An HF Radar Based Integrated Maritime Surveillance System

Levent SEVGI[1,2] & Anthony M. PONSFORD[1]
[1]Raytheon Systems Canada Ltd, Integrated Systems Division, Waterloo, On, N2J 4K6 CANADA
[2]ITU Electronics and Communication Eng. Dept, 80626, Maslak-Istanbul TURKEY

Abstract: In this paper, the physics behind an Integrated Maritime Surveillance system based on HF surface wave radars (HFSWR) is discussed. Due to the complexity of the system a comprehensive understanding of electromagnetic wave (EM) propagation, antenna design, EM wave – ocean wave interaction, target reflectivity, interference sources and their stochastic behaviours is essential. The success of the system depends on powerful processing techniques to extract target information from a complicated real signal environment. Here, these problems are addressed from theoretical as well as practical points of view. Characteristic examples, based on numerical modelling, simulated synthetic data and real operational data, are presented. IMACS/IEEE CSCC'99 Proceedings, Pages: 5801-5806

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1 Introduction

Countries with substantial coastal regions require greatly enhanced systems to monitor activity occurring within their Exclusive Economic Zone (EEZ). Activity will include isolated or grouped, moving and/or anchored surface targets and low-flying aircraft. The targets may be military or commercial, friend or foe, small or large. According to the United Nations Convention on the Law of the Sea (UNCLOS) of 1992, participating countries have extensive rights of exploitation within the EEZ, which extends up to 200 nautical miles (nm) from shore. Beside the economic benefits, a participating country carries responsibilities such as prevention of smuggling, terrorism and piracy; the effective management and protection of off-shore fisheries, search and rescue, vessel traffic services, pollutant control as well as meteorological and oceanographic data collection.

Such a system has been developed and is under evaluation on Canada's East Coast. The Integrated Maritime Surveillance (IMS) system uses a variety of electronic sensors and communication devices to provide a complete overview of activity within the EEZ.

2 Integrated Maritime Surveillance

The questions behind IMS are simple. How could the picture described in the introduction be viewed on a computer monitor in an Operations Control Centre (OCC)? What would the reliability of the picture be and how close would the OCC picture be to the real one? Do all targets in EEZ appear in this picture? Are there virtual targets? Are all targets classified and identified?

Although the answers to all these questions are complex, the key issue in developing the IMS system is simple; understanding the physics behind the concept. In order to bring the IMS system to reality, EM wave-ocean wave interaction, wave propagation characteristics, target reflectivity, undesired interference sources must all be analysed and well understood.

What sensors are available to monitor the EEZ? Traditional land-based microwave radars are limited to line-of-sight, which means a maximum range of 50-60km even with an elevated radar platform. The EEZ can be covered by a microwave radar in a patrol aircraft, but requires three to five aircraft (well above 20,000ft) with many hours on station. Satellites have neither the spatial nor the temporal resolution to provide this surveillance in real-time. Sky wave high frequency (HF) radars can be used for this purpose, but they need large installations, are expensive and detection of surface targets is still limited. The optimum sensor is Surface Wave HF radar.

3 The IMS System and HFSW Radar

The IMS system with HFSWRs as primary sensors consists of four basic segments [1]:

- Radar Surveillance is provided by two long-range HFSWRs.
- Direct Identification is based on Automatic Dependent Surveillance (ADS) systems
- Indirect Identification is obtained from communications, patrol crafts and mandatory reporting procedures, etc.

- Multi-sensor Data fusion automatically correlates tracks derived from HFSWRs with ADS and other information.

The nerve centre of the IMS system is the Operations Control Centre (OCC). Remote operations of the HFSWRs, fusion of radar tracks with the ADS tracks and collection of all other information is handled in OCC.

IMS uses HFSWR as the primary sensors. The requirements for the IMS system are two-fold. First; to detect, track, classify and identify targets on and above the ocean surface out to 200nm. Second; to remotely sense and map surface currents, winds and sea-state. No single sensor can achieve all these objectives. Effective surveillance requires the integration of data from a number of complementary sensors. In IMS, the main sensors are HFSWRs. The radar data as well as the ADS are fused in OCC to obtain a real time picture of activities within the EEZ. Indirect information (e.g., from patrol crafts, communications, mandatory reporting procedures, etc.) is also fused in OCC.

HFSWR removes the line-of-sight limitation of the traditional MW radars. They use vertically polarised surface waves that follow the curvature of the earth. Long ranges can be achieved because of their relatively low attenuation when propagated over the highly conductive ocean surface. With today's technology and signal processing techniques. HFSWR can provide continuous, all-whether 24-hour coverage in regions up to 200nm in range and 120° in azimuth. HFSWR are used not only in detecting and tracking targets but also in supplying meteorological and oceanographic data.

4 Physical Aspects of HFSWR

The IMS system relies on the detection process of HFSWRs supported by the ADS reports [1]. The HFSWRs use the lower end of HF band (typically 3MHz-6MHz) which brings its own characteristic problems;

- the propagation characteristics of surface wave over spherical earth with rough surfaces including possible mixed-paths [4],
- Radar Cross Section (RCS) behaviour of radar targets, where the radar wavelength and the target dimensions are in the same order [5],
- predicting the performance of large transmit and receive antenna arrays located over lossy ground [6]
- finding an unoccupied frequency in an already over-crowded spectrum,
- detecting a target signal embedded in noise, interference and clutter [7].

