National Defence | Défense nationale

Maritime Engineering Journal

Canada's Naval Technical Forum

94
Since 1982

Fall 2020

CNTHA News Inside!

Focus

Innovation is alive and well in the RCN's naval technical support community

Canada

Bravo Zulu, Captain (Navy) Routledge!

An RCN Naval Technical branch first

In July, Captain (Navy) Seana Routledge became the first female Naval Technical Officer to be promoted to this rank. She is currently serving as a Deputy Project Manager for the Canadian Surface Combatant project in Ottawa, and is a member of the branch's senior advisory Naval Engineering Council. Watch for our profile of this veteran technical officer in our Winter issue in December.

Maritime Engineering Journal

(Established 1982)
Fall 2020

Director General Maritime Equipment Program Management

Cmdre Lou Carosielli, CD

Senior Editor
Capt(N) Sébastien Richard, CD
Chief of Staff MEPM

NCM Editorial Advisors
CPO1 Gerald Doutre
DGMEPM Unit Chief

CPO1 Monika Quillan
DNPS 3-3-4, DGMEPM

Project Manager
Lt(N) Youngjun Hwang

Production Editor/Enquiries
Brian McCullough
MEJ.Submissions@gmail.com

Associate Editor
Tom Douglas

Graphic Design and Production Services
d2k Graphic Design & Web
www.d2k.ca
Tel. (819) 771-5710

***Maritime Engineering Journal* on Canada.ca:**
https://www.canada.ca/en/department-national-defence/corporate/reports-publications/maritime-engineering-journal.html

Our complete back catalogue continues to be maintained by the Canadian Naval Technical History Association at:
http://www.cntha.ca/publications/m-e-j/

Commodore's Corner

Forum

Feature Articles

News Briefs

CNTHA News

Thinking outside the box sometimes means putting things inside a box. Turn to page 5 to find out what HMCS *Glace Bay* was doing with this "sea can" on her quarterdeck.
(Royal Canadian Navy photo)

The *Maritime Engineering Journal* (ISSN 0713-0058) is an unofficial publication of the Canadian Armed Forces published by the Director General Maritime Equipment Program Management. Views expressed are those of the writers and do not necessarily reflect official opinion or policy. Mail and requests for free subscriptions may be sent to: **The Editor, Maritime Engineering Journal, DGMEPM, NDHQ, 101 Colonel By Drive, Ottawa, Ontario, Canada, K1A 0K2. Unless otherwise stated, *Journal* articles may be reprinted with proper credit. A courtesy copy of the reprinted article would be appreciated.**

COMMODORE'S CORNER

Innovation is a driving force behind many aspects of our naval materiel enterprise

By Commodore Lou Carosielli, CD

Having taken up my appointment as Director General Maritime Equipment Program Management (DGMEPM) on July 9, it is with much humility that I follow in the footsteps of my DGMEPM predecessors. The seven years I just completed with the Project Management Office of the Canadian Surface Combatant — first as Chief of Staff, then as Deputy Project Manager, and finally as Project Manager — were extremely fulfilling both professionally and personally, and I am very excited to now be entrusted with my new responsibilities and duties as DGMEPM and Chief Engineer of the Royal Canadian Navy (RCN). In fact, this has been a goal of mine ever since I first set foot inside the Louis St. Laurent building on my initial posting to the National Capital Region and MEPM in 2002.

This being my first Commodore's Corner for the *Journal*, I would like to take a moment to recognize **Capt(N) Sébastien Richard** for his exceptional performance as Acting DGMEPM during the seven months prior to my arrival. Tasked with meeting the technical needs of the RCN in a severely resource-constrained environment, both in terms of personnel and funding, Seb kept a steady hand on the helm as he dealt with a myriad of issues and competing priorities just as the world was scrambling to adjust to a rapidly evolving viral pandemic. His stalwart dedication and in-depth knowledge of the MEPM enterprise kept things functioning as smoothly as anyone could possibly have hoped for, and in so doing served the Assistant Deputy Minister (Materiel) branch and the RCN extremely well.

Who could ever have imagined that we would be starting off a new decade by dealing with a global pandemic? Certainly not me. It has been a very interesting year so far to say the least, and the naval materiel enterprise has responded superbly to the COVID-19 difficulties by finding safe, innovative ways to carry on delivering critical technical and engineering support to the in-service fleet and major capital projects. Even as we observed the bittersweet homecoming of HMCS *Fredericton* on July 28, and paused to remember the lives of the service members who were lost on April 29, other ships were already ramping up to continue meeting the RCN's operational commitments

Photo by Cpl Jeff Smith

Assistant Deputy Minister (Materiel) Troy Crosby (left) oversaw the appointment of Cmdre Lou Carosielli as DGMEPM in July.

— HMCS *Toronto* sailing to take *Freddie*'s place on Operation Reassurance, HMCS *Regina* and HMCS *Winnipeg* preparing to join RIMPAC 2020 off Hawaii (August 17-31), and the crew of HMCS *Harry DeWolf* working hard to prepare for the exciting delivery of our first Arctic and Offshore Patrol Ship on July 31.

Whether we are talking about developing and introducing some new technical capability for the fleet, or about managing our resources to remain agile and responsive to current and anticipated needs, it is *Innovation* with a capital "I" that is the driving force behind virtually every aspect of our enterprise. In late 2019, a new Naval Materiel Technology Management section was created in MEPM to coordinate the introduction, adoption and validation of future technological opportunities and practices. The team is looking for innovative ways to support the current fleet through emerging technologies and human-systems integration management, and is the technical authority for everything dealing with the "Internet of things": augmented reality, cloud computing, human-machine interfaces, and additive manufacturing (3D printing). The team is working closely with RCN stakeholders to ensure we deliver on the RCN's Digital Navy initiative, and we can expect to hear more from them as our enterprise moves forward.

It has been a few years since I was last behind MEPM lines, but I believe I'll soon find the rhythm, especially working with such an outstanding team of people. No one can say how long we will be dealing with the impacts of

COVID-19, so it is imperative that we all bring our best ideas forward for improving our business operation, and supporting the current and future fleets to the fullest. In our normally complex realm of fast-paced technology change that has become even more complicated by an insidious pandemic, we need to look at every opportunity to investigate innovative new technologies so that we can test the limits of what we can effectively implement with the fiscal and personnel resources at our disposal.

Take care, everyone.

FORUM

The Royal Canadian Navy's "Digital Navy" Initiative

(with files from RCN Navy News)

The RCN made significant headway in strengthening its forward-looking posture on strategic innovation with the roll-out of the Digital Navy initiative last February. The initiative aims to empower all members of the naval team with the digital tools and capabilities they need to ensure the RCN remains a relevant and capable force, thereby satisfying key objectives of Canada's defence policy, *Strong, Secure, Engaged*, and the Royal Canadian Navy's *Strategic Plan 2017-2022*.

The wide-ranging initiative is designed to lead all areas of the naval enterprise, from business and HR management functions to front-end operations and maintenance, toward a more digitally mature stance that streamlines processes, and supports an inclusive culture that embraces uncertainty and learning through experimentation.

Under the leadership of the Director Digital Navy, naval engineer Capt(N) Jacques Olivier, the Digital Navy Office manages all programmatic aspects of the *Digital Navy Action Plan*. This endeavour identifies and describes the digital initiatives that will be undertaken by the RCN over the next two years to further the ambition and vision articulated in *Digital Navy: Enabling Canada's Naval Team for the Digital Age*. Core functions include program alignment, process enhancement, communications, training, and performance measurement. The goal is to establish mechanisms to ensure the RCN has a continuous, forward-looking capability to identify new and emerging digital technologies that have the potential to be most impactful to the Navy in the future.

Some of the modern and leading-edge digital technologies being contemplated to keep the RCN ahead of the digital curve include:

- secure cloud computing and mobile technologies aimed at keeping sailors better connected while deployed, and while working from home during COVID-19;
- cognitive computing techniques like artificial intelligence that are driving improvements in data analytics and autonomous vehicles;
- robotic process automation to assist with repetitive, rules-based administrative processes;
- virtual and augmented reality technologies with the potential to enhance training delivery and how shipboard maintenance is conducted;

(Continues next page...)

Submissions to the *Journal*

The *Journal* welcomes unclassified submissions in English or French. To avoid duplication of effort and ensure suitability of subject matter, contributors are asked to first contact the production editor at MEJ.Submissions@gmail.com. Contact information may be found on page 1. Letters are always welcome, but only signed correspondence will be considered for publication.


RCN photo

The Digital Navy initiative aims to empower all members of the naval team with the digital tools and capabilities they need to ensure the RCN remains a relevant and capable force.

- additive manufacturing techniques like 3D printing that can help to improve equipment availability; and
- digital twin technologies to optimize the operation and maintenance of our platforms.

In June 2019 the RCN hosted a roundtable discussion with industry and academia in Ottawa to discuss and solicit feedback on the draft strategy for the Digital Navy initiative. Turnout for the event exceeded expectations with close to 100 participants, including 65 industry representatives from nearly 45 companies.

The event included five break-out sessions where smaller groups were given an opportunity to discuss how the RCN envisioned leveraging digital technologies in the areas of personnel, materiel sustainability, individual training and education, readiness and collective training, and business management and communications. The feedback and recommendations received from the participants proved highly valuable in shaping the *Digital Navy* guidance document.

To begin exposing members of the naval team to the innovative design methodologies that will feature prominently as the Digital Navy initiative is implemented, a digital use case workshop was conducted in Toronto in August 2019 with a team of military and civilian members from Fleet Maintenance Facility (FMF) Cape Scott, FMF Cape Breton, Director Naval Personnel and Training, and naval staff from Ottawa. The workshop was very successful in helping participants gain insights into the world of innovative design from a user's perspective.

For instance, a mobile application called the RCN App is currently being developed under the Digital Navy initiative to provide sailors with more convenient access to information and administrative services they would normally only be able to tap into from work. User groups have been engaged to solicit feedback and suggestions on the app before its official release.

The Digital Navy initiative and its companion Action Plan are available online at:

http://www.navy-marine.forces.gc.ca/en/innovation/digital-navy.page?

FEATURE ARTICLE

"EW in a Box" – Engineering a Modular Electronic Warfare Solution for the RCN from Conception to Deployment

By LCdr Graham Hill (CFEWC)
with collaborative input by Stephan D'Aoust (NRC) and Brad O'Quinn (uOttawa)
Illustrations courtesy the authors.

As naval engineers, we are fortunate to have access to a plethora of positions and assignments. Even when excluding "purple" or out-of-trade positions, I would argue that the variety of engineering work available to us greatly exceeds offerings found in the private sector. Each assignment allows us to contribute a piece to the larger enterprise; whether it be starting the options analysis phase for a new diesel generator, or working hand-in-hand with a prime contractor to deploy new firmware on a software-defined radio. What is rare is the opportunity to engineer not just a piece, but a complete end-to-end solution in less than a year, which I recently was able to achieve in my current position at the Canadian Forces Electronic Warfare Centre (CFEWC) in Ottawa.

A Short Primer on CFEWC

CFEWC is somewhat of an unknown entity within the DND/CAF, as a large part of our mission involves classified analysis work. As the only Naval Combat Systems Engineering Officer (NCS Eng) at the unit, and coming in as head of the Collection and Certification (C&C) department, I wondered exactly what the unit had previously accomplished, and how it was different from the Naval Electronic Warfare Centre (NEWC) I had heard fleeting stories about when completing my Phase VI training package.

CFEWC is the centre of excellence within DND/CAF for electronic warfare (EW) and non-communications-based electronic intelligence (ELINT). We are located at Shirley's Bay in the west end of Ottawa (Figure 1). Our headquarters is the Canadian Forces Information Operations Group (CFIOG) based at Canadian Forces Station Leitrim. We are a truly joint unit with more than 17 different military trades working toward a common goal of supporting CAF operations. Our activities range from providing intelligence and EW orders of battle to our allied "Five Eyes" partners and deployed RCN frigates, to conducting operational, test and evaluation (OT&E) services for all elements of the CAF. We engage in EW operations when required.

Figure 1. The Canadian Forces Electronic Warfare Centre, located at the Shirley's Bay communications research complex in Ottawa.

I do have some enterprise support, and also have a small future capabilities team tasked to investigate our future requirements, come up with innovative solutions, and then execute these solutions with outside expertise.

Modular engineering designs for ships have been discussed at great length, but few have seen action in the Royal Canadian Navy to date. As things turned out, a career's worth of engineering contacts, experience as a project manager in DGMEPM and head of department (HoD) aboard ship, as well as the many (many) reminders on the importance of naval materiel assurance over the years would prove absolutely critical in this engineering success story.

EW in a Box – Conception

When I arrived at CFEWC in July 2018, my position had not been filled for more than six months, but I was fortunate to have inherited an experienced military team, most of whom had worked in the realm of EW longer than the traditional posting cycle. The acting department head had also made the wise decision to "down tools" during those six months to concentrate on a capability refresh. Many of our electronic support measure (ESM) sensors and test equipment were getting on in years, and with the publication of Canada's 2017 Defence Policy (*Strong, Secure, Engaged*), EW was suddenly having to regain some of its Cold War stature in the face of the changing global geopolitical landscape.

