aft so both sides of the central strut and debris deflector strut could be fully observed for debris and bubble flow). In addition, a broadband omni-directional hydrophone (EDO 6140 with pre-amps) was to be installed in the interior of the gondola to monitor changes in acoustic performance. It is anticipated that the hydrophone will detect increases in acoustic noise caused by debris or structural problems in the gondola.

Readying the ship

The EM1002A strip out internal to the ship took place at Institute of Ocean Sciences in mid-December. Some spare transmit/receive boards were returned to the manufacturer as part of a trade-in agreement. The EM710 boxes and the 9 new SBP transducers – all labelled for later connection – were loaded aboard the ship prior to its voyage to the shipyard (Allied) in Vancouver. Due to Christmas holidays, the ship did not go into drydock until the first week of January 2009. The EM1002A ram and transducer (hull unit) was removed by the shipyard and set aside for future use aboard another CCG vessel as previously discussed.

Shipyard

The vessel and gondola construction contract was awarded to Allied Shipyard of Vancouver in mid-December. An initial meeting with the shipyard was held Thursday December 18, 2008 to review the requirements for the refit and for the gondola fabrication and equipment installation. The vessel docking plan included blocking appropriate to remove the EM1002A and ram and install the new gondola and transducers. Thanks to some clever reworking of the crewing schedule by the CCG Assistant Marine Engineer Supervisor, a full 7 week drydocking period was available. This was fortunate as the shipyard was closed for 4 days in early January due to inclement weather (snow storm) in Vancouver.

While there had been initial discussions about having a different shipyard construct the gondola (for reasons of expediency and also because elliptical leading edge construction is beyond the capability of many shipyards), in the end it was easier to let the contract for all the work to the same yard. There were also discussions about sealing the gondola, filling it with air, fresh water or oil as ways of increasing its life (minimizing exposure to salt water corrosion). In the end, due to the project lifespan of the Vector (less than 10 years) and the complexities in trying to get a water-tight compartment, the interior of the gondola was treated with anti-corrosion coating and allowed to flood with salt water.

Ports were added to the top of the gondola to install two pan/tiltable low-light underwater cameras and to allow access to the transducers and cabling inside. An inlet port on the bottom of the gondola and plumbing for a sea water sampling loop inside the ship were incorporated so that surface sound speed was being measured at the transducer face – something that was not possible for the EM1002 installation. The final requirement of the shipyard was to ensure that the lower face of the gondola did not have negative pitch when the vessel is underway. This was accomplished by careful adherence to the BMT design.

3.5 kHz array

The 3.5 kHz SBP (9 TR109 transducers configured in a 3x3 array) was located on the opposite side of the central strut (port side) to the EM710 arrays in order to keep them separated as much as possible. Analysis of EM1002A data clearly showed interference from the 3.5 kHz array (2x3 located further aft and inside the ship) in the backscatter.

Following some discussion, a decision was made to run all 9 TR109 3.5 kHz cables from the gondola through the Roxtec seals into a junction box for combining all 9 connections into one wire inside the ship. This approach provides better security for the 3.5 kHz array and better diagnostics should a transducer fail. Mounting a junction box in the gondola, should any failure happen there, could result in loss of the whole array.

More discussion occurred about how to mount the transducers inside the gondola. Different bottom plate thickness and material types were considered based on their ease of installation and their attenuation factors. Polycarbonate windows were considered, but in the end the ease of construction using steel plate won out and the attenuation due to firing the transducers through 3/8" steel plate was thought to be negligible at 3.5 kHz. Finally, spacing of stainless studs for mounting each transducer so that there would be no lateral contact between transducers via the clamps was determined to be 1.75".

Science sonars

The existing science transducers, mounting rings and cables were recovered from the science transducer pod. The mounting rings and transducers were still in good shape, but some of the cables required repair work before reinstallation in the gondola and some cables were not long enough and had to have extensions added. At the request of the fisheries scientists, the 38, 120 and 200 kHz single-beam transducers were reconfigured into a tight triangular pattern. This makes sonar calibrations using dual calibration spheres at 30-40 metres depth much easier. The transducers in the science pod had been configured in line. The 12 kHz Airmar transducer was mounted in the forward part of the gondola.

