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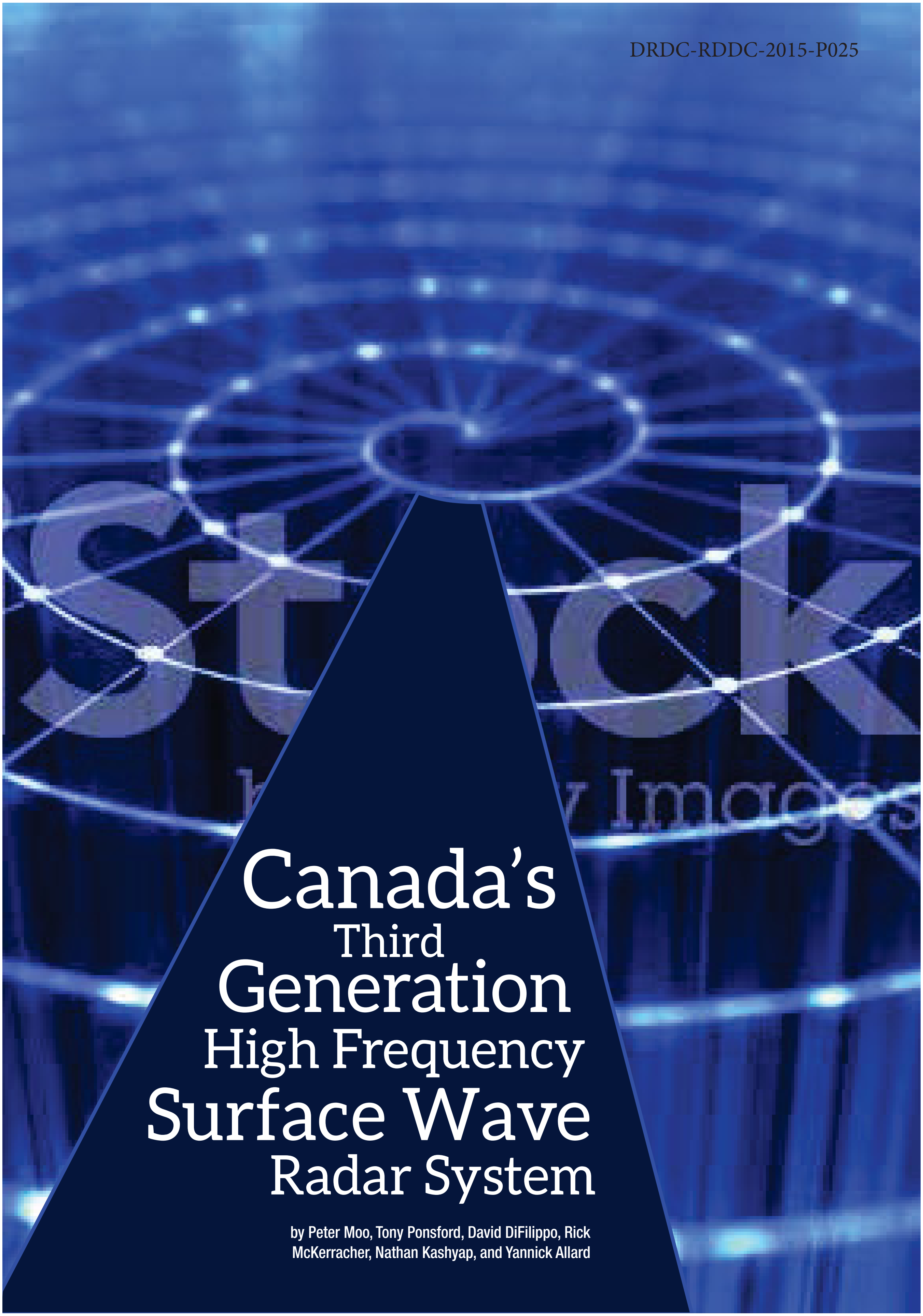


Canada's Third Generation High Frequency Surface Wave Radar System

by Peter Moo, Tony Ponsford, David DiFilippo, Rick McKerracher, Nathan Kashyap, and Yannick Allard

Introduction

The granting of coastal nations' sovereign rights over their 200 nautical miles (nm), Exclusive Economic Zone (EEZ) established the requirement for persistent surveillance. The need to provide continuous surveillance of shipping activity out to and beyond the EEZ led to a reassessment of High Frequency Surface Wave Radar (HFSWR).