Therefore, as a result of some well-executed procurement efforts by my predecessor, I inherited a couple of new pieces of state-of-the-art equipment, including an ES-5080 digital receiver-based ELINT/ESM system from L3Harris, a hardened antenna mast, and two new (still in the plastic) special equipment vehicle (SEV) / militarized sea containers on loan from the 21 Electronic Warfare Regiment in Kingston. While the intent of these capability upgrades was to bolster our OT&E support services, a team of us at CFEWC began to envision a path toward field operations, and collaborating with the Navy just seemed like the right way to go. The Maritime Coastal Defence Vessels (MCDVs) had been successfully deploying SEVs for extra accommodations and diving payloads for years, and new platforms such as the Arctic Offshore Patrol Ship and the Joint Support Ship have been designed to strap on modular payloads to their flight deck. From the tactical to the strategic level, the idea of engineering an EW support package, or "EW in a box" (Figures 2 and 3) for naval platforms made perfect sense.

CFEWC actually has a long history of connectivity with the RCN. Despite being a unit within the Information Management Group whose chain of command is currently dominated by Signal and Communication Electronics Engineering (CELE) officers, our organization nomenclature is all naval-based, the commanding officer for much of the unit's existence has been a naval warfare officer, and the dominant non-commissioned trade remains the Naval Electronic Sensor Operator. Beyond this, CFEWC had never conducted an exercise with the RCN, but this was about to change as the new pieces of equipment I was looking at seemed destined for use at sea.

Initial Development Work

After getting the go-ahead from my chain of command in November 2018, I wasted little time putting together a proposal for the RCN with the intent of leveraging the Maritime Evaluation (MarEval) process. The MarEval would focus primarily on the survivability of the SEV and its associated EW equipment in the maritime domain; any other goals of opportunity, such as a first-of-class trial for our new ES-5080 EW system, would be of secondary importance.

Initial meetings with DGMEPM's Non-Combatant (NC) division, and with the Directorate of Naval Requirements (DNR) proved extremely fruitful. Our solution was effectively envisioned as non-intrusive to the ship, meaning no engineering change package would be required. The fact that we were self-financing the endeavour, excluding asking for a ride on the back of a ship, also helped facilitate the process to a speedy approval. Through additional communications with the people at Maritime Forces Atlantic (MARLANT) who would be implementing the MarEval, it was determined that our opportunity would come aboard the Maritime Coastal Defence Vessel HMCS *Glace Bay* (MM-701) during joint multinational maritime Exercise Cutlass Fury 19 off the coasts of Nova Scotia and Newfoundland in September 2019.

I must admit that despite my initial assumptions that little to no engineering analysis would be required to put together the "EW in a box" solution, some gentle prodding from LCdr Cynthia Caborn at NC put me on the right path to requesting that a more vigorous engineering design analysis of our proposal be commissioned. Taking equipment to sea and ensuring it is survivable is an extraordinarily challenging task, and planning for the safety of my team became a priority for me over the 2018-2019 Christmas and New Year break.

Figure 2. HMCS *Glace Bay* with the "EW in a box" special equipment vehicle (SEV) deployed during Exercise Cutlass Fury 19. The EW mast is nested atop the container.

Figure 3. The EW mast in its extended, deployed position.

My first stop in January 2019 was the Naval Architecture desk within the Directorate of Naval Platform Systems (DNPS 2) at MEPM. Although I was informed that their professional services contract for ship structural modelling was currently in a state of flux, the conversation reminded me that I had recently renewed a fabrication memorandum of understanding between CFEWC and the National Research Council (NRC) months earlier. And in an immense discovery completely grounded in good fortune, I learned that NRC had structural modelling and design expertise of exactly the engineering rigour I was looking for. Even though at this point I didn't know it, they had been lead authors for a 2003 study commissioned by Defence Research and Development Canada examining the sea state forces experienced by an at-sea MCDV. This was the exact platform we had been given by the RCN to deploy the "EW in a box."

The requirements provided to NRC were straightforward and few in number, including:

1. The installation must be able to withstand sea state 4 when deployed (mast extended);
2. The installation must be able to withstand sea state 6 when stowed (mast nested);
3. The sea container must not be modified in any way, and the support system must be removable; and
4. The complete system must be delivered by August 16, 2019.

As we were both government agencies, I wasn't as concerned as I normally would be when using a private sector contractor. It is difficult to describe just how much CFEWC and my team owe to the professional and knowledgeable personnel at NRC with whom we collaborated on this engineering endeavour. Without the expert team of **Stephan D'Aoust** and his deputy engineer **Brad O'Quinn** from the University of Ottawa, this MarEval and modular equipment demonstration would have never got away from the jetty. This next section – written by Stephan and Brad – illustrates just how detailed their engineering input was.

Design Work Summary*

*From National Research Council publication, "Methodology for Designing an MCDV Antenna Support System," by Stephan D'Aoust and Brad O'Quinn, April 14, 2020. The full paper is available online at: https://tinyurl.com/y3nxuav7

After visiting CFEWC and taking exact measurement of their components using a Creaform Handyscan 700 3D scanner, we proposed a design consisting of three main elements: a bridge that can be set onto the SEV to support the mast, four ISO corner adapters to allow straps to be anchored, and a payload adapter plate that allows the antenna and radio frequency distribution unit (RFD) to be installed on the mast and provide locations for attaching guy lines (Figure 4). We felt that this concept would best constrain the numerous degrees of freedom in the system and could be easily manufactured. With this concept, we went about conducting an analysis of the maximum forces and torques the components would be subjected to at sea, and then selected the appropriate materials. The main software tools used for the analysis were Solidworks (for 3D modelling and drawings), and ANSYS (for Finite Element Analysis of the internal stresses, as well as to compute natural frequencies).

(Continues next page...)

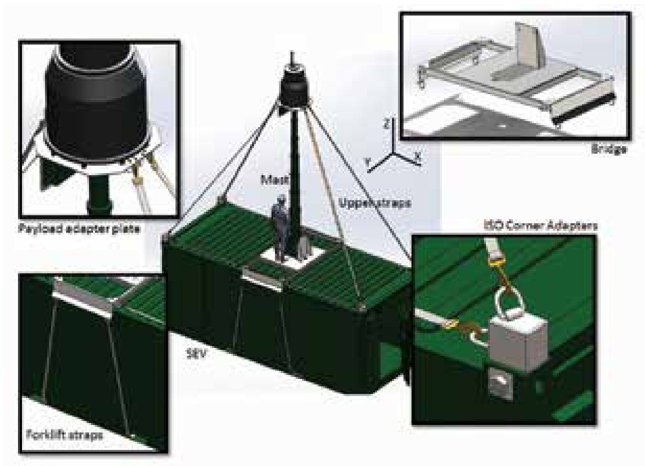


Figure 4. Final design.

The design conditions imposed on the antenna support system were derived from the conditions in which the antenna would be deployed or nested (the sea state) and approximations for the maximum roll angle during these conditions. These conditions considered the worst-case scenarios for both the nested and deployed states – up to sea state 4 (SS4) deployed, and sea state 6 (SS6) nested, with a maximum roll of 25° and 40° respectively. The roll angle was the main motion of consideration throughout these calculations as the acceleration about the roll axis (a product of the maximum roll angle) is larger than that of the pitch axis. A sea state table supplied by DND (Figure 5) provides the wave period at the varying states, as well the wind speed:

We then went about calculating the primary forces that would act on the design – those due to inertial acceleration from the rocking motion, and those due to wind drag.

In addition, the following key assumptions (conservative in nature as to calculate the worst-case scenario) were made:

1. Simple harmonic motion is assumed, which models the behaviour of the ship to have periodic motion where the restoring force is directly proportional to the displacement, and acts in the direction opposite to that of the displacement;
2. Wind gusts are considered to act perpendicular to the mast even during extreme rolls;
3. The ship's centre of gravity was lowered to the waterline;
4. The additional rigid support on the base has been left out of the analysis, but would have further stiffened the mast;
5. For all strap calculations, it is assumed that each set of straps (horizontal, upper and forklift) acts independently during operation, where in reality they would all be working together to balance out forces.

STANAG 4194
TABLE D-1 – NATO SEA STATE NUMERAL TABLE FOR THE OPEN OCEAN NORTH ATLANTIC

Sea State Number	Significant Wave Height (m)		Sustained Wind Speed (knots) *		Percentage Probability of Sea State	Modal Wave Period (sec)	
	Range	Mean	Range	Mean		Range **	Most Probable ***
0 - 1	0 - 0.1	0.05	0 - 6	3	0.70	-	-
2	0.1 - 0.5	0.3	7 - 10	8.5	6.80	3.3 - 12.8	7.5
3	0.5 - 1.25	0.88	11 - 16	13.5	23.70	5.0 - 14.8	7.5
4	1.25 - 2.5	1.88	17 - 21	19	27.80	6.1 - 15.2	8.8
5	2.5 - 4	3.25	22 - 27	24.5	20.64	8.3 - 15.5	9.7
6	4 - 6	5	28 - 47	37.5	13.15	9.8 - 16.2	12.4
7	6 - 9	7.5	48 - 55	51.5	6.05	11.8 - 18.5	15.0
8	9 - 14	11.5	56 - 63	59.5	1.11	14.2 - 18.6	16.4
> 8	> 14	>14	>63	>63	0.05	18.0 - 23.7	20.0

* Ambient wind sustained at 19.5 m above surface to generate full-developed seas. To convert to another altitude, H_2, apply $V_2 = V_1(H_2/19.5)^{1/7}$
** Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.
*** Based on periods associated with central frequencies included in Hindcast Climatology.
REVISED MARCH 1964

Figure 5. Sea state table showing wave periods and wind speeds.

Total drag torque for the antenna and mast in both sea states was calculated, and can be found in the following table:

Table 1: Drag torques created about the mast base

Component	Sea State 4	Sea State 6
Antenna	162.57 lbf*ft	226.33 lbf*ft
Mast	124.22 lbf*ft	36.77 lbf*ft
Total Drag Torque =	286.79 lbf*ft	263.10 lbf*ft

Torque is simply the force multiplied by the lever arm, which changes between SS4 and SS6 as the mast is collapsed. And while it is understood that only the total torque about the base is relevant (which includes both drag and inertia forces), it is valuable to note that when the mast is nested it loses 80 percent of its height, dramatically reducing the associated lever arm, but also reducing its wind profile. Table 1 shows that the total drag torques are comparable across sea states despite the wind speed more than doubling. Though the torques associated with the antenna alone are greater in SS6, the system's total torque is higher in SS4 because the drag force is a function of the cross-sectional area. When the mast is nested, this area reduces significantly such that the wind speed's influence is significantly reduced.

Next, inertial torques about the base were calculated and tabulated in Table 2:

Table 2: Inertial torques created about the mast base

Component	Sea State 4	Sea State 6
Antenna	1,833.94 lbf*ft	480.83 lbf*ft
Mast	1,016.17 lbf*ft	252.02 lbf*ft
Total Inertial Torque =	2850.12 lbf*ft	732.85 lbf*ft

Inertial forces are created by the acceleration (or deceleration) of the antenna and mast mass, which in this case arises from the angular acceleration of the ship as it rolls about its axis. It can be clearly seen that the inertial component of the torques are far more significant than the torque from drag forces, though the drag forces should still be considered as they are non-negligible. It should also be noted that, as previously discussed, the sea state 4 conditions produce a much larger torque about the base – almost exclusively since the mast is extended in these conditions, which provides a much longer lever arm for forces to act about. It's also interesting to note that SS6's larger periodicity (more time between waves) reduced the inertial accelerations despite having 15° more roll angle.

The total system torque is simply both the drag and inertial torques combined as seen in Table 3:

Table 3: Total torque about the mast base

Component	Sea State 4	Sea State 6
Antenna	1,997 lbf*ft	707 lbf*ft
Mast	1,140 lbf*ft	289 lbf*ft
Total Torque =	$T_{T\text{-}SS4}$ = 3,137 lbf*ft	$T_{T\text{-}SS6}$ = 996 lbf*ft

With these torque values established, we went about determining the maximum tension in the support straps attached to the antenna plate, as they will reduce the stresses on the mast and its base, and translate them to the ISO corners. The ISO corners would have at least an order of magnitude more strength than anything else in the system. Using known system geometry (unit length of the straps when deployed), the resultant forces in the system's straps were calculated in Table 4:

Table 4: Forces in the system's straps

Component	Sea State 4	Sea State 6
Upper Support (Guy Wire) Straps	541 lbf	416 lbf
Forklift Support Straps	394 lbf	320 lbf
Horizontal Support Straps	160 lbf	197 lbf

Based on the findings, it can be seen that the upper support straps (guy wires) will experience the largest tensile loads, at ≈ 541 lbf. This load occurs during SS4, which was expected as the extended mast generates far more torque to be reacted to entirely by the two straps alone (in the design scenario). Pre-tension was then applied to this value, as well as a suitable safety factor, to determine the required strength of the straps. Given that the highest strap tension was shown to be 541 lbs, Kinedyne Rhino straps were selected as they have a 3335-lb working load limit, providing a six-times factor of safety. These straps are inexpensive and durable, and custom part numbers from Kinedyne allow them to be ordered at the required lengths with end-configurations suited to the design geometry.