While there was a request to install new split-beam fisheries sonars in the gondola, neither the transducer, mounting rings nor required cables were available while the vessel was in the shipyard. This upgrade will have to wait for a future vessel dry dock period. The proposed 38 kHz split beam replacement will have a narrower beam and hence a larger diameter. More fabrication work will be required to adapt to the new triangular pattern required by this extra diameter. However, additional room in the gondola was reserved for this transducer.

Sonar synchronization

Because of the number of sonars of various frequencies installed in the gondola (resulting in closer proximity than in the previous installation), we had to consider what sort of synchronization would be needed. Sonar synchronizers are available commercially, but can be quite pricey. For normal hydrographic operations, the multibeam is either operated by itself, or in combination with the SBP on geo-science cruises. The fisheries sonars, if operated together, will probably be controlled by a multi-frequency sonar topsides.

For CHS, the multibeam sonar needs to be the master, with other sonars slaved to it. So the challenge was to find a simple and inexpensive hardware and/or software solution to have the SBP trigger a transmit from the EM710 transmit trigger (NMEA message). The ORE topsides currently configured for the SBP on the Vector does not accept a trigger pulse. However, it is normally operated by Chesapeake SonarWizSBP software, which is capable of accepting an external trigger. Once the ORE topsides are replaced with a planned future upgrade to a Knudsen chirp SBP, this triggering issue will have to be revisited.

The 12 kHz sonar had been used to provide nadir depth input to the MVP-30 controller, allowing it to retrieve the sensor fish before getting too close to the seafloor. This sounder also has to be synchronized to the EM710. It was thought that the EM710 could be configured to issue a NMEA depth message to the MVP-30 and eliminate the need for the 12 kHz sonar to be on during multibeam operations.

The Skipper EML 224 dual-axis Doppler velocity log was not anticipated to cause any interference with the sonars because is operates using electromagnetic energy and not acoustic.

Sensor survey

The Kongsberg Maritime [2006] EM710 installation manual cautions users of the more stringent requirements for precision of sensor coordinates and installation angles than had been acceptable in the past, or for earlier generation systems such as the EM1002A. While no specifics are provided in the manual [ibid.] regarding survey equipment to be used or methodology to be followed, the manufacturer will supply examples (reports) of other sensor installation surveys conducted by e.g. BLOM [2007] if requested. It was not clear to CHS in advance that Kongsberg Maritime was recommending we use this approach. In any case, CHS does not have the equipment, software or expertise to conduct precision photogrammetric surveys, as used in the BLOM survey [ibid.].

Thus, CHS used the traditional survey methods (1" total station) that had been used for successful EM sonar installations as were shown in an earlier section of this paper. This resulted in the coordinates, angular offsets and estimated uncertainties shown in Table 4. Due to an unidentified calibration error with the rented total station, the sensor survey measurements had to be repeated with a different instrument (laser level), which added to delays in the shipyard. This was further exacerbated by a blunder made by the survey team (ruler taped to the level rod upside-down) which may have added an extra day's delay.

TX Array 1 (fwd)	**Required precision**	**Final value**	**Precision achieved**
Position (x)	± 0.05 m	0.676 m	± 0.002 m
Position (y)	± 0.05 m	0.280 m	± 0.002 m
Position (z)	± 0.02 m	1.986 m	± 0.002 m
Pitch	± 0.05°	0.82°	± 0.06°
Roll	± 0.20°	0.15°	± 0.37°
Heading	± 0.10°	0.30°	± 0.06°
TX Array 2 (aft)			
Position (x)	± 0.05 m	-0.295 m	± 0.002 m
Position (y)	± 0.05 m	0.276 m	± 0.002 m
Position (z)	± 0.02 m	2.001 m	± 0.002 m
Pitch	± 0.05°	0.97°	± 0.06°
Roll	± 0.20°	0.25°	± 0.37°
Heading	± 0.10°	0.21°	± 0.06°
Rx array			
Position (x)	± 0.05 m	-1.114 m	± 0.002 m
Position (y)	± 0.05 m	-0.101 m	± 0.002 m