Canada has been investigating the use of HFSWR for persistent surveillance of the EEZ for more than 20 years. Early development cumulated in 2003 with the deployment of two SWR-503 HFSWR systems for monitoring the economically significant Grand Banks region on Canada's east coast. Raytheon Canada Limited (RCL) subsequently sold a number of SWR-503 systems to international customers; however, operation of the Canadian systems was terminated in 2007 due to concerns related to the potential for the systems to cause interference to HF communication users. The international systems continue to remain in operation.

The competition for spectrum space between radar and communication users is nothing new. In 1904 the German engineer Christian Hülsmeyer patented and demonstrated the first practical radar known as the "telemobiloscope" as an anti-collision device for ships. Although successful, the system caused interference to the local radio communication systems and the technology was consequently not adopted. It would be a further 30 years before radar would re-enter service.

The requirement for providing persistent surveillance of the EEZ remained, and in 2010 Defence Research and Development Canada (DRDC) completed a comprehensive study of applicable technologies. The study concluded that HFSWR remained the most viable sensor for persistent

Figure 1: Radar transmit site.

surveillance based on a combination of cost and performance. At the same time, RCL started the development of their next generation HFSWR to address obsolescence issues associated with the SWR503 design. Primary design requirements included being a modular and scalable architecture, having the ability to support wideband operation, and to be compatible with other users of the HF spectrum. This latter requirement led to the development of a conceptually new power amplifier design that resulted in a constrained bandwidth and ultra-low spectral side-lobes. The new generation radar also included an enhanced spectrum management system and reduced real estate requirements all at a low-cost. This last requirement resulted in additional requirements to maximize commercial-off-the-shelf (COTS) equipment and digital technology, and maximum reuse of SWR-503 software. The system was specified as a minimum to match the SWR-503 performance.

Independently and in parallel, the DRDC team developed its system requirements for a new generation HFSWR that would meet Industry Canada's stringent requirements for operating on a non-interference mode with HF communication users while remaining available 24/7. Other enhancements were also sought.

In 2011 Raytheon Canada was awarded the contract to design and build a third generation HFSWR system for *Persistent Active Surveillance of the EEZ (PASE)*. This third generation HFSWR system would be installed and demonstrated at a site located near Halifax, Nova Scotia.

Third Generation HFSWR Overview

The Third generation HFSWR system is a mono-static pulse Doppler radar. The radar site consists of co-located transmit (Figure 1) and receive sites (Figure 2). The radar equipment shelter is located at the centre and to the rear of the receive array (Figure 3). The radar electronics are based on a software radar design concept and utilizes direct conversion receiver-exciter technology that eliminates much of the analog hardware associated with traditional radar.

The extensive use of COTS products results in lower recurring cost, shorter system delivery schedules, increased system reliability and maintainability.

The third generation radar incorporates an ultra linear HF power amplifier specifically designed, by RCL, for pulsed Doppler radar operation. The HF power amplifier design results in very low spectral side-lobe levels and consequently minimal spectral leakage that otherwise would have resulted in adjacent channel interference.

The radar operates simultaneously on two independent frequencies in an interleaved pulse mode. The data collected on each frequency thread is processed in multiple-parallel paths optimized for different categories of vessels. The data from the two frequencies and multiple processing paths are consolidated prior to the input of the multi-target tracker.