Finally, Finite Element Analysis (FEA) was used to analyze the model to confirm which materials and stock sizes should be selected for the bridge (steel) and payload support (aluminum), based on the loads they will see due to the various forces and torques (from system mass and from straps tugging locally). FEA was also employed to determine material stresses and conduct modal analysis, confirming that the proposed system geometry and material choices properly absorb and dissipate all forces in both SS4 and SS6. As a final check, the mast's original equipment manufacturer confirmed that the mast would perform as expected given our anticipated vectors and loads.

Stress analysis on the bridge showed that the maximum stress is less than 2 kilopounds per square inch (ksi), well under our 44-ksi steel yield strength. This result assumed that the guy wires are in place, but the bridge has been designed to withstand the worst-case scenario where multiple failures occur. Similarly, the payload platform's maximum stress was shown to be less than 4 ksi, well under the 35 ksi attributed to 6061-T6 aluminum. Given the somewhat mass-insensitive nature of the requirement, the design has been oversized to account for extreme cases at minimal disadvantage.

With all the above calculations and models, the design was certified and given over to the NRC manufacturing division for production.

Acceptance Testing

For those of you interested in digging further into the calculations, Stephan and Brad's full paper is well worth reading.

Once the proposal, design engineering, and fabrication of the mounting solution for our hardened mast were complete, the CFEWC team conducted a full mock-up of our upcoming mission right here on the Shirley's Bay campus. Even though it was outside the scope of our arrangement, NRC participated and even actioned some final structural modifications in-situ. The final design exactly satisfied our initial requirements. The mast collar and platform did not alter the SEV in any way (which would void its lifting certification), and it was easy to assemble and set up once craned onto the SEV. With regard to withstanding at-sea moments, all the modelling indicated that the design exceeded our operational requirements. This allowed us to proceed on exercise, confident in the modular solution NRC had produced.

Something not yet mentioned is the preparations that were required to integrate the SEV with the ship. SEVs have been carried aboard MCDVs for years, but setting up hotel services aboard *Glace Bay* was no easy task, and took months of coordination with Maritime Operations Group Five (MOG 5) Group Technical Officer LCdr Steve Morrell and his staff. On my staff, I also had SEV subject matter expert Sgt Brent Parks who had been cross-trained on a myriad of army platforms as an Electro-Optical Technician. Each team was invaluable in its support – providing insight on power connections, the conversion of ship power to SEV power needs, securing the pod to the MCDV sweep deck, and conducting waterproofing and rust corrosion prevention. In addition, MOG 5 went above and beyond in ensuring the heavy-lifting equipment and personnel were available to assist with final craning on and off throughout the month of September.

Deployment Results

Our time on Exercise Cutlass Fury 19 aboard HMCS *Glace Bay* from September 9 to 18 was a complete success, even though my team and I held our collective breath for the first 24 hours as we raised and lowered the EW mast in conditions bordering sea state 4. We achieved our primary objective of being able to operate our "EW in a box" in the maritime domain – the equipment met all specifications, and it was a fantastic experience being back in an operational environment. The inside of the SEV proved the perfect work environment, and upon inspection back home at CFEWC, we found little indication of water ingress or corrosion. Discussions with Fleet Diving Unit Atlantic before we deployed informed us on the importance of a thorough post-deployment cleaning routine. Two days before Cutlass Fury was scheduled to start, post-tropical storm Dorian descended on Halifax, causing more than a dozen ships to head out to sea to ride out the storm in more sheltered waters. This serious weather event gave us an unplanned opportunity to see how our cabling and strap set-up would fare in winds in excess of 160 km/h, and we were pleased to see that everything held.

The crew of *Glace Bay* was gracious and hospitable, as those of us who had never been on a ship in the past went about acquiring their sea legs. We made it a point to give tours of the SEV to whomever showed interest, and the crew reciprocated in kind. I myself had never sailed on an MCDV in the past, and I came away very impressed by the crew's professionalism and fortitude, including learning first-hand about the types of missions they had been assigned in the months preceding our embarkation.

Conclusion

After the success of this MarEval, CFEWC's modular EW payload stands ready for employment on multiple ship classes. Modular solutions present the RCN with a cost-effective and configurable technology set, which will only increase in strategic value as timelines for new ship classes extend to the right, and current ship systems on the *Halifax* class require more and more national procurement funds to be kept at high readiness.

Acknowledgments

Many teams and individuals not already mentioned assisted with this endeavour. LCdr Mark Bartek (DNPS 2) and LCdr Tony Carter (PMO JSS) gave me a crash course on naval architecture and design analysis, and really put me on the right path to engaging NRC. Capt Richard Gardiner and Lt Sean MacKinney, who led the C&C department until my arrival, were the driving forces behind acquiring all the new technologies we packed up into the "EW in a Box" MarEval demonstrator. I therefore cannot take full credit for the idea, nor the months of effort they expended within the IM Group convincing senior ranks of the importance of EW as part of the future CAF. The previous commanding officer of CFEWC, LCol Charles Kerber, also provided tremendous support, including committing design funding, and was hugely supportive in expanding CFEWC's frontline capabilities.

LCdr Graham Hill is currently the Navigation Sub-Section Head and PM HCM-FELEX in DGMEPM. He was the Collection and Certification Officer at CFEWC when this article was first drafted and only one of two Naval Engineers employed within CFIOG. The C&C Officer position is closely linked to that of the Officer-in-Charge of the Naval Electronic Warfare Centre (also an NCS Eng), which is also located on the Shirley's Bay Campus, around the corner from NDHQ Carling Campus. His original intent was to present the above information at the 2020 MARLANT Naval Technical Seminar, which was cancelled due to the emergence of COVID-19.

Team Photo: From left to right: LCdr Graham Hill, CPO2 John Taylor (HMCS *Trinity*), Sgt Shaun Bradley (CFEWC), LS Felicia Amyot (CFEWC), AB Jennifer Ringor (HMCS *Trinity*), MS Bryce Williams (CFEWC), Capt Viktor Vazhailo (CFEWC), and Sgt Brent Parks (CFEWC).

Stephan D'Aoust has been a mechanical engineer with the National Research Council for nearly 20 years. During that time, much of his work has been in service to DND designing vehicle-based equipment and system integration.

Brad O'Quinn is a BASc Mechanical Engineering graduate from the University of Ottawa, and was on a co-op work term at NRC during this project.

FEATURE ARTICLE

GPS Performance for Ships in the Arctic

By Lt(N) Kevin Hunt

Photo by LS Dan Bard

HMCS *Montréal*, Operation Nanook 2017

Common misconceptions regarding the performance of the Global Positioning System (GPS) at high latitude include coverage gaps at the polar regions and positioning accuracy being independent of latitude. In reality, GPS delivers worldwide coverage, but positioning accuracy is inconsistent across changes in latitude, particularly at high latitude. Therefore, GPS performance has the potential to be degraded in the Arctic. If Canada is going to be a leader in Arctic operations, we must understand not only how to safely navigate in the Arctic, but also how our ships' systems perform at high latitude.

This article discusses the challenges of satellite navigation at high latitude and how GPS performance is affected in the Arctic. While the data presented highlights changes to positioning accuracy with changes in latitude, the total change in horizontal positioning accuracy at high latitude is trivial. The impact on safe navigation and the performance of combat systems is negligible. For this article's entirety, low latitude is defined as 0°N ≤ x < 60°N and high latitude is defined as 60°N ≤ x ≤ 90°N.

The Global Positioning System

Global Navigation Satellite System (GNSS) is the term for satellite-based navigation systems, where three-dimensional positioning is estimated through pseudo-range multilateration. The American NAVSTAR (GPS), Russian GLONASS, European Galileo, and Chinese BeiDou systems are all examples of a GNSS, each providing an unlimited number of users with continuous all-weather geospatial positioning data.

Each GPS satellite continuously broadcasts a precise timing signal as part of its navigation data message on two frequencies (L1 = 1575.42MHz and L2 = 1227.60MHz). Also included are the satellite-specific ephemeris data and the constellation-specific almanac data. A receiver tracks each signal's time of arrival (TOA) and, based on the signal's transmit time from the satellite, calculates the time of flight (TOF). The instantaneous range to each satellite is termed the pseudo-range measurement, since TOF is affected by a number of environmental factors, errors, and biases that altogether result in positioning error. The receiver uses the pseudo-range measurements and almanac data to estimate its position relative to the constellation, which is outputted to the user in the geodetic coordinate system (latitude, longitude, and altitude).

GPS positioning accuracy is affected by both the instantaneous satellite geometry relative to the receiver, and the cumulative ranging errors collectively known as "User Equivalent Range Errors" (UEREs).

First, since pseudo-range measurements from similarly-located satellites magnify timing, a variety of satellite bearings and elevations is preferred for geometric diversity. A minimum of four satellites is required for three-dimensional positioning, with high-elevation satellites solving altitude ambiguity. Modern receivers have sufficient channels to monitor all in-view satellites, resulting in an equal or superior positioning accuracy compared to only ranging off the four best satellites. The additional pseudo-range measurements provide redundancy and enable Fault Detection and Exclusion, where the receiver identifies timing errors and disregards out-of-tolerance signals. The relative satellite geometry is quantified by Dilution of Precision (DOP), where Geometric DOP (GDOP), Position DOP (PDOP), Vertical DOP (VDOP), Time DOP (TDOP), and Horizontal DOP (HDOP) are unit-less representations of how diluted the position estimate is on a particular coordinate. If the line-of-sight between the receiver and each satellite forms a tetrahedron in the sky, as seen in Figure 1, a larger tetrahedron with geometric diversity leads to a smaller and more favourable DOP for enhanced three-dimensional positioning accuracy.

Second, ranging errors and biases also degrade the measurement accuracy. Other than satellite clock error and ephemeris error, both of which the US Department of Defense continuously strives to minimize, the most significant source of error is ionospheric error. Additional sources of error include tropospheric error, multipath error, receiver error, user error, weather, and ionospheric scintillation. A receiver's position estimate is refined by accounting for as many of these errors as possible through models and error correction algorithms.

Altogether, GPS positioning inaccuracy can be defined as:

Positioning Error = (DOP) • (UEREs)

The combination of satellite motion and varying ranging errors results in continuous fluctuations of positioning error that are always present in GPS positioning. At high latitude, the change in perspective of the GPS constellation, as well as more prominent UEREs, could further increase GPS positioning error. Therefore, these factors are worth investigating to ensure safe navigation in the Arctic.

GPS Positioning Accuracy in the Arctic

GNSS positioning at high latitude is challenged by three factors: non-ideal satellite geometry, increased UEREs, and reduced satellite redundancy. Each of these factors will be investigated to analyze how ship positioning accuracy is affected in the Arctic.

First, the GPS constellation was designed so that four satellites remain visible to most parts of the Earth, even if a number of satellites fail. An orbital inclination of 55° focuses coverage over the temperate regions, where users directly beneath the satellite orbital paths receive optimal coverage from a homogenous spread, and satellites at the zenith. Consequently, no GPS satellites pass at the zenith north of 55°N latitude. Despite this limitation, the satellites' high orbital altitude ensures their continued visibility, even at the North Pole. However, to a receiver north of 55°N latitude, GPS satellites appear lower on the horizon as latitude increases, resulting in non-ideal geometry (Figure 2).

At the North Pole, the highest GPS satellite only appears approximately 45° above the horizon. Although the satellites remain visible, the positioning error equation says that this altered relative geometry should affect the GPS positioning

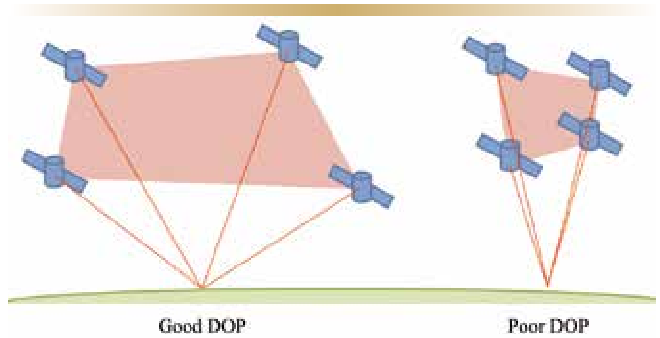


Figure 1. A larger tetrahedral volume from various satellite bearings and elevations enhances three-dimensional positioning accuracy.