Position (z)	± 0.02 m	2.011 m	± 0.002 m
Pitch	± 0.20°	0.94°	± 0.37°
Roll	± 0.025°	0.30°	± 0.06°
Heading	± 0.10°	0.23°	± 0.06°
Motion Sensor			
Position (x)	± 0.05 m	0.000	-
Position (y)	± 0.05 m	0.000	-
Position (z)	± 0.10 m	0.000	-
Pitch	± 0.05°	0.0°	± 1.0°
Roll	± 0.025°	1.0°	± 1.0°
Heading	± 0.10°	359.6°	± 1.0°
GPS antennae			
Position 1 (x)	± 0.05 m	0.766 m	± 0.01 m
Position 1 (y)	± 0.05 m	-2.515 m	± 0.01 m
Position 1 - RTK (z)	± 0.02 m	-13.455 m	± 0.01 m
Position 2 (x)	± 0.05 m	0.755 m	± 0.01 m
Position 2 (y)	± 0.05 m	2.206 m	± 0.01 m
Position 2 - RTK (z)	± 0.02 m	-13.455 m	± 0.01 m
Water line			
Position (z)	± 0.02 m	4.297-WL m	± 0.01 m

Table 4 - EM710 sensor survey results, compared to Kongsberg Maritime installation specifications

In addition, the requirements for precision machining of the gondola where the transducer frames were to be installed had not been made clear to either CHS or the shipyard in advance, although the requirements for precision in the installation of the mounting frames is provided in Chapter 3 of the installation manual [Kongsberg Maritime, 2006]. CHS should have provided the shipyard with a copy of the installation manual well in advance. Cleaning paint and welding splatter off the surfaces where the mounting frames sat added more delays. In fact, it took several iterations of installing the frames, placing in the transducers, making the sensor survey measurements, recognizing that the transducers were not seated properly (twists in the transducers caused by high spots under the frames), removing everything, shimming, reinstalling and re-measuring only to find different problems. This was very frustrating for both CHS and Kongsberg staff trying to get a proper installation. Providing specific details in the installation manual about this requirement, and communications with both CHS and shipyard well in advance by Kongsberg Maritime would have gone a long way to reducing this confusion and frustration, and subsequent rework and delays.

Ultimately, the gondola was cleaned and made free of paint and weld splatters, the frames were installed correctly and without twists, the transducers put in place and the final sensor survey was completed. The cabling was then run through the strut and into the ship, seals put in place and connections made to the transceiver unit in the multibeam room.

Despite the problems encountered, the vessel was launched and returned to IOS by the planned date. The EM710 was turned on and set to pinging without incident. The subsequent Science patrol went ahead a few days later than planned, but not due to any delays associated with the gondola/EM710 installation. Future installations might consider adopting an approach to sensor surveys similar to those done on CCGS Matthew for their EM710 [e.g. Cunningham, 2005].

SAT results

CHS had 8 days of Vector ship time booked from April 3-11, 2009 for Kongsberg at-Sea Acceptance Trials (SAT), Harbour Acceptance Trials (HAT) and more rigorous proving of the new systems' capabilities. The installation engineer from Horten returned to the west coast of Canada for these trials, along with a new recruit to the Canadian office of Kongsberg Maritime who would observe and learn. In addition, John Hughes Clarke from the University of New Brunswick Ocean Mapping Group was contracted to conduct more in depth system testing and produce a report of capabilities and deficiencies.

CHS did not get possession of the Vector until noon on April 3. At that time loading and setting up of all the equipment commenced. By late afternoon, a ground fault had been identified and the EM710 had still not been put into operation. The Vector set sail the following morning with all systems working and a patch test was carried out. She returned to the dock on Friday (Good Friday) April 10, 2009 and was unloaded.

Sea-acceptance trials

There are three requirements of Kongsberg Maritime for any new multibeam sonar installation before fully accepting the system as operational, and signing off the paperwork required to start the clock ticking on the three-year warranty period for the system:

- Setting to work (STW); √
- Harbour acceptance test (HAT); √ and
- Sea acceptance test (SAT). √

The first two tests can be conducted with the ship alongside the dock; the last test requires that the ship put to sea.