The tracker associates time sequenced detections to form tracks. These tracks are identified with a unique ID. However, it is well known that radar by itself cannot positively identify a vessel; for this, other information sources are required. Therefore, the output of the tracker is fed to a fusion processor where the radar derived tracks are associated with self-reporting identification sources. Those radar tracks that are not associated with other data sources, or are otherwise behaving in an anomalous manner, can then be highlighted for follow-up action.

Enhanced Detection and Tracking

The tracking of smaller vessels in higher sea states is typically limited by the presence of ocean clutter. For HFSWR, the radar clutter cell is bounded in range by the width of the compressed waveform, in azimuth by the width of the formed beam and in range-rate by the Doppler filters. To enhance detection of small vessels, it is necessary to minimize these dimensions. Since the range and Doppler resolution has already been minimized, the only remaining option is the beam-width. The beam-width is inversely proportional to the antenna aperture and this is limited at HF by the availability of coastal real estate.

A solution to the problem of reducing the beam-width without increasing the physical length of the receive array was developed based on a multiple input multiple output like architecture used to generate a virtual aperture array (patent pending). The technique generates narrower receive beams that reduce the physical area of the radar resolution cell and therefore improves the detection range of smaller vessels. Conversely the technique can

Figure 2: Radar receive site (co-located with the transmit site).

Figure 3: Radar equipment shelter located to the centre and rear of the receive array.

also be used to maintain performance while reducing the physical aperture of the radar.

The third generation HFSWR system uses a variety of techniques for improving the track accuracy, track repair, and false track elimination. Track maintenance and accuracy is improved using a combination of forward and backward interactive multiple model filtering. A track segmentation algorithm is used to associate track segments such that the displayed track appears as a single track with a unique ID. False tracks are eliminated using adaptive track promotion logic whereby the track initiation criteria are modified according to the density of detections within the local vicinity. The tracker also maintains a track score that is related to the measurement errors of the associated detections. It is only when this track score achieves a set value that the associated track is forwarded to the display. The combination of these techniques effectively eliminates the display of false tracks.

The PASE configuration tracks ocean-going vessels throughout the 200 nautical mile EEZ.

Fusion Processor

Radar is used to track and classify vessels but cannot provide positive identification. For this type of identification, other systems must be utilized.

For example, the requirement for vessels to self-report using the Long Range Identification

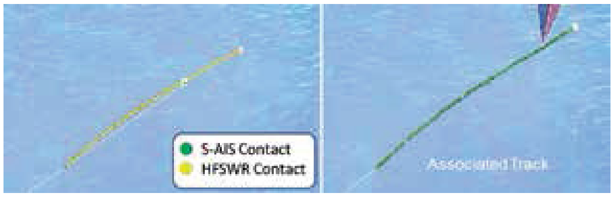


Figure 4: Coincident radar track and space intercepted AIS report are associated into a single, identified track.

Figure 5: Vessel manoeuver recorded by the High Frequency Surface Wave Radar track but missed by space intercepted AIS due to infrequency of reports. (AIS contacts are within the red circles.)

and Tracking (LRIT) system was established in 2006 by the International Maritime Organization (IMO). LRIT regulations apply to ships engaged on international voyages and require that these vessels automatically report their position to their flag administration at least four times per day. Other contracting governments may request information about vessels in which they have a legitimate interest.

Another source of identification is the Automated Identification System (AIS). AIS is an IMO mandated short range, VHF anti-collision system that broadcasts, among other things, non-encrypted host vessel identification and location. Range is limited by design to approximately line-of-sight. Interception of AIS signals using a satellite based receiver allows worldwide coverage throughout the EEZ and international waters.