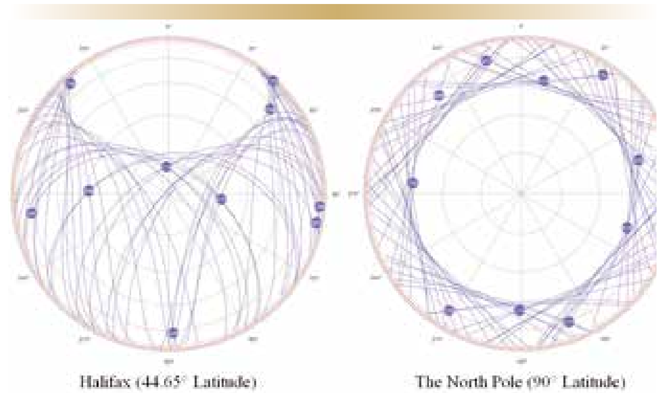


Figure 2. Comparison of skyplots for in-view GPS satellites over a 24-hour period.

error for receivers at high latitude. The result of how changes in latitude affect DOP is shown in Figure 3. This data was collected from GPS simulation software, taken along the randomly selected 94°W longitude at 10-minute intervals, and averaged over a 24-hour period, assuming that all GPS satellites are functional and a 10° elevation cut-off.

The changes in DOP at high latitude are due to a lack of satellites at the zenith, and appearing lower on the horizon as latitude increases. This change in relative satellite geometry is detrimental for altitude accuracy, evidenced by the increase in VDOP, and thus PDOP and GDOP. This loss of altitude accuracy is the major concern for GPS users at high latitude. However, ship positioning is strictly concerned with HDOP, which quantifies the two-dimensional positioning error on the water.

Since ships are not concerned with altitude estimates, the satellite geometry requirement of one satellite at the zenith to refine DOP on the z-axis is not required. The geometry of satellites appearing lower on the horizon as latitude increases beyond 55°N latitude is actually favourable for two-dimensional positioning, and thus ship positioning in the Arctic. The relative consistency of HDOP across all latitudes means that in terms of the non-ideal satellite geometry at high latitude, ships will not be disadvantaged in the Arctic.

The second factor that challenges GNSS positioning at high latitudes is the increased UEREs, predominantly ionospheric delay and scintillation. The lower satellite elevation angles result in higher ionospheric noise and refraction that increase positioning error. Differential processes cannot cancel ionospheric error since the ionosphere affects all satellite signals. Scintillation is the result of the increased and sometimes unpredictable ionospheric irregularities, which occur predominantly in the polar region. Scintillation is known to interfere with all satellite communications, degrading signal quality and preventing lock-on. Thus, scintillation threatens the continuity of GPS coverage more than positioning integrity. Unfortunately, receivers cannot compensate for the variable interference and erratic errors that come from scintillation, which can even lead to intermittent GPS outages where DOP is so high that a position estimate is unusable.

Lastly, receivers at high latitude do not benefit from the luxury of redundant in-view satellites. Although there are always four satellites visible, at times there are fewer visible compared to low latitude, and thus there is less capacity for a receiver to disregard certain satellite signals with known

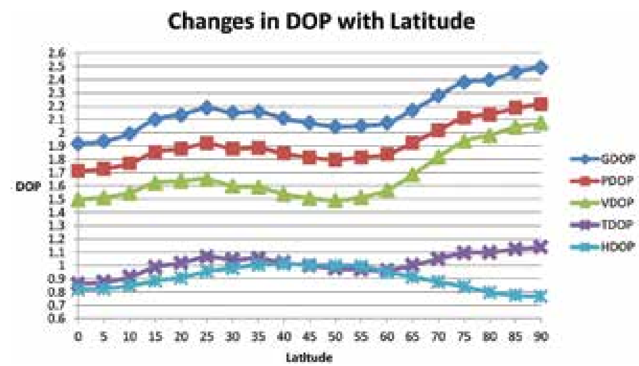


Figure 3. Changes in GDOP, PDOP, VDOP, TDOP, and HDOP due to changes in latitude.

timing errors. Additionally, receivers in the Arctic are more susceptible to coverage gaps if a number of individual GPS satellites fail – although the outage would be short-lived until other satellites appear over the horizon.

In the end, the change in relative satellite geometry at high latitude is slightly favourable for horizontal positioning. However, increased ionospheric delay and unpredictable scintillation can cause elevated HDOP values at high latitude, resulting in degraded positioning accuracy and even GPS outages. Unaugmented single-frequency receivers are considered lucky to continuously estimate their position within 10 metres of their true position at low latitude. Due to increased UEREs at high latitude, single-frequency receivers have experienced horizontal positioning errors of 15 metres in the Arctic, and vertical positioning errors of up to 75 metres.

Effect of High Latitude on Board RCN Ships

The dual-frequency receivers equipped on board RCN ships and submarines, which also decrypt the precision/secure code on the L1 frequency, enhance positioning accuracy and also provide resistance to GPS jamming. Dual-frequency receivers calculate the difference between the TOA of both the L1 and L2 frequencies, thus refining the pseudo-range measurement to the satellite by eliminating the first order ionospheric delays. This use of a second frequency compensates for the standard ionospheric error experienced at low latitude, and also the increased ionospheric error experienced at high latitude from lower satellite elevation angles.

At low latitude, dual-frequency GPS receivers are capable of sub-metre horizontal positioning accuracy, according to unclassified sources. Still, ships regularly experience HDOP

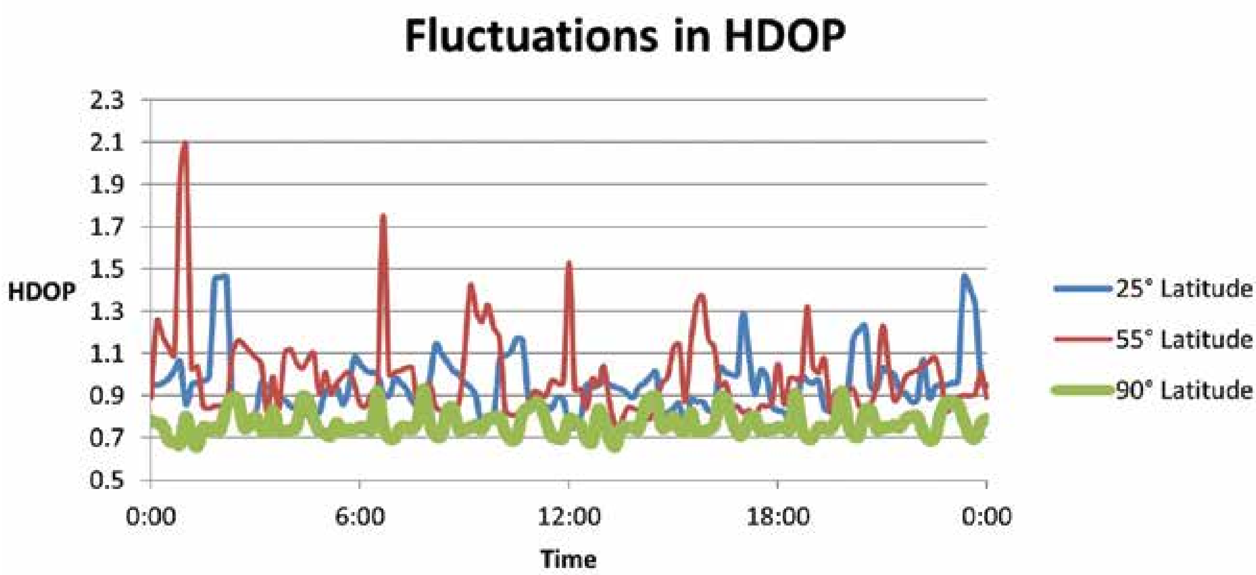


Figure 4. Fluctuations in HDOP at different latitudes.

instability with limited impact to safe navigation. Figure 4 illustrates the fluctuations in HDOP for a receiver at three different latitudes (25°N, 55°N, and 90°N) over the same 24-hour period and conditions as Figure 3.

The data presented in Figure 4 shows not only a decrease in average HDOP at high latitude, but also less variation in HDOP at high latitude. Therefore, ships navigating at high latitude will experience less fluctuation in HDOP than experienced at low latitude.

Since HDOP is relatively unaffected by changes in latitude, and with dual-frequency receivers eliminating the increased ionospheric delay at high latitude, RCN ships will experience negligible differences in GPS positioning accuracy between low and high latitude. However, intermittent increases in HDOP and GPS outages can still be experienced due to the effects of scintillation. If scintillation were to degrade GPS positioning accuracy, all shipboard GPS end-users would be subject to the same positioning degradation; however, the impact on safe navigation and performance of combat systems is trivial. A few examples follow.

The Shipboard Integrated Navigation and Display System (SHINNADS), used by bridge watchkeepers for route planning and safe navigation, continuously receives GPS position. If the effects of high latitude do increase HDOP beyond a set threshold, the SHINNADS operator is immediately alerted. The elevated HDOP values indicate a reduction in horizontal positioning accuracy, as well as GPS-calculated speed which is extrapolated from sequential position measurements. If GPS position is in doubt, the position estimate can be verified through triangulation and/or radar ranging. However, traditional chart navigation is further complicated in the Arctic due to a lack of infrastructure, poor map surveying, rough weather, and an absence of landscape definition. Under GPS outage conditions, SHINNADS alerts that GPS connectivity is lost and the operator changes the position source to maintain safe navigation. When GPS connectivity is regained however, jumps in the SHINNADS position can occur due to the change in positioning source.

The Automatic Identification System (AIS) continuously broadcasts and receives ship and voyage information for situational awareness. Under degraded GPS conditions, AIS will not only broadcast its own inaccurate position, but will also receive other ships' inaccurate position since the system is at the mercy of the other ships' GPS receivers. Fortunately, any position inaccuracies in one's own and other ships' GPS positioning from UEREs are small relative to the safe distances normally maintained between ships.

With its Kalman filtering process, the two Shipboard Inertial Navigation Systems (SINS) maintain independent position estimates. However, inertial navigation systems are not designed to be absolute positioning systems. SINS position estimates are refined from external inputs including GPS speed and position for resets and to calibrate gyroscope drifts. Therefore, any degraded GPS positioning data is subjected to the SINS. In the unlikely event that GPS connectivity is interrupted or lost altogether, SINS can supply an uninterrupted estimate of the ship's position based on computed reckoning. However, SINS positioning is not as accurate as GPS due to its calibration and inherent accumulation of error over time; without any GPS input, SINS accuracy will degrade even further with time. Note that SINS itself is subject to increased error at high latitude since system error approaches infinity as the ship nears the pole. To ensure continued functionality at high latitude, SINS is entered into an alternate coordinate system between 85°N and 90°N latitude.

In terms of weapon systems, the Advanced Harpoon Weapon Control System receives a direct GPS data feed for flight information programming of the Block II missile, with a secondary feed from the Combat Management System. Any increased ranging and timing errors at high latitude, as well as an increased risk of GPS outages, could negatively affect the performance of cruise missiles (including the Harpoon Block II) if navigating via pre-set GPS waypoints. In the event that GPS speed is substituted for ship's log speed as part of the fire-control solution, any inaccuracies in position and speed due to high latitude would only be a minor factor in the main gun's firing accuracy.

Lastly, GPS time helps maintain synchronization of ship systems. While the onboard time server tracks the passage of each second, GPS specifies what time it is. If GPS is lost, the time server is referenced for the passage of time and the performance of onboard systems and communications will then be based on how well all systems remain synchronized. When GPS connectivity is regained, transients and jumps in time can occur if the ship's network and GPS time have a significant delta.

Improving GPS Positioning Accuracy in the Arctic

Even though the effects of high latitude on GPS will not jeopardize the safe navigation of RCN ships in the Arctic, there is still merit in improving GPS positioning accuracy at high latitude. Scientific research, surveying, drilling, and UAV operations are only a few examples of the applications relying on high-precision and high-accuracy GPS positioning in the Arctic. Ships with single-frequency receivers will also be disadvantaged by the effects of lower satellite elevation angles, and thus subject to greater positioning errors at high latitude. Therefore, methods to improve the accuracy of satellite navigation at high latitude are being researched since degraded positioning accuracy concerns not only safe navigation, but is also a national security issue.

The most practical solution for increasing high-latitude positioning accuracy is additional satellite transmit frequencies. As shown by the increased performance of dual-frequency receivers, multiple frequencies reduce the effect of ionospheric error on positioning accuracy, thus refining the position estimate without the need for additional user hardware.

GPS satellites in polar orbits would provide overhead coverage at high latitude, thus improving VDOP. With its higher orbital inclination of 64.8° to cover northern Russia, GLONASS provides increased positioning accuracy in the Arctic compared to GPS. However, GPS satellites in alternate orbits are not cost-effective since most users are at lower latitudes, and the move would also reduce the uniformity of the GPS constellation. A number of initiatives, including High-Integrity GPS, are examining the practicality of using non-GPS satellites in high-inclination orbits to augment GPS coverage, and thus reduce both acquisition times and DOP, particularly at high latitude.