At a minimum, the SAT requires that the vessel steam three overlapping parallel lines, with one cross line, perform a statistical assessment of the overlapping and crossing data and prove that the system meets its own specifications and all the entered calibration parameters are correct. But there are many more things that can be learned about the complete system with more elaborate testing. And that's where John Hughes Clarke came in.

The cruise plan for the Vector SAT, depending on weather conditions in British Columbia in April included the following EM710 assessments:

1. Bad-weather plan:
    a. Saanich Inlet – basic patch test to confirm calibration numbers; steaming to a flat area with some sea-state in Juan de Fuca Strait, off Race Rocks to create a reference surface and conduct wobble analysis and TPU analysis in the presence of vessel motion, comparison to IHO specifications;
    b. Boundary Passage sand-waves – repeating EM1002A surveys of the same area to see changes, but also to examine the benefits of improved spatial resolution for geoscience;
    c. Hotham Sound, Howe Sound to look at how the system deals with steep rock slopes to the side simultaneously with relatively deep, soft seabed below the ship; comparisons with EM1002A data; change analysis; uncertainty estimates at greater depths;
    d. Knight and Bute Inlets, time permitting, to compare improved resolution of seabed features against existing EM1002A data;

   e. Savary Island surrounds – a new mapping project to first identify boulders on a flat sand seabed, conduct detailed target detection tests, then comparison to IHO specifications; and
   f. Galiano ridge sponge reef imagery to determine what improvements in acoustic backscatter may contribute to sponge reef analysis.
   g. Steaming over, or beside artificial dive sites (sunken vessels) G.B. Church and HMCS McKenzie to look at water column detection

2. Good-weather plan
   a. Same as a above;
   b. Some or all of b-g, time permitting; plus
   c. Steam offshore to the shelf break in order to determine the extinction depth of the EM710, on the way collecting a long time series of real-time heave from the POS/MV version 4 motion sensor with delayed heave logged for later comparison and analysis; to confirm maximum swath width and sector coverage; to look at deep water (chirp, single-ping) target detection (bioherms and headscarps); and to look for evidence of Doppler heave artefacts in chirp pulses.
   d. Logging water column data on LaPerouse Bank to determine the capabilities for fisheries science work (looking for schools of fish).

In addition, an examination of the contamination of the EM710 backscatter (in particular) from SBP interference if not properly synchronized was to be carried out. Fortunately, the SBP was successfully synchronized to the EM710 using the SonarWizSBP software.

Fortunately, good weather showed up in time to steam out to the shelf break. On Sunday April 5, 2009, the deep water capabilities of the EM710 were tested, as were the depth capabilities of the Science sonars.

Sonar performance

- EM710 Max depth (2000). Depths of 2000 metres were observed off the shelf break, but the data was quite noisy after about 1800 metres. Useful upper limit during the SAT seemed to be about 1750 metres. Hughes Clarke [2009] recommends no surveying deeper than 1500 metres (Figure 13).
- EM710 Max swath width (2500). Swath widths exceeding 2 kilometres were observed during the SAT. At depths of approximately 1000 metres, swath widths of up to 2200 metres were observed [ibid.]. Maximum swath width was not achieved during the SAT.
- EM710 Max swath angle (140). Angular coverage was set to ± 70° during the SAT and appeared to work well for most tasks, other than detection of small targets in the outer beams. Using a ± 65° sector, IHO Special Order vertical uncertainty specifications were comfortably met [ibid.]
- EM710 Max number of beams (800). Initially, dual ping was not working. Replacement boards were loaned from CHS East Coast (from the Matthew EM710 system) on April 6 and requested from Norway in addition. 380 beams were observed in single-ping mode. Dual-ping mode started working after the defective boards were replaced.
- EM710 resolution, target detection, better detail on sandwaves previously imaged, boulder fields in shallow water; bioherms in deep water/chirp mode/single ping. Resolution was greatly improved over the EM1002A, especially with dual-ping working. The ability to resolve targets (Figure 17) to meet IHO Special Order requirements with

wider swath coverage and at higher vessel speeds will be of great help to CHS. Significant improvement in the quality of the acoustic backscatter were also noted (Figure 15) [ibid.]