The more we understand these problems the better the solution; allowing effective detection, tracking and fusion algorithms. These items are discussed below with characteristic illustrations.

4.1 Surface Wave Propagation

HFSWR uses surface wave propagation. The surface wave propagation mechanism over a smooth sea is well understood. The problem is complicated when surface roughness is included. Moreover, multi-mixed path (i.e., land-sea-land transitions) propagation further complicates the problem. Significant effort has been given to the understanding of these propagation effects as summarised in [4]. To fully illustrate the characteristic behaviour of surface waves consider the scenario of two islands, 20km and 50km in length, at distances 50km and 170km away from the radar, respectively. Surface wave path loss along this path at two frequencies is plotted in Fig.1.

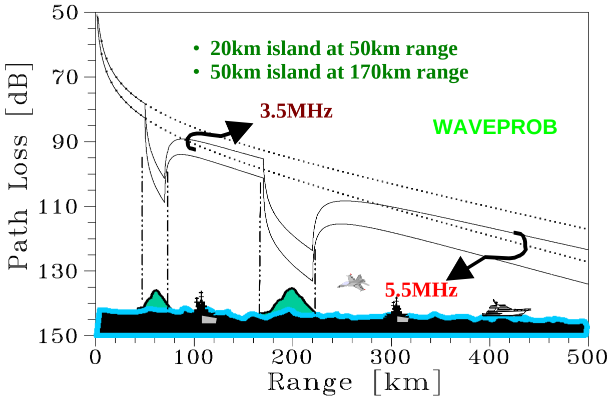

Fig.1: Surface wave path loss versus range

As clearly illustrated in the figure, typical two-way path loss for the HFSWR signal is between 220dB to 260dB. This must be compensated for by the system parameters (i.e., transmit power, antenna and signal processing gains). Also, the sharp increase in path loss over the island and the signal recovery beyond illustrates the ability of the HFSWR to detect targets behind an island [3].

4.2 Radar Cross Section

HFSWR target reflectivity is quite different than microwave radars. While the RCS regime is optical for microwave radars, it is in the resonance region for HFSWRs, where the length of the target is in the order of the radar wavelength. Frequency variation of RCS of a typical surface target is plotted in Fig.2. Here, Finite-Difference Time-Domain (FDTD) and Method of Moment (MoM) techniques are used to model RCS behaviour of a 45m-vessel [5]. A commercial MoM package (NEC2 software [8]) has been used to calculate the array performance. NEC is very effective in modelling complex structures that can be represented by wire-grids. It can be observed that depending on the aspect angle, frequency and size of the target, up to 20dB RCS differences may occur in the RCS.

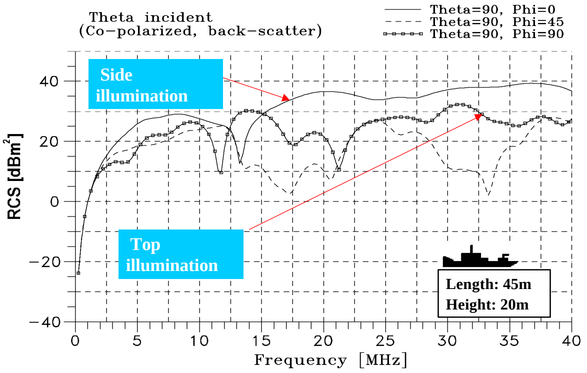

Fig.2: RCS versus frequency of a typical surface target at three different aspect angles.

During the Canadian East Coast IMS trials [1], questions arose concerning the detection of a large oil platform (Hibernia [9]) and nearby manoeuvring tankers [2]. Hibernia is a large construction with 110m underwater depth, 90m above surface height and a diameter of 110m. There is a tall flame tower and two cranes. Large tankers (approx. 100m length) load oil from the platform.

The RCS behaviour of Hibernia itself and its mutual RCS interaction with nearby tankers have been modelled using both FDTD and MoM techniques. The simple MoM model of Hibernia is shown in Fig.3 and its bi-static horizontal RCS behaviour at 3.5MHz is plotted in Fig.4.

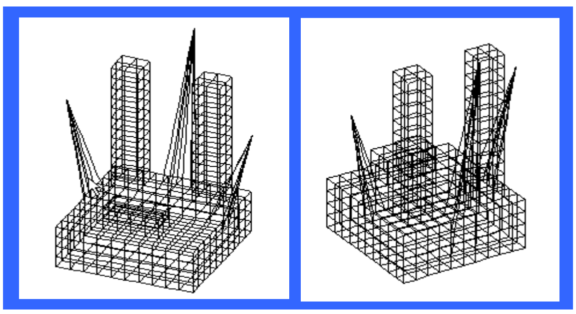

Fig.3: MoM wire-grid model of Hibernia

The plots are normalised to their maximum values. Forward and back scatter maximum RCS values are indicated in top and bottom right corners, respectively. It can be observed that there may be as much as 10dB-backscatter RCS difference depending on the aspect angle.