The effects of high latitude on GPS will not jeopardize the safe navigation of RCN ships such as this AOPS patrol vessel in the Arctic.

Differential GPS (DGPS) augments positioning accuracy through error-correction signals; however, DGPS coverage is limited by its network of shore-based infrastructure which, at the time of this writing, does not extend into the Arctic. While extension of DGPS infrastructure into the Arctic would promote accurate positioning for both military and commercial ships, the remote nature of the Arctic makes space-based differential solutions more practical. Satellite-based Augmentation Systems (SBAS) provide augmented GNSS positioning with other satellites; however, the North American-specific Wide Area Augmentation System (WAAS) does not extend fully into the Arctic, resulting in a polar gap of coverage. Augmentation services on high-inclination orbits would support high-integrity navigation at high latitude for not only maritime users, but aerial assets as well. However, these space-based solutions are all still subject to ionospheric error and scintillation. As the Arctic becomes more accessible, seasonal DGPS shore beacons and high-endurance UAVs could provide short-term solutions for augmented positioning coverage with error correction broadcast to specific regions, and would not be subject to the same errors as space-based solutions.

In terms of receivers, continued research into atmospherics and modelling of signal propagation at high latitude could help receivers better identify and compensate for timing errors, thus minimizing positioning error. If not equipped with dual-frequency receivers, civilian ships are disadvantaged at high latitude, subject to the higher noise from lower satellite elevation angles. Receivers compatible with multiple GNSS systems offer the ability to improve positioning integrity not only at high latitude, but all around the world. Working with complementary GNSS that operate satellites in different orbits helps reduce the DOP worldwide, and thus maximizes positioning accuracy. However, like differential solutions, all signals by complementary space-based systems are disturbed by ionospheric error and scintillation. Furthermore, each GNSS and augmentation service operates on unique frequencies, initiating new logistical and national security concerns, especially for military assets.

On board ship, there are limited strategies to improve GPS positioning accuracy. GPS antennas are best mounted so that they have an unobstructed view of the sky on all courses, and so that multipath reflections and electromagnetic interference are minimized. Formation of ice on the antenna should also be avoided. It is also recommended to mount GPS antennas as close to the vessel's centre of gravity as possible to avoid loss of signal lock from antenna accelerations in any measurable sea state. Finally, caution should also be exercised when operating with handheld GPS units in the Arctic, since the cold may degrade their performance.

Conclusion

Despite the GPS constellation not being optimized for polar coverage, its performance at high latitude remains adequate for horizontal positioning. For those with dual-frequency receivers, the lower satellite elevation angles at high latitude will not jeopardize safe navigation. The combination of dual-frequency capability and redundant SINS means that RCN ships are ideally equipped for high-latitude navigation. However, the elevated risk of GPS outage conditions at high latitude will place a higher reliance on other navigation equipment and navigation practices in the Arctic, including SINS.

Academic research continues on GNSS performance at high latitude to fully understand the effects, and to develop methods to minimize positioning error. To build on the analysis of combat system performance at high latitude, further research can focus on the challenges of external communications and underwater warfare in the Arctic.

Acknowledgements

The author would like to acknowledge the subject matter experts at the Fleet Maintenance Facility Cape Scott who contributed their expertise and opinion to this article.

Lt(N) Kevin Hunt is the Deputy Combat Systems Engineering Officer at the Fleet Maintenance Facility Cape Scott in Halifax, and prior to that was the Combat Systems Engineer on board HMCS Windsor (SSK-877). He holds two Master's degrees in Space Sciences and Aeronautics, with research in GPS coverage at high latitude for UAV guidance and navigation.

References

Finnish Ministry of Transport and Communications. (2020, Jan 9). Challenges in Arctic navigation and geospatial data. Retrieved from http://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/161989/LVM_2020_1.pdf

Jensen, A.B.O. (2010, Oct). Challenges for positioning and navigation in the Arctic. Retrieved from https://mycoordinates.org/challenges-for-positioning-and-navigation-in-the-arctic/

National Research Council. (2011). National Security Implications of Climate Change for US Naval Forces. Washington, DC: The National Academic Press. doi: 10.17226/12914

FEATURE ARTICLE

Underwater Gravity-based Navigation for Long-range AUV Missions

By Lt(N) Parth Pasnani and Dr. Mae L. Seto
Illustrations courtesy the authors.

The Spring 2019 edition of the *Maritime Engineering Journal* (MEJ 89) featured an overview of autonomous underwater vehicles (AUV) and their suitability for the military context. To use these robotic vehicles effectively, the accuracy of their underwater localization and navigation must be achieved to within an acceptable tolerance — a challenging endeavour given the physical limitations of the environment in which they operate. Since GPS signals attenuate quickly with water depth, other methods must be employed.

This article briefly introduces the three main AUV navigation methods currently in use — inertial, baseline, and geophysical (i.e. terrain-based) — and while they each have their own strengths, they have shortcomings that limit their use beyond short-range operations. However, recent research into *gravity-based* underwater navigation that I presented as part of my Master's thesis earlier this year offers promising results in terms of enabling reliable long-range AUV position localization and navigation – important factors in taking full advantage of an AUV's unique capabilities.

Inertial Navigation

An on-board inertial navigation system (INS) improves an AUV's simple dead-reckoned position estimate (based on compass heading and Doppler velocity log speed) by integrating motion sensor information from accelerometers and gyroscopes. However, even INS position estimates will drift [1] due to small measurement errors that compound over time.

The best inertial navigation systems have a drift of about 0.1 percent of the distance travelled, whereas modestly priced units drift at between two and five percent of distance travelled. For best results, an INS should be used in concert with other navigation information such as GPS when the UAV is surfaced, but this can be problematic if the AUV is operating under ice or at great depth.

Figure 1. AUVs working under ice or at great depth rely on inertial systems for navigation, but do not have access to GPS information to correct for small INS drift errors.

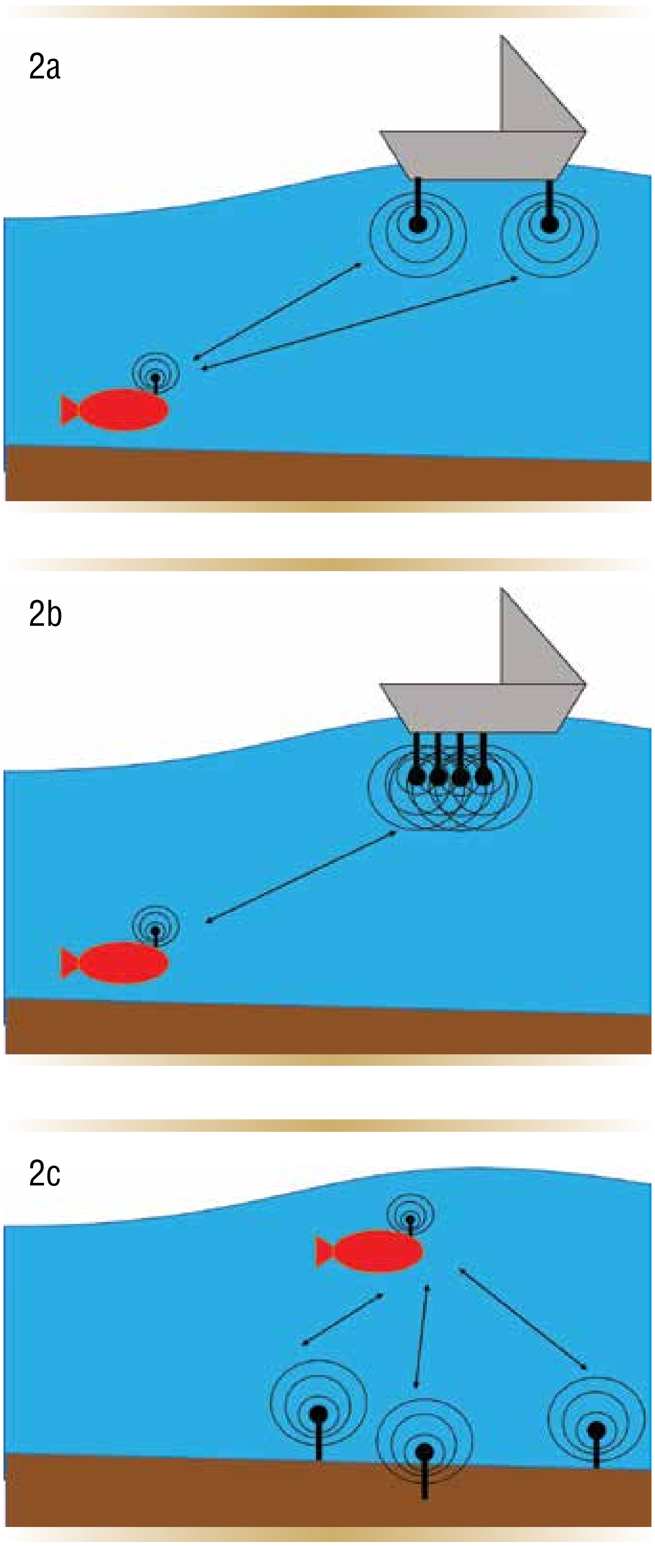


Figure 2. Baseline methods for AUV localization and navigation require that the vehicle remain within communication range of the transceivers: (a) short baseline (SBL); (b) ultra-short baseline (USBL), and (c) long baseline (LBL).

Baseline (acoustic beacon) Navigation

Baseline navigation systems use spaced underwater acoustic transceiver beacons and modems to conduct time-of-flight (TOF) measurements to an AUV, using an assumed sound-through-water speed. Position localization is similar to GPS in that is uses trilateration — the TOF measurements between the underwater vehicle and the acoustic beacons determine the AUV's range from each beacon, and thus yield its position relative to all the beacons.

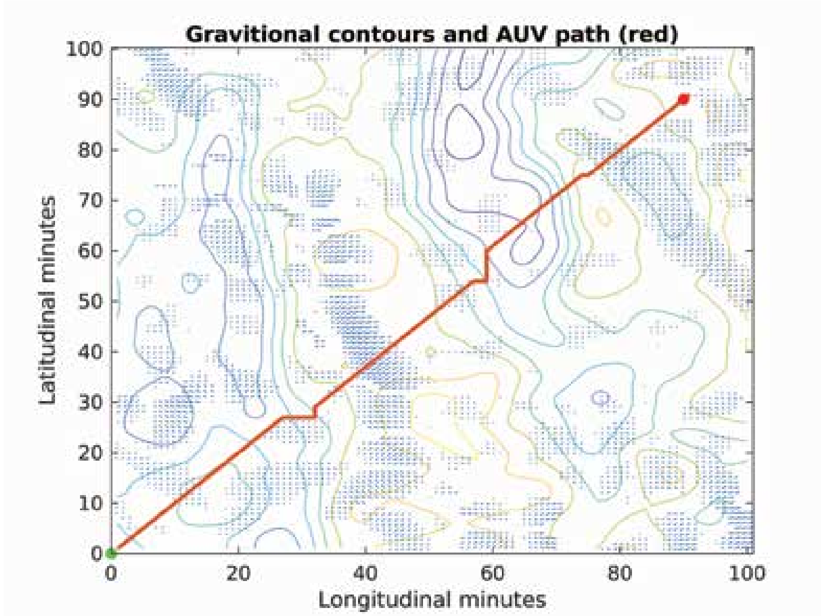
There are three baseline methods: *Short baseline* (SBL – Figure 2a) places transceivers fore and aft on a ship's hull to triangulate and localize the AUV relative to the ship, which in turn knows its position by GPS or other means. With *ultra-short* baseline (USBL – Figure 2b), the AUV's location is determined by TOF and phase differential across an array of transceivers along the ship's hull. The disadvantage with both of these is that the AUV must remain within communication range of the ship, which obviously limits the missions it can perform. In SBL, the positional accuracy depends on the length of the baseline (or ship). SBL and USBL are best suited for applications where the AUV operates within a small area like a dam or lake. *Long baseline* (LBL – Figure 2c), on the other hand, uses widely spaced buoyed beacons over an area to acoustically determine the ranges to the AUV and thereby determine its location. Installing the beacons directly onto the sea floor would raise the accuracy of the position fix over moored beacons by eliminating any drift caused by underwater currents.

Baseline methods remain a reliable means of accurate localization, but their major drawbacks are the cost and time involved with supporting the AUV with either a ship or buoys, and the limited AUV operating range. As such, they are not a solution for long-range AUV navigation.

Terrain-based Navigation

Geophysical or terrain-based navigation (TBN) systems use sonar, optical, magnetic, and gravity-based sensors to exploit environmental features for localization. The challenge with all TBN lies in identifying and classifying features in the environment, and then being able to reacquire them later. The better the quality and number of features in the environment, the better the TBN performance. Recent research has focused on geophysical sensing methods due to their potential to enable long-range underwater navigation and localization, especially when used in conjunction with an inertial navigation system.

(Continues next page...)