- EM710 Water column backscatter proved to be useful, not only for imaging the artificial dive site G.B. Church, but also for imaging internal waves (Figure 14).
- Evidence of Doppler heave effect in chirp mode (EM710). This known problem with the EM710 was observed in deeper water (Figure 13) [ibid.]

The following images are from the draft EM710 trials report [Hughes Clarke, 2009].

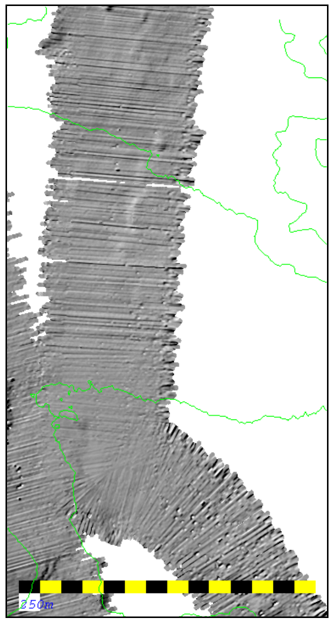

Figure 13 - EM710 in 1500-1600 metres depth (note presence of Doppler heave artefact)

Figure 14 – EM710 water column imaging - internal waves off Race Rocks, Victoria

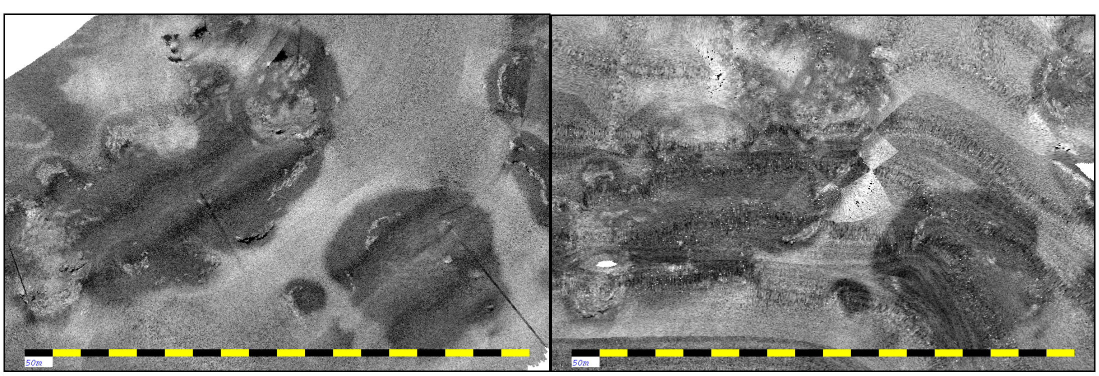

Figure 15 - EM710 (left) and EM1002A (right) acoustic backscatter over sponge reefs in Howe Sound

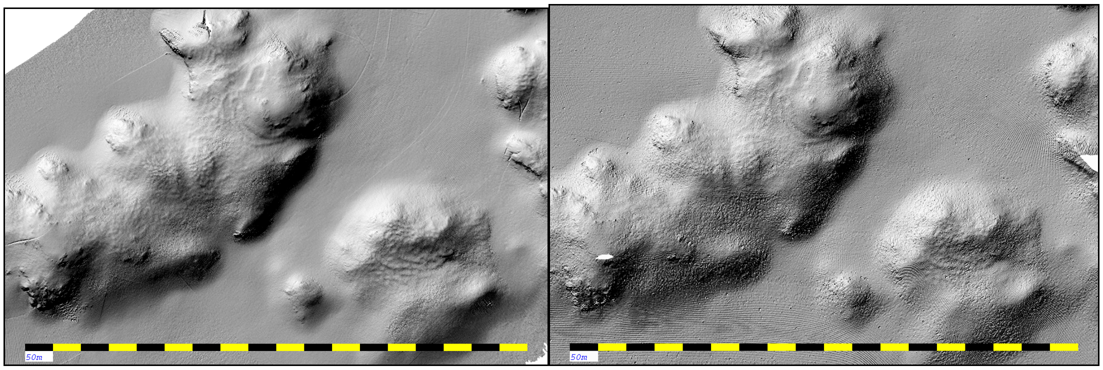

Figure 16 - EM710 (left) and EM1002A (right) bathymetry over sponge reefs in Howe Sound