Space-based interception of AIS broadcasts for global monitoring of maritime traffic is a service offered by a number of commercial companies. Data rates are dependent on the number of satellites in orbit as well as the location of the vessel, density of traffic,

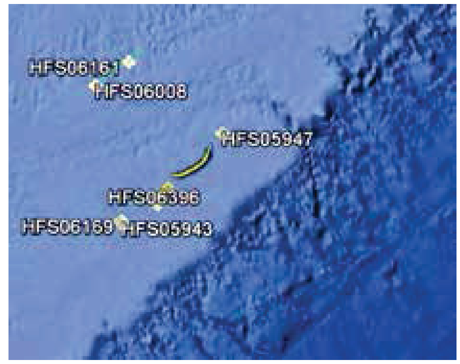


Figure 6: Screen capture of non-cooperative vessels. Vessels tracked by the HFSWR but which are not reporting via AIS.

and contracted service. Update rates are significantly less frequent than that observed by ground-based radar and reports can have a significant latency.

It should be noted that there is currently no IMO requirement for commercial fishing vessels, no matter what their size, to carry AIS. Fishing activity is generally regulated by national law. (Currently, in Canada it is not required that fishing boats carry AIS. However in the United States, by March 1, 2016, all commercial fishing boats 20 metres or more will be required to do so.) Vessel Monitoring Systems (VMS) are generally used in commercial fisheries to allow regulatory organizations to monitor the position, time at a position, course, and speed of fishing vessels. The VMS system is designed to handle commercially sensitive information and typically provides hourly position reports.

In order to automatically assign identification from these sources to a radar track, a track fusion process is used. This fusion process relies on the measurement error ellipses. The process analyzes the error ellipses of both the radar track and identification report in both space and time. When there is a significant overlap, a track to report association, as illustrated in Figure 4, is performed such that the vessel identity is transferred to the radar track.
This track association offers several benefits.

It provides an improvement in track history which is useful within many day to day operational tasks. Figure 5 highlights such possible improvement in track history. As shown, due to a lack in satellite AIS receiver coverage, a large portion of the track, which was undertaking a manoeuvre, was missed (AIS contacts are within the red circles).

The remaining radar tracks (i.e., those that have not been associated to an AIS track) provide useful information to complete the Recognized Maritime Picture by highlighting unknown vessels that are travelling inbound and therefore enable the deployment of additional surveillance assets in area that really matters.

Pro-Active Remote Intelligent Spectrum Management (PRISM)

Operation as a non-primary user with in the congested HF band is ensured by the inclusion of a Pro-active Remote Intelligent Spectrum Management system (PRISMs).

There is no portion of the HF band (3-20 MHz) allocated to radiolocation as a primary service. HFSWRs must operate on a non-interference and non-protected basis with respect to allocated users. The most significant enhancement in the third generation system has been the development of the PRISMs.

The PRISMs is located at the remote radar site and includes a dynamic channel occupancy analyzer with automatic frequency shifting capability. This combination has been developed to minimize the probability of causing interference to primary uses of the HF band and removes the requirement for an operator to physically switch the radar carrier frequency when a primary user is detected. The PRISMs prevents transmission on specific barred channels and bands, and monitors the radar channel occupancy over the entire frequency spectrum in which it can operate, including the radar channel of operation. The PRISMs also includes the capability to automatically switch the radar carrier frequency after a defined period of time and can modify the radar carrier bandwidth to fit within the available spectrum.

If there is no available spectrum, then the third generation system includes the capacity to operate in a "safe-haven" mode within the portion of the Medium Frequency (MF) band.

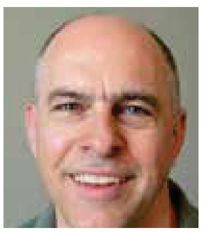
Summary

The PASE program has demonstrated the capabilities of a third generation HFSWR system to operate in the congested HF band without causing interference or other disruption to other "primary" users of the spectrum. The system has been shown to have the ability to shift frequency and adapt its bandwidth of operation to match that available while maintaining performance. The HFSWR system has been shown to produce high quality and high confidence tracks of all vessels within its area of coverage.

The PASE program has also demonstrated the automatic association of radar tracks to self-reports originating from cooperative vessels. This association process allows the tracks associated with cooperative vessels to be identified and those tracks associated with non-cooperative vessels (Figure 6) to be highlighted for further action.