Gravity gradient map courtesy of Scripps Institution of Oceanography

Figure 3. Research indicates there is benefit in having an AUV follow a route that is information-rich with distinct gravity measurement waypoints (red line), rather than attempt to reach its objective via a straight-line course.

Sonar systems are able to acoustically identify and classify environmental features as navigation landmarks, and thus create a map of the seabed structure. Imaging sonars, such as side-scan, insonify the seabed and measure the intensity of the acoustic returns to assemble a seabed image. Ranging sonars use transducer arrays that transmit acoustic waves, then process the returns by beamforming to obtain ranges to produce bathymetric maps that could be used for feature-based navigation. However, given the high frequencies they use, they are not usually used for long-range navigation.

A disadvantage of sonars is their active transmission of sound and energy into the environment. Collaborating AUVs could interfere with one another, disturb nearby marine life, and generally raise the local acoustic ambient. Attention has thus focused on other terrain-based methods for localization and navigation.

Optical, or vision-based, navigation systems use stereo cameras to estimate the range to features by parallax or stereo-matching, and do not put much energy into the environment. While these systems are widely used with ground and air robots, they have limited range under water due to inadequate lighting and light-scatter. Nonetheless, they are well-suited in situations where the AUV is very close to its target, such as was demonstrated using a special simultaneous localization and mapping (SLAM) algorithm in association with onboard inertial navigation information during a deep-water survey of the *RMS Titanic* [2].

Magnetic field-sensing instruments can also be used by AUVs for short-range localization, but are less appropriate for long-range navigation due to the constant movement of the Earth's magnetic poles. Since global magnetic maps do not necessarily reflect the current actual state of a specific area, recent research has focused on exploiting local magnetic disturbances in close proximity to the sea bottom for navigation and mapping [3]. A disadvantage of magnetic-based navigation is its susceptibility to interference from the AUV's own electromagnetic emissions.

Gravity-based localization, however, seems to offer better promise for long-range navigation, particularly when used to support onboard inertial navigation.

Gravity-based Navigation

Unlike the Earth's magnetic field, our planet's gravity field is stable and persistent. The Scripps Institution of Oceanography in La Jolla, CA — a division of University of California San Diego — compiles publicly available global gravity maps with a spatial resolution of one square nautical mile. Motivated by tectonic structure surveys and climate change research, these maps can be used to assess gravity-based localization algorithms [5], which in turn inspired my own Master's project research on localization using gravity-based sensors, such as gravimeters, with modern navigation techniques [6]. As part of my thesis, I demonstrated, through simulations, that long-range underwater navigation using gravity-based measurements (as an aid to inertial navigation) was indeed feasible [7].

As mentioned, the state of the art in inertial-based navigation is capable of accuracy with a 0.1-percent drift error for distance travelled. After one nautical mile (1.8 km) of travel, the error is just 1.8 metres, which is acceptable, but the drift error will continue to grow as the AUV proceeds on its mission. However, if the AUV could get a gravity position fix every 1.8 km, the localization error could be reduced considerably. The gravimeter measurements are point measurements with their own error (~ 5 mGal), so even if the AUV travelled with no INS drift error, it might not find the precise gravity point measurement it was targeting if it were in an area of similar gravitational values. To use gravimeter measurements for localization and navigation, the AUV might therefore need to conduct a search with the help of a gradiometer that measures rate of change in the gravity acceleration vector so that it could pick out a more easily identifiable gravity landmark and thus get its bearings.

One of my thesis objectives was to determine whether there was any benefit in having an AUV follow a route that is information-rich with distinct gravity measurement waypoints, rather than attempting to reach its objective via a straight-line course (Figure 3). While the AUV might have to manoeuvre about at a cost of fuel and time, there was shown to be value in having the AUV work to maintain a more accurately known position along its entire route. This conclusion was supported by an associated research model that weighed an increase in information points gained against distance travelled, the objective being to see where the tipping point was in terms of maximizing localization information and minimizing travel. If a gravity map for a specific area were available, a metric based on earlier work [7] could be applied to plan an information-rich route that could decrease localization error for a notional 100-nm (185-km) mission by a minimum of 25 percent over the straight-line case.

Conclusion

One great advantage of gravity-based navigation is that it does not require the AUV to transmit energy into the environment, thereby making it less detectable and therefore less vulnerable to outside interference or jamming. The AUV is simply sensing a physical terrain quantity through passive means. Inertial navigation aided by gravity-based navigation slows the localization and navigation error growth enough to make it a method worth considering for extended operations, and further research, culminating in a real-world implementation, which would demonstrate its potential.

Bibliography

1. L. Paull, S. Saeedi, M. Seto and H. Li, "AUV Navigation and Localization: A Review," *IEEE Journal of Oceanic Engineering*, pp. 131-149, 2014.
2. R. M. Eustice, H. Singh, J. J. Leonard and M. R. Walter, "Visually Mapping the RMS Titanic: Conservative covariance estimates for SLAM information filters," *The International Journal of Robotics Research*, pp. 1223-1242, 2006.
3. J. Quintas, F. C. Teixeira and A. Pascoal, "An integrated system for geophysical navigation of autonomous underwater vehicles," *IFAC PapersOnLine*, pp. 293-298, 2018.
4. D. T. Sandwell, R. D. Müller, W. H. F. Smith, E. Garcia and R. Francis, "New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure," *Science*, pp. 65-67, 2014.
5. L. Wu, J. Ma and J. Tian, "A self-adaptive unscented Kalman filtering for underwater gravity aided navigation," *IEEE/ION Position, Location and Navigation Symposium*, pp. 142-145, 2010.
6. P. Pasnani, "Long Range Underwater Navigation using Gravity-Based Measurements," *M.ASc. Thesis*, 2020.
7. P. Pasnani and M. Seto, "Terrain-Based Localization and Mapping for Autonomous Underwater Vehicles using Particle Filters with Marine Gravity Anomalies," in *Proc. 11th IFAC Conf. Control Applications in Marine Systems, Robotics, and Vehicles*, Opatija, Croatia, 2018.

Lt(N) Pasnani is the Combat Systems Engineering Officer on board HMCS Windsor (SSK-877). He successfully defended his Masters of Applied Science dissertation in Electrical and Computer Engineering at Dalhousie University in April 2020.

Dr. Mae Seto is an Associate Professor with the Dalhousie Faculty of Engineering, and the Irving Shipbuilding Chair in Marine Engineering and Autonomous Systems. She was Lt(N) Pasnani's graduate supervisor.

FEATURE ARTICLE

The Naval Engineering Test Establishment's Support for RCN Innovation with Unmanned Systems

Part 1: NETE Unmanned Systems Centre of Excellence

By Siegfried Richardson-Prager and Dr. Mae L. Seto

The Naval Engineering Test Establishment (NETE) notional Unmanned Systems Centre of Excellence (USCE) has been under development for the past three years with a mandate to create and maintain operational and technical subject matter expertise (SME) in unmanned systems that operate in all naval and marine environments – i.e. underwater, surface, and above water (aerial). The USCE will consolidate expertise in unmanned systems to competently address concept and technical development, evaluation, and material support, and to provide unique associated services to the Royal Canadian Navy (RCN).

The USCE includes a recently stood-up capability in the NETE Halifax detachment's Burnside (Dartmouth) facility, consisting of a staff of six technologists and engineers who will provide the expert technical and operator support for any RCN-acquired unmanned vehicles – referred to generically as UXVs. The facility currently houses NETE's unmanned aerial vehicles (UAVs), unmanned surface vehicles (USVs), and unmanned underwater vehicles (UUVs) acquired for the Maritime Multi-Domain Control System (MMDCS) project (see following articles). Additionally, NETE is building expertise in remotely operated vehicles (ROVs), where the operators and pilots trained by the original equipment manufacturers (OEMs) have pursued additional training toward Transport Canada certification as advanced operators, and have also received training in marine practices, safety, and operations.

Each operator/pilot is backed up by two others who have been similarly trained to ensure a timely response to NETE taskings. The NETE Halifax team is supported by software and engineering designers, developers, and testers from both NETE Montreal and NETE Ottawa. Throughout this evolution, the NETE team has built an excellent rapport with the Fleet Diving Unit (Atlantic) and other local waterfront authorities here in Halifax to operate and evaluate new UXV capabilities. NETE Ottawa supports a number of UXV-related initiatives, including the Canadian Armed Forces Unmanned Aircraft System Provision of Services (CAF UPS), the Intelligence Surveillance, Target Acquisition and Reconnaissance (ISTAR) project, the Puma unmanned aircraft system, project NOMAD, and ROV and UUV evaluations for the Major Surface Combatant (MSC) project, and Director of Naval Requirements (DNR). As well, the entire team works closely with the UXV OEMs and support contractors for the provision of material, technical, and evaluation support.

Members of the NETE USCE team also assist DNR 2 with the NATO Standardization Agreement (STANAG) 4817 Custodial Support Team (Multi-Domain Control System) to define and develop a NATO STANAG interface for unmanned systems in all the naval environments. DNR 2 represents Canada on this NATO STANAG working group. A common interface across all three domains facilitates interoperability, streamlines operator training, and future-proofs against the rapid development of unmanned systems and their payload sensors. It also means it is possible to create a truly universal control system with a common open interface that all compliant UXVs can utilize in future Maritime Multi-Domain Control Systems.

The NETE USCE is currently tasked with:

- leading the MMDCS advanced development model minor capital acquisition project;
- supporting DNCS 7's test and evaluation of UUV and ROV performance with FDU(A);
- providing support for DNR 2 UAV tasks;
- providing input into requirements for Canada's remote mine-hunting system procurement; and
- supporting the Major Surface Combatant (MSC 6) office for Project NOMAD using a USV.

As part of the innovations and future capital programs, there will be new developments, exploitation, and test and evaluation activities that require NETE support. This will enhance the NETE USCE team's expertise, and provide a relevant centre of excellence for unmanned systems in the RCN.

Cdr (Ret'd) Siegfried Richardson-Prager is a project manager for several tasks under the USCE. Dr. Mae L. Seto is a senior engineer with the MMDCS Project. Both are with the DND Naval Engineering Test Establishment detachment in Halifax, NS.

FEATURE ARTICLE

The Naval Engineering Test Establishment's Support for RCN Innovation with Unmanned Systems

Part 2: A NETE Advanced Development Model for a Maritime Multi-Domain Control System (MMDCS) for Unmanned Systems

By Dr. Mae L. Seto and Siegfried Richardson-Prager

The Maritime Multi-Domain Control System (MMDCS) is a DNR 2 minor capital acquisition project tasked to the Naval Engineering Test Establishment. The intent is to develop a stand-alone advanced development model (ADM) of a true multi-domain control station to integrate the deployment of unmanned vehicles (UXVs) from a naval platform, whether they be designed for underwater (UUV), surface (USV), or above-water aerial (UAV) missions (Figure 1).

In the past, a control station that integrated ground and aerial vehicles would be termed a multi-domain or universal control station, even though it might only integrate specific ground and aerial vehicles. Maritime underwater and surface vehicles have unique communications and operational requirements, and were not considered when defining the interfaces for previous UXV multi-domain control systems. The Maritime Multi-Domain Control System ADM project is looking to address this gap.

Objective – Build to a common interface standard

The MMDCS is intended to have an open common interface that will accommodate and integrate all candidate UXVs by having the original equipment manufacturers (OEMs) share their UXV interfaces through an interface control document. The NATO STANAG 4817 Multi-Domain Control System works on a common standard for this exact purpose. DNR 2 and NETE contribute to this NATO working group that builds on the contributions and lessons learned from JAUS (Joint Architecture for Unmanned Systems)[1], NATO STANAG 4586 (standard for UA Control Systems)[2], and JANUS (underwater communications)[3], among others, toward a true multi-domain control system. These standards have always been motivated by interoperability.

(Continues next page...)