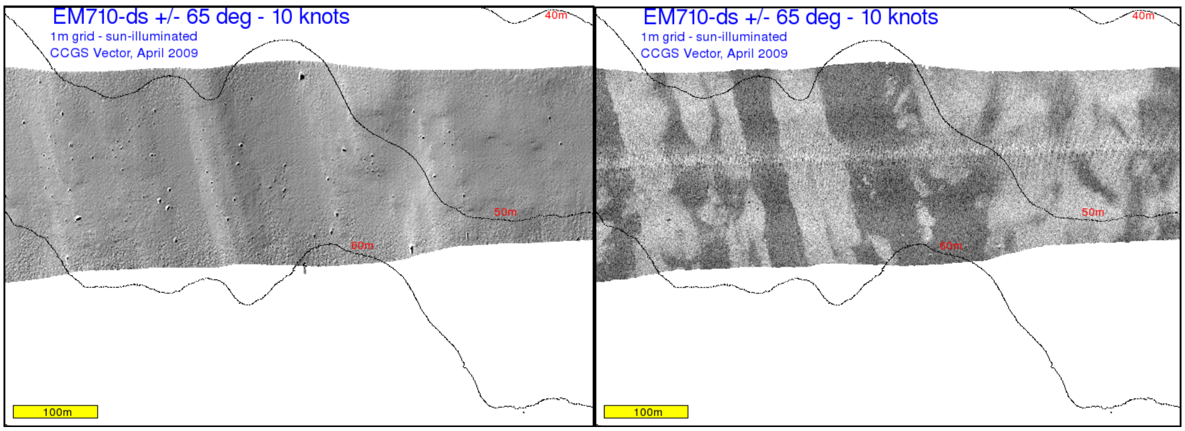

Figure 17 - EM710 bathymetry (left) and backscatter (right) over boulder fields off Savary Island

- 3.5 kHz improved performance. Two of three potential improvements to this system were implemented prior to the SAT: upgrading the installation from an in-hull (with bubble wash down an issue) to an in-gondola installation; and upgrading from a 2x3 to a 3x3 array. A planned upgrade to a chirp pulse system (Knudsen) from the shorter narrow band pulses (ORE) was not implemented in time for the SAT.
- Science sonars. 12, 38 and 200 kHz Science sonars were tested during the SAT. The 38 kHz sonar performed well, achieving depths of 800 metres. Problems were noted with the performance of the 12 kHz sonar that will need to be addressed. The 120 kHz sonar was not tested.
- Sonar interference, requirements for synchronization. The 3.5 kHz SBP was slaved to the EM710 using SonarWizSBP software. This ensured that the EM710 was not in receive mode while the SBP was transmitting. Interference from the SBP (unsynchronized) had been observed in EM1002 backscatter on the previous installation. In addition, the EA500 12 kHz and the 38/200 kHz Knudsen sonars were synchronized to the EM710 trigger. There are some possible improvements to the SonarWizSBP software that will be passed on to the manufacturer (Chesapeake).
- Broad-band hydrophone with PicoScope digitizer. The signal levels are just right for the vessel noise dynamic range. This proved to be a tremendous diagnostic tool, identifying problems in the spectrum of both the ORE 3.5 kHz SBP and the EA500 12 kHz sonars. Further investigation of why these sonars are not operating to their full capabilities is required. The ORE amplifier may not be operating properly.