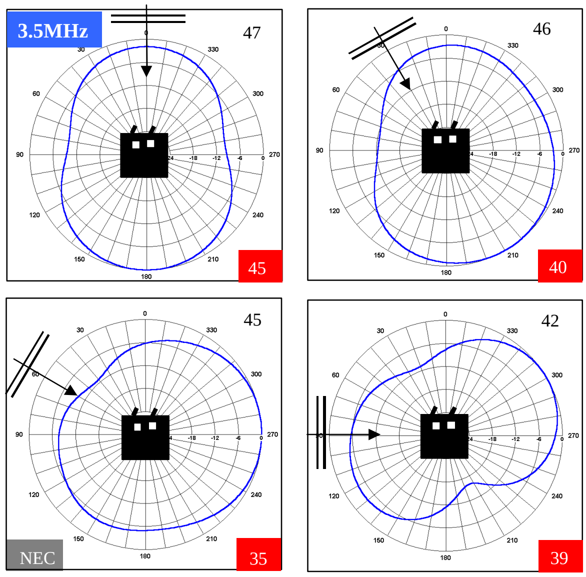

Fig.4: Bi-static RCS behaviour of Hibernia

Another important RCS problem is the mutual interaction of large targets. These may be two nearby surface targets or a surface tanker and Hibernia as mentioned above. To better understand this interaction two test objects were chosen to represent a tanker and Hibernia. These are two metal rectangular prisms having lengths of 20m×100m×20m and 20m×20m×80m in x,y and z, respectively. Again FDTD and MoM techniques are used. An example is given in Fig.5, where FDTD and MoM results are compared.

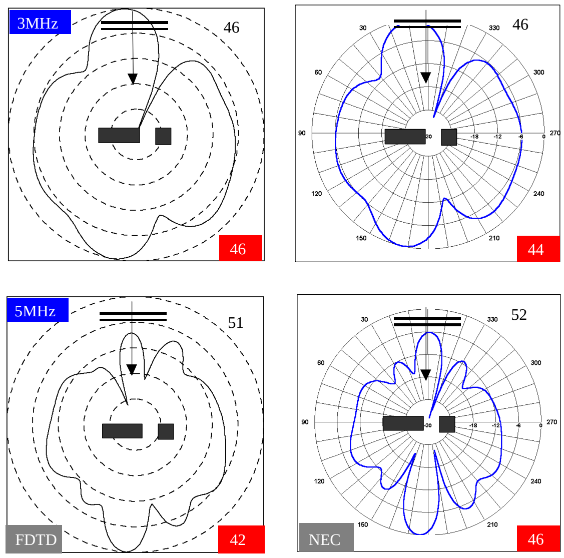

Fig.5: Mutual RCS interaction of Hibernia and oil tanker models

In applying numerical modelling techniques careful consideration must be given to the limitations as well as the advantages of different approaches. For example, it should be known that FDTD gives a full-wave solution, whereas, MoM does not take diffraction into account. Keeping this in mind, the difference between the plots in Fig.5 can be explained.

The discrete models used in RCS simulations are assumed to be in free space. Target reflectivity and mutual interaction is more complicated when modelled over sea surface.

4.3 Antenna Performance

HFSWRs (the sensors in the IMS system) process information obtained from the interaction of electromagnetic waves, ocean waves and targets. Therefore, the antenna systems are critical. The requirement is for a high-gain, transmit antenna that floodlights the observed search area. Digital beam synthesis is used on receive to form multiple narrow beams that covers this search area. The receive array is designed to reduce back-located site noise as well as over-head ionospheric interference, together with broad band performance in both azimuth and gain. A typical four-element *quadlet* array channel designed to meet the mentioned goals is pictured in Fig.6. Since the array is located over lossy ground, good ground screen design is essential to increase the gain and lower the vertical radiated beam.

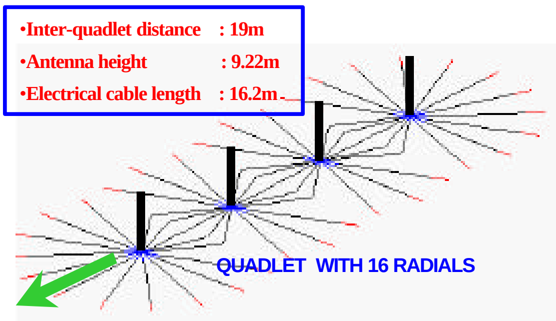

Fig.6: HFSWR receive array channel and a 16-element radial ground screen layout

Vertical radiation patterns of this quadlet channel at different operating frequencies are plotted in Fig.7 and the normalised gain is given in the inset.

Generally, HFSWR uses either 16 or 24-channel arrays to obtain 5°-8° horizontal beam-widths. A 24-channel array has been modelled to illustrate digital beam synthesis. A typical NEC output is given in Fig.8, where a 24-channel array is located over lossy ground without a ground screen.