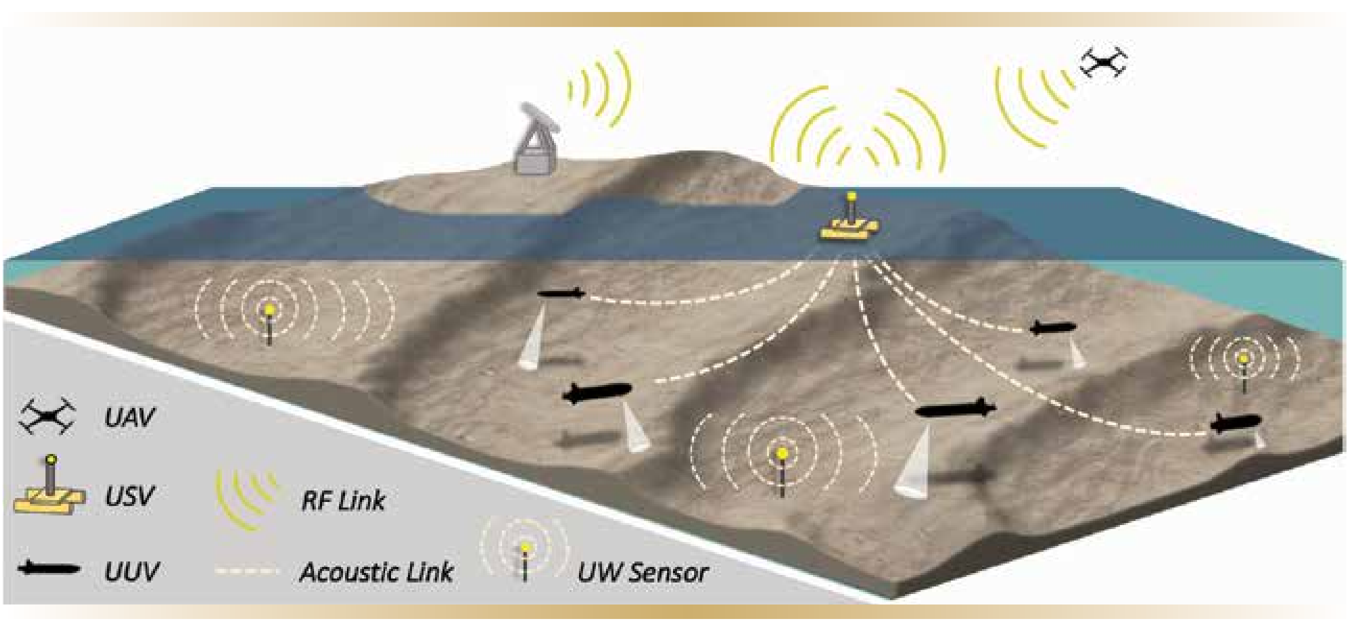


Figure 1. The Maritime Multi-Domain Control System will allow integrated operation of multiple unmanned systems across multiple domains.

Deliverable – Requirements toward a naval platform MMDCS

The MMDCS tasking is an opportunity for the RCN to learn about the engineering and requirements for such a control system. The project deliverable is a report that details the requirements of a Royal Canadian Navy MMDCS, informed by a full engineering build and in-water verification of an advanced development model, engagement with OEMs, and experience in operating UXVs. The report will define and evaluate MMDCS requirements in terms of:

- capabilities and specifications;
- the interface control document;
- interface requirements for operations room data in-/out-flow;
- aids to manage the work load;
- additional sensor, network and bandwidth needs; and
- decision aids for piloting, coordination and information management.

MMDCS common interface advantages

Smaller footprint

One of the advantages of a multi-domain control system with a common interface is a reduction in stove-piped systems. Stove-piping occurs when a system, with its proprietary interface and communications protocols, is unable to freely interoperate with other systems or controllers. In the context of a naval platform, this increases the physical footprint and number of operators required to deploy UXVs from a ship.

Streamlined training

Another advantage of an MMDCS is that operators would train to a mostly common human-machine interface (HMI) and mission planner across all three domains. They would not need to train for a new proprietary HMI or mission planner if a new UXV were purchased for any environment. The MMDCS abstracts out vehicle class particulars that vary from vendor to vendor, as well as particulars that vary across classes of vehicles (i.e. environments).

Protection against UXV obsolescence

Such advantages, coupled with a flexible and interoperable multi-domain control system, would serve to future-proof against rapid evolution of UXVs and their payload sensors. Although the UXV is an integration of multiple diverse technologies (e.g. sensors, robotics, fault tolerance, artificial intelligence, communications, etc.), they do not all develop at the same pace, nor are they necessarily synchronized with one another. A UXV might undergo a number of sensor upgrades before it is replaced by a factory-fresh vehicle with an integrated new sensor suite.

platform centered	⇢	**capability centered**
stovepipe/ legacy systems		distributed/networked/ cooperative

Figure 2. Current design paradigm for UXVs.

Having a common open MMDCS interface means that any non-recurring engineering (NRE) needed to integrate a new vehicle or payload sensor is minimized. For example, if an improved thermal imaging camera were introduced by the Navy for shipboard use, its control as a payload sensor aboard a USV could be easily implemented through the MMDCS because a payload camera open interface had been previously defined.

All of this is possible because the MMDCS works across a common interface, as opposed to integrating directly with any of the proprietary inner workings of the vehicle or its payload sensors. There is a one-time MMDCS software (vehicle interface) node that has to be created to interface with the OEM applications programming interface, which is part of the required non-recurring engineering.

Interoperability

Allied groups working to a common interface can interoperate their UXVs more readily, as was demonstrated during Exercise Unmanned Warrior 2016's "Hell Bay" technical cooperation component[4] in Scotland. [Author Dr. Mae Seto was Canada's lead scientist for this component. – Editor]

Over the last five years there have been quite a few UXV OEMs in all domains that understand the value of opening their interfaces – at least in a limited form. The OEMs often have an application programming interface that an end-user or third-party developer can access, and which is geared more to serve a UXV user community that is becoming more educated in customizing payload solutions for particular UXV applications. Since the emphasis with UXVs has moved away from platform-centred solutions toward *capability*-centred solutions (Figure 2), the MMDCS is concentrating on leveraging the trend in open vehicle interfaces to make a controller that is not limited to any particular OEM, UXV type, or where possible, the domain.

Figure 3. Futuristic concept of the MMDCS.

Development, integration and verification with multi-domain UXVs

The MMDCS prototype development is proceeding in three phases. Phase I consists of laboratory design and development, with testing using vehicle simulators and in-house verification tools. Phase II is shore-based testing of initial integration of the RCN's current inventory of UXVs to the MMDCS. Phase III is ship-based verification and testing from a vessel of opportunity of the prototype system using all UXVs concurrently. Phases II and III will be primarily performed in the Halifax approaches and surrounding waters.

To fulfill project requirements, NETE has acquired three state-of-the-art UXVs for test operations in all three domains (see following article), and is working with the OEMs to integrate these vehicles with the MMDCS. As of summer 2020, this four-year minor capital acquisition project is at its halfway point, and will be progressing with the engineering design and build process. Upcoming in summer 2021 are the Phase II harbour acceptance tests (HATs) and Phase III sea acceptance tests (SATs), followed by a one-year warranty period to exploit the new capability.

Beyond a control station

The MMDCS on-board platform will have two consoles for a coordinator and an information manager (Figure 3). The coordinator is provided with information to de-conflict the water/air space, approve MMDCS mission recommend-ations, monitor UXV states and missions, and maintain the master UXV situational awareness picture. The information manager manages, extracts and interprets payload sensor information that can be passed to others aboard ship for further analysis. The two consoles are side-by-side and are interchangeable in their roles. More such consoles could be distributed across other platforms, or on land, as needed by the scope of the UXV missions.

UXVs deployed from naval platforms require piloting, coordination, and information management, and handling all three functions with multiple vehicles in play is difficult and can lead to operator overload. The MMDCS will show that it is more than a glorified universal control station, as it will include sophisticated operator aids to mitigate this situation. One of these will interpret the payload sensor data that is streamed back to the consoles so that an operator who is not a specialist on a particular payload sensor can interpret the results and determine their significance with respect to the UXV mission and its impact on ship operations. The operator can decide if this information should be forwarded to others for further action. As well, information from environmental-specific sensors such as weather stations, Automatic Dependent Surveillance-Broadcast (ADS-B), marine Automatic Identification System (AIS), Global Positioning System (GPS), and other inputs, will be streamed into the MMDCS to help the operators plan a mission that might involve one or more UXVs across multiple domains.

The Maritime Multi-Domain Control System ADM project represents an exciting step forward in closing a significant gap in the integration and control of naval UXV operations. It may be a minor capital project, but it is already showing major promise in investigating the delivery of innovative new technology to the fleet.

Dr. Mae Seto is a senior engineer with the MMDCS Project. Cdr (Ret'd) Siegfried Richardson-Prager is the project manager of the Maritime Multi-Domain Control System.

References

1. Serano, D., "Introduction to JAUS for Unmanned Systems Interoperability – Joint Architecture for Unmanned Systems," STO-EN-SCI-271-02, May 2015.
2. STANAG 4586 – Standard Interfaces of UCS for NATO UAV Interoperability, STO-EN-SCI-271-03, May 2015.
3. Borden, J., "JANUS: a digital underwater signaling standard for network node discovery and interoperability," Proceedings of SPIE 11015, Open Architecture / Open Business Model Net-Centric Systems and Defence Transformation 2019, Baltimore, MD, May 2019.
4. Canada's contributions to Unmanned Warrior 2016, (https://www.canada.ca/en/defence-research-develop-ment/news/articles/exercise-unmanned-warrior-an-international-exercise-using-autonomous-tech-to-detect-underwater-mines.html), last accessed May 16, 2020.

FEATURE ARTICLE

The Naval Engineering Test Establishment's Support for RCN Innovation with Unmanned Systems

Part 3: NETE Acquires Unmanned Systems for its Maritime Multi-Domain Control System (MMDCS) Project

By Corey Venturini and Dr. Mae L. Seto

At a minimum, the MMDCS is a universal control station for unmanned vehicles (UXVs) operating in the underwater, surface and above-water domains relevant to naval platforms. The MMDCS' open architecture and interoperability with commercially available UXVs are important features. The three initial unmanned vehicles selected for the implementation and testing of the MMDCS, at an advanced development model state, required that the vehicle OEMs share their interface control documentation to facilitate the integration of the vehicles to the MMDCS. As well, the selected unmanned vehicles had to have open architectures to be able to host user-developed capabilities.

The **R70 SkyRanger™ UAS** unmanned aerial system (Figure 1) from FLIR Systems in Waterloo, Ontario is a multi-function quadcopter. Toward MMDCS objectives, it is easy for the user to integrate both hardware and software payloads. The R70 SkyRanger operated by NETE came with two main camera payloads – the HDZoom 30 and the EO/IR (electro-optical/infrared) MK II. Both cameras have notable clarity at extended ranges, with 30x optical zoom and 60x digital zoom. FLIR's mission control software applied to the video feed enables the operator to automatically track mobile objects. This UA system is fully autonomous, but can be remotely controlled, and has the unique ability to pass mission data to a second SkyRanger mid-flight. The FLIR SkyRanger UAS is utilized by more than 20 militaries across 30 countries worldwide.

The **Iver3** from L3Harris-OceanServer in Fall River, MA is a lightweight, portable torpedo-shaped unmanned underwater vehicle (UUV). For the MMDCS objectives, UUVs have communication and navigation limitations not addressed in past universal control stations designed for surface-operated and above-water UXVs. The payload sensors are a Klein 3500 side-scan sonar, and an interferometric bathymetric sonar (Figure 2). The Iver3 uses an acoustic modem for underwater communications, and a

All photographs courtesy NETE

Figure 1. A SkyRanger R70 UAV successfully lands during a NETE training run at the FLIR facility in Waterloo, Ontario.

Figure 2. NETE's IVER3 UUV deployed in an icy Bedford Basin (Halifax, Nova Scotia).

Figure 3. The C-CAT3 USV during a deployment in Bedford Basin.

navigation solution built around the state-of-the-art iXblue Phins inertial navigation system. While underwater, the Iver3 is fully autonomous. NETE has deployed this vehicle multiple times in Bedford Basin and in the Halifax Harbour approaches to image submerged wrecks and mine countermeasure targets, among other objects. In addition to its role with MMDCS, it was used in comparison trials with the REMUS 100 UUVs operated by Fleet Diving Unit (Atlantic) – see MEJ 89, Spring 2019 issue. The Iver3 UUVs have been applied to defence, scientific, and industrial missions worldwide. Four of these vehicles were notably part of the multi-vehicle collaboration trials at the Royal Navy (RN) Unmanned Warrior 2016 exercise.

The **C-CAT3** unmanned surface vehicle from L3Harris-ASV in Portchester, UK is a robotic catamaran hull-form (Figure 3). Its wet sensors include an altimeter and bathymetric sonar. The above-water sensors are two visible wavelength cameras – one fixed, and the other capable of pan-tilt-zoom. The USV's role is to relay control signals/data between the MMDCS and a submerged UUV. The cameras transmit video to the MMDCS for situational awareness. Since the device also uses an underwater acoustic modem to communicate with an underway UUV, and RF radio to communicate with the MMDCS, the MMDCS can communicate in near real-time with the submerged UUV. The USV can be remotely controlled through Wi-Fi, 4G cellular, or UHF radio. Like the other two unmanned vehicles, the USV can be autonomously controlled. The C-CAT3 USV has a similar controller and interface to the C-Worker 5 (same OEM) that participated in the multi-vehicle collaboration with the four Iver3 UUVs during Exercise Unmanned Warrior 2016.

Table 1 summarizes the individual UXV performance characteristics. The endurance and range of each vehicle type (based on nominal vehicles on a single battery charge) depend on the duty cycle of the payload sensors, or the radio range in the case of the SkyRanger UAS. The USV and UUV endurance can drop by more than 30 percent with all payload sensors running at a high duty cycle. These UXVs are maintained and operated out of NETE's Unmanned Systems Centre of Excellence in Halifax.