Other sensor performance

- Surface sound speed consistency – new sampling loop with inlet at transducer face. Evidence suggested that the surface sound speed sampling loop performance had been greatly improved by getting the intake away from the hull. Bubble interference in the previous installation frequently resulted in bogus surface sound speed readings, causing serious refraction artefacts if no action was taken to stop using the surface readings. In addition, the intake for the EM1002A installation was not at transducer depth, further exacerbating the problem. Having the EM710 and surface sound speed intake on the gondola at the same depth has resulted in proper beam steering, greatly reducing uncertainties due to refraction.
- UW cameras – bubble wash down, visibility and usefulness. Visibility in Saanich Inlet was quite poor due to suspended particulates (flocculent matter). In Juan de Fuca Strait, water clarity was better and the cameras were able to observe clouds of bubbles flowing along the hull above the gondola, which means the gondola is doing its job.
- Any evidence of gondola flexure? No evidence, but drastic vessel manoeuvres were not performed.
- EML224 performance? Topsides were not installed prior to the SAT.
- Timing delays, POS/MV problems with real-time heave? On the long lines out to the shelf break, evidence of real-time heave problems was observed. This was corrected by changing heave filter parameters and by applying the delayed heave (smoothed) solution. It is recommended that delayed heave be applied to all EM710 data sets [Hughes Clarke, 2009]

Vessel performance

- Top speed reduced? Anecdotally, there was no evidence of reduced top speed. The captain felt that top speed may have in fact increased slightly. The Vector is known to be more fuel efficient at 10 knots, than the 7 knots sounding speed used for EM1002A surveys.
- Fuel consumption increased? Too soon to tell. It will probably require a full season of all types of science programs in order to determine if fuel consumption has changed. Fuel consumption is also affected by use of generators, so the contribution from the gondola may be difficult to isolate.
- Minimum turn radius reduced? Without pre-gondola performance figures, this would be difficult to confirm. Anecdotal comments from the ship's captain during the SAT suggest that more work is required for hard-over manoeuvres.
- Line keeping easier? Without pre-gondola performance figures, this would be difficult to confirm. No anecdotal comments from the crew were available at the time of writing.
- Roll and pitch damping? Without pre-gondola performance figures, this would be difficult to confirm. Inclining experiments may be conducted later this year after the installation of a new crane. Anecdotal comments from the ship's captain during the SAT suggest that stability is better overall, which may be contributions from the gondola, but also the increased dead weight from the restored water tanks (providing an additional 4 ton below waterline).

Other improvements

- Cooks cabin restored fully? Not quite, but it is more usable than with the EM1002 and ram installed. It is thought to be about 99% restored to its original state. The crew are certainly much happier with the restored space.
- Potable water tank mostly restored? While potable water supply aboard the Vector has not been fully restored to pre-2002 levels, the crew are grateful for the partial restoration of the tank towards its original size. This helps increase the endurance of the vessels which benefits all CCG and Science groups, especially for work in remote areas where access to water is difficult.
- Reduced nuisance noise in crew accommodations from SBP? Nuisance noise may have in fact increased. The location of the SBP transducers has changed and they are no longer in an oil-filled bath. The transducers are transmitting through the skin of the gondola, which transmits through the gondola strut to five hull ribs such that the noise permeates through both accommodations and work areas. In addition, because the SBP is now slaved to the EM710 in order to avoid acoustic interference, pulses are no longer uniformly spaced, making the noise source less easy to get accustomed to. Efforts are focusing on improvements to how this sonar is synchronized, reducing the ping rates and making them uniform. In addition, administrative controls (periods of quiet time) may have to be implemented so crew can get the required rest to remain alert on the bridge.

Summary

From the acquisition of the EM710 in late March 2008, to the SAT in April 2009 many people were involved, much consultation was carried out, lots of money was spent[2], the effort was great, but ultimately we have today several vastly improved sonars systems on board Vector for conducting better hydrography, geoscience and fisheries science. We can do better seabed (and water column) mapping more efficiently than ever before. It is hoped that the many things we learned can be transferred to other installations and future inshore oceanographic science vessels in Canada and other countries.

Recommendations

1. CHS (EM710 MBES only)
    a. Ensure good communication of installation requirements between Kongsberg and the shipyard;
    b. Check calibration of all instruments prior to shipyard sensor surveys;
    c. Consider adopting more rigorous sensor survey approaches, such as BLOM [2007] or Cunningham [2005] for future installations;
    d. Get results of the FAT prior to SAT commencement to ensure sub-standard boards are replaced before leaving the dock;
    e. Investigate and resolve outer sector yaw stabilization offset and starboard side downward (0.3%d) bias observed in EM710 during SAT;
    f. Until yaw stabilization issues are resolved, disable it for shallow and very shallow mode surveys (depths < 200 metres);

[2] Initial system purchase $783K; getting the full system/gondola installed amounted to $472K, plus overtime, staff time in project management, administration, travel and at-sea acceptance trials tipped the balance in excess of $1.36M CAD

   g. Provide best available tides for SAT and full sensor alignment survey details to John Hughes Clarke so that more detailed residual analysis can be carried out;
   h. Until real-time POS/MV heave issues are addressed (see below), apply delayed heave on all surveys;
   i. Improved vertical referencing solutions such as surveying to the ellipsoid (PPK, PPP) should be considered in lieu of the existing tidal zoning approach;
   j. Address small misalignment and time delays observed during wobble analysis;
   k. Increase sounding speed to 10 knots (formerly around 7 knots);
   l. Increase swath angle to +/- 65º (formerly 60º);
   m. Restrict EM710 operations to depths < 1500 metres;
   n. The "x_log_offset = 20 (dB) " adjustment to the water column gain should be applied routinely on system start up for improved delineation of weak water column scatterers using the shorter pulse lengths;
   o. Request that the bridge navigational sounder be disabled during water column imaging, provided safe navigating depths can be confirmed;
2. Kongsberg
   a. Add a caveat (under ideal conditions) to the specification sheet claim that the EM710 is capable of 2000 metres water depth and 2500 metre swath width;
   b. Conversely, it would be okay to boast about the IHO Special Order target detection capabilities of this sonar;
   c. Fix the Doppler heave problems observed in the chirp mode data;
3. Applanix
   a. Address observed problems with real-time heave artefacts within the set motion bandwidth;
4. Chesapeake
   a. Allow SonarWIZ.SBP software to accept an external trigger from the EM710;
5. NRCAN
   a. Replace ORE 3.5 kHz transceiver/SonarWiz software combination with an integrated digital solution as per Hughes Clarke [2009];

Future work

As of this writing, the second set of Health Canada nuisance noise tests had not been conducted, so there is no proof that the gondola installation (an engineering control) has reduced the nuisance noise in the crew accommodations. In addition, the Vector has not been configured to run the SBP using chirp pulses, which could add an additional nuisance noise component (frequency change, longer duration pulses).

With no multi-frequency sonar controller on board during the SAT, not all the science sonars could be tested to see if their performance had been improved or to see if there are any sonar interference issues that might require further sonar synchronization. No fisheries science has been conducted using these sonars as of this writing, so the improvement in calibration due to a tight triangular configuration has yet to be proved. Eventually, perhaps at the next Vector dry-dock in 2011, these transducers will be replaced with split beam versions, making major improvements in the quality of fisheries science conducted from the Vector.

The EM1002A ram has not been installed in the John P. Tully, and it may be several years away. It is hoped, however, that putting the fisheries sonars on this ram, getting them below the bubble layer, will greatly improve their performance.

In order to take advantage of the new capabilities of the EM710, it will be important to integrate the acoustic seabed backscatter into our existing seabed classification processing stream.

Finally, it is important to take what we have learned from this installation and make plans for future inshore oceanographic research vessel systems – the Vector's eventual replacement.

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Biography

Rob Hare, P. Eng., C.L.S., is Manager of Data Acquisition and Technical Services for the Canadian Hydrographic Service in the Pacific Region of Canada. His responsibilities include managing the west coast seabed mapping program and a network of permanent water level and tsunami response gauges. A native of Victoria, British Columbia, he graduated magna cum laude in Surveying Technology from the British Columbia Institute of Technology in 1982 and soon after joined the CHS. In 1987, after working for 5 years as a field hydrographer, he obtained a Canada Lands Surveyors' commission. Late in 1987 he returned to school, graduating in 1991 with a BSc. Engineering in Geomatics from University of Calgary. He is a registered professional engineer in the province of B.C. He is Canada's representative on the IHO S-44 (Standards for Hydrographic Surveys) working group and has numerous publications on uncertainty estimation for hydrographic survey systems.