Peter W. Moo received a B.Sc. in mathematics and engineering from Queen's University at Kingston and a MSE and a PhD in electrical engineering systems from the University of Michigan, where he was a National Science Foundation Graduate Fellow. In 1997 he was a visiting researcher at General Electric Corporate Research and Development, Schenectady, New York. From 1998 to 1999 Dr. Moo was a postdoctoral fellow in the Department of Computer Science at the University of Western Ontario. Since 1999, he has been a defence scientist at Defence Research and Development Canada, where he is currently Leader of the Wide Area Surveillance Radar Group in the Radar Sensing and Exploitation Section. His research interests include multiple input multiple output radar, HF surface wave radar, space-time adaptive processing, and radar resource management.

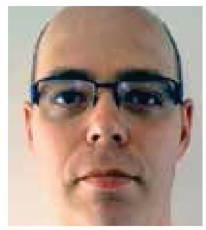
Tony Ponsford graduated with distinction in radar from Plymouth Navy College (UK) in 1977. In 1981 he received B.Sc. in radar and maritime technology, graduating with first class honours, from the University of Wales. In 1991 he was awarded a PhD from the University of Birmingham (UK) in recognition of his pioneering work in High Frequency Surface Wave Radar (HFSWR). For the past 24 years, Dr. Ponsford has held various engineering positions at Raytheon Canada where he is currently a Principal Engineering Fellow, Technical Director, and Manager of R&D. He is an IEEE AESS Distinguished Lecturer on maritime domain awareness. In 2011, he received the IEEE Ottawa Section "Outstanding Engineer Award" for his scientific contributions in the development and advancement of HFSWR and maritime domain awareness.



David DiFilippo received a B.Sc. in engineering physics from Queen's University in 1980, and an S.M. in aeronautics and astronautics from the Massachusetts Institute of Technology in 1984. From 1980-2014, Mr. DiFilippo was a defence scientist at Defence Research and Development Canada, where he led R&D efforts in a number of areas, including motion compensation for airborne synthetic aperture radars, active missile approach warning systems for fighter aircraft, electronic protection for airborne pulsed Doppler radars, High Frequency Surface Wave Radar for over-the-horizon surveillance of ships, and through-wall radar for urban battlespace surveillance. During this period of time, he also represented Canada on several panels for The Technical Cooperation Program and the North Atlantic Treaty Organization involved in collaborative radar research. Mr. DiFilippo is currently a radar consultant.

Rick McKerracher received a B.Sc. in engineering from the University of Saskatchewan in 1984, and a M.Sc. in electrical engineering from Queen's University in 1991. For the past 24 years he has held various positions within engineering at Raytheon Canada Limited where he is currently an Engineering Fellow and System Design Authority for all High Frequency Surface Wave Radar activity. In this role Mr. McKerracher was Raytheon's technical design authority for the PASE HFSWR program. In 2007 he received the Raytheon Excellence in Engineering and Technology award for System Engineering on the FAA/DoD Long Range Radar Service Life Extension Program.

Nathan Kashyap earned a Bachelor of Mathematics in computer science at the University of Waterloo in 2004. He has been a computer scientist at Defence Research and Development Canada-Ottawa (DRDC-O) since September 2005. While working in the Network Sensors and Sensor Fusion group at DRDC, Mr. Kashyap's research has involved software solutions for military C4ISR systems, data fusion algorithms, service oriented architectures, and ISR sensors and models. His current interests include ISR system of systems concept evaluations and software project management.



Yannick Allard received a B.Sc. in physics and a M.Sc. in geography at the University of Sherbrooke. From 2001 to 2008, he has been a member of the research and development department of Lockheed Martin Canada. Since August 2008, Mr. Allard has worked for OODA Technologies, where he is responsible for software project management and development for data analysis and visualization applications. His current interests include big data analytics and information fusion.