Going forward, even though these vehicles were specifically selected for the MMDCS project, they are versatile and adaptable enough that they can be utilized for other evaluation activities in support of the RCN and DGMEPM.

Corey Venturini is an intermediate engineer and lead SkyRanger R70 pilot. Dr. Mae L. Seto is a senior engineer with the MMDCS Project. Both are with the DND Naval Engineering Test Establishment in Halifax, NS.

Table 1: Summary of UXV Performance Characteristics

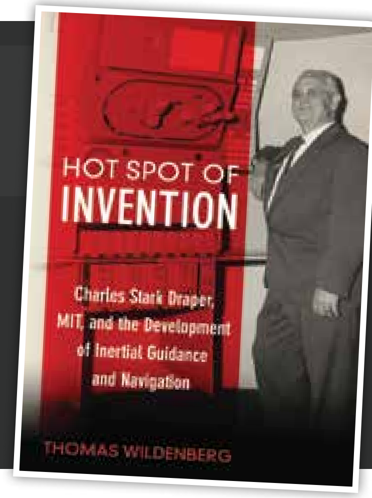
Domain	UXV Type	Max Speed (kt)	Altitude/Depth Rating (m)	Endurance (min)	Range @ Cruise Speed (m)
above-water	quadrotor UAS	27	4,572 (altitude)	40	8,000 (radio range)
surface	catamaran USV	8	sea level	360 – 480	6,500 (@ 3.5 kt)
underwater	torpedo-like UUV	4	100 (depth)	480 - 840	37,000 (@ 2.5 kt)

BOOK REVIEW

Hot Spot of Invention — Charles Stark Draper, MIT, and the Development of Inertial Guidance and Navigation

Reviewed by Brian McCullough

Author: Thomas Wildenberg
Publisher: U.S. Naval Institute Press
ISBN: 9781682474693
Hard back, 320 pages, 32 illustrations
https://www.usni.org/press/books/hot-spot-invention



In his epic 1902 poem *Sea-Fever*, the one-time British poet laureate and merchant seaman John Masefield wrote the immortal words: *And all I ask is a tall ship and a star to steer her by*.

The sentiment is one I can easily identify with, having navigated various ships of the Royal Canadian Navy by stars and sextant during my own time at sea in the 1970s. I find the art of determining a ship's position on an empty ocean without the aid of artificial satellites or sophisticated electronics to be deeply satisfying. But what about when there is no actual star "to steer her by?"

Around the time I was struggling with my first star sights aboard HMCS *Qu'Appelle* on a run down to Jamaica in January 1974, the Institution of Civil Engineers in the U.K. was getting ready to present the brilliant American scientist and engineer Charles Draper with the Kelvin Gold Medal for "his development of guidance systems for naval vessels, aircraft, rockets, missiles, and spacecraft."

Most people who knew him called him "Doc," but Charles Stark Draper (1901-1987) was also the man who was often referred to as the "Father of Inertial Navigation." His dynamic leadership and inspirational teaching style at MIT's Instrumentation Laboratory in Cambridge, Massachusetts led to the development of a floated gyroscope that you might say placed a navigational guide star inside a box. In effect, they had exploited a spinning gyroscope's ability to maintain the direction of its spin axis regardless of what the outer frame holding it is doing.

As we learn from Thomas Wildenberg's fascinating personal and technical biography of Draper, published by the Naval Institute Press in November 2019, among Doc Draper's many accomplishments were the development of a prototype in 1953 that proved the feasibility of a Submarine Inertial Navigation System (SINS), and the Apollo Guidance Computer and DSKY display and keyboard guidance, navigation and control system that took the astronauts to the Moon. One of his early design successes was a gyro-stabilized gunsight for the United States Navy's shipboard anti-aircraft guns during the Second World War.

Wildenberg is an independent historian and scholar whose special interests include naval aviation and technological innovation in the military. He does an amazing job of showing how Charles Stark Draper's extraordinary talent for applying science to engineering was supported by MIT, to the extent that the laboratory that would one day bear Draper's name became a centre of innovation – a hot spot of invention – that attracted high-profile government research projects. *Build the right kind of incubation environment, and they will come.*

The book's thorough attention to the intertwined story of Draper and the MIT Instrumentation Laboratory is itself supported by a helpful glossary, an index, and extensive end notes and source material citations.

We are looking for book reviewers from among serving or retired members of the CAF/DND Naval Technical community!
MEJ.Submissions@gmail.com

NEWS BRIEFS

Government of Canada receives first new Arctic and Offshore Patrol Ship

With files from National Defence / Canadian Armed Forces News

The RCN marked the most significant milestone in its shipbuilding program with the July 31 delivery of the first of six new Arctic and Offshore Patrol Ships (AOPS). HMCS *Harry DeWolf*, named in honour of Second World War naval hero **VAdm Harry DeWolf**, is the first ship built for the RCN under the National Shipbuilding Strategy.

"Bravo Zulu and thank you to all of those across the Government-Industry shipbuilding team – especially Irving Shipbuilding Inc., the builder – whose collaboration has made Canada stronger today," said RCN Commander VAdm Art McDonald.

Specifically designed to patrol Canada's offshore waters and northernmost regions, this new class of ship will be at the core of an enhanced Canadian Armed Forces (CAF) Arctic presence. The ship will undergo a formal commissioning ceremony in summer 2021, followed by an Arctic deployment.

Construction for the following three ships is ongoing, with construction of the fifth and sixth ships expected to begin in 2021 and 2022, respectively. The RCN has announced that the sixth ship of the class will be named after Victoria Cross recipient, RCNVR pilot **Lt Robert Hampton Gray**, who died in action leading a flight of Corsair aircraft against enemy warships in Japanese home waters on Aug. 9, 1945. [Learn more at: https://parallaxfilm.com/episode/last-battle-of-hampton-gray/]

Photo courtesy Irving Shipbuilding Inc. (CNW Group/Irving Shipbuilding Inc.)

Mr. Kevin McCoy, President, Irving Shipbuilding Inc (left) and Vice Admiral Art McDonald, Commander of the Royal Canadian Navy (right) at the official Acceptance Ceremony for HMCS *Harry DeWolf* at CFB Halifax Dockyard on July 31, 2020.

DND photo

Lt Robert Hampton Gray, VC, DSC, MiD(2).

HMCS *Harry DeWolf*
DND photo by Mona Ghiz

AWARDS


Photo courtesy CRCN

Royal Military College of Canada Carruthers NTO Sword

NCdt Cael Halvorsen
For academic achievement and exemplary performance
(With Capt(N) Jim Carruthers, RCN (Ret'd))


Photo by Brian McCullough

NTO Spirit Award RAdm Mack Silver Plate

Lt(N) Emma Reed
For demonstrating the spirit that enables naval technical excellence
(With RAdm Chris Earl)

PRESERVING CANADA'S NAVAL TECHNICAL HERITAGE

CNTHA

NEWS

Canadian Naval Technical History Association

CNTHA News
Est. 1997

CNTHA Chairman
Pat Barnhouse

CNTHA Executive Director
Tony Thatcher

Directorate of History and Heritage Liaison
Michael Whitby

Maritime Engineering Journal Liaison
Brian McCullough

Webmaster
Peter MacGillivray

Webmaster Emeritus
Don Wilson

CNTHA News is the unofficial newsletter of the Canadian Naval Technical History Association. Please address all correspondence to the publisher, attention Michael Whitby, Chief of the Naval Team, Directorate of History and Heritage, NDHQ
101 Colonel By Dr
Ottawa, ON K1A 0K2
Tel. (613) 998-7045
Fax (613) 990-8579

www.cntha.ca

IMCS Development for the Canadian Patrol Frigate – A Poster Project for RCN Innovation

By Cdr (Ret'd) Peter MacGillivray, MSc, PEng

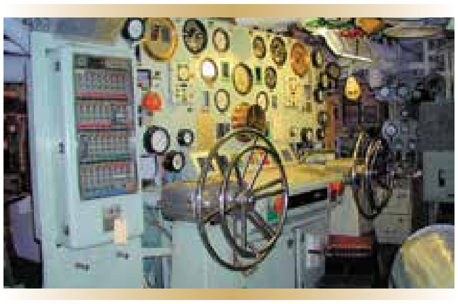
We are all familiar today with sophisticated computer-based controls, but as recently as 1995 it was common in warship control systems to find direct controls and gauges.

Until almost the close of the 20th century, the machinery control system (MCS) technologies in operational RCN ships included post-Second World War technologies for the *Restigouche*-class destroyer escorts (Figure 1), discrete digital hybrid technologies for the DDH-280 tribal-class destroyers (Figure 2), and the Integrated Machinery Control System (IMCS – Figure 3) for the *Halifax*-class Canadian Patrol Frigates (CPF).

Through the efforts of innovative Canadian pioneers, the RCN led the world's navies in the implementation of what is so common today: computer-based integrated platform control technology. The computer revolution was beginning to shape the modern world in the late 1970s, and with amazing foresight, energy, and determination the staffs of DGMEM/DMEE 7 (machinery control section) drove a 10-year development program that saw Canada lead the world with IMCS in the CPF, with the support of the Defence and Civil Institute of Environmental Medicine (DCIEM), as well as key contractors.

Six of the International Ship Control Systems Symposium (SCSS) proceedings from 1978 through 1993 (5th-10th SCSS) chronicle the innovative efforts by RCN staff, both military and civilian, working with Canadian industry, to develop the world's first computer-based IMCS. Canadian technical papers presented at these conferences paint a vivid picture of these uniquely Canadian developments, driven completely by the Navy.

(Continues next page)



DND/CAF photos

Figure 1. The steam throttles and other machinery controls and gauges on the engine-room console of a *Restigouche*-class destroyer escort.

Figure 2. The machinery control console aboard a DDH-280 tribal-class destroyer.

Figure 3. The Integrated Machinery Control System console designed for the *Halifax*-class frigates.

At the 5th SCSS in 1978, the United States Navy's lead paper questioned whether or not automation itself, let alone computer control, was even feasible with computers. Other national papers addressed rudimentary implementation of digital electronics for secondary surveillance only. Canada argued that use of IMCS technology carried promises of improved reliability, operator capability, as well as savings in procurement and through-life costs. Skepticism was tangible, and critical non-believers numerous.

At this same conference, Canada presented papers describing the detailed requirements for a computer-based Ships Integrated Machinery Control System (SHINMACS), and the RCN plan for developing such a "glass control room" (i.e. on a computer screen) system. At successive symposia, technical papers described the developments the RCN was driving to meet these goals. Finally, at the 10th SCSS in Ottawa in 1993, the Navy presented the first-of-class results for the IMCS in CPF — we had succeeded! No other Navy in the world had even yet to attempt a fully integrated IMCS.

It should also be noted that marine system technologies were becoming much more highly sophisticated with the introduction of gas-turbine engines, electronic controllers and the like, and there was an emerging need to reduce the risk of human error when operating highly complex equipment. The major advantage of the SHINMACS man-machine interface (MMI) was in relieving the watchkeeper from having to monitor a plethora of gauges and dials in order to maintain a mental picture of the machinery plant's behaviour.

The development of the IMCS for CPF was challenged by having to meet "off-the-shelf requirements." The 1977 specification was based largely on the DDH-280 machinery control system that used discrete digital components such as NOR and NAND logic gates, etc., and the staff had to forecast which "off-the-shelf" components might be available in time for the first CPF delivery in 1990. Note that the first militarized chip microprocessor (Intel 80186) was not certified until 1982 — the same year the CPF proposals were evaluated.

SHINMACS development was driven by the belief that, by executing strategic research and development to take advantage of the explosive growth in computer technology, IMCS could be realized in CPF with near-state-of-the-art components. Key R&D projects over a span of years to develop SHINMACS to meet the CPF requirement included:

- developing a sophisticated simulation that could be used to refine the ergonomic requirements developed earlier by DCIEM to support the SHINMACS MMI;
- developing a mock console known as the Standard Machinery Control Console to run the simulation, delivered in December 1983; and
- delivering an Advanced Development Model (ADM) that demonstrated the distributed architecture to prove the concept (June 1985).

The ADM contract was let to CAE Control Systems, with a requirement to use the RCN's then-standard AN/UYK-502 computer. When the AN/UYK-502 proved incapable of handling the SHINMACS requirements, it was replaced on the fly with the Intel 80186 processor. As the ADM progressed, various components nearing military certification (memory, displays, I/O devices) were implemented. By delivery time, the shipbuilder had selected CAE IMCS as the system for CPF. CAE pioneered the naval use IMCS "glass controls," and revolutionized the industry.

The rest, as they say, is history, but it is worth reminding ourselves that it was the vision and determination of RCN engineers that were instrumental in driving Canada to lead the world in the field of computer-based integrated platform control technology.

Cdr MacGillivray was IMCS Project Manager from 1982 to 1984, and DMEE 7 section head of the machinery control systems section in DGMEM from 1990 to 1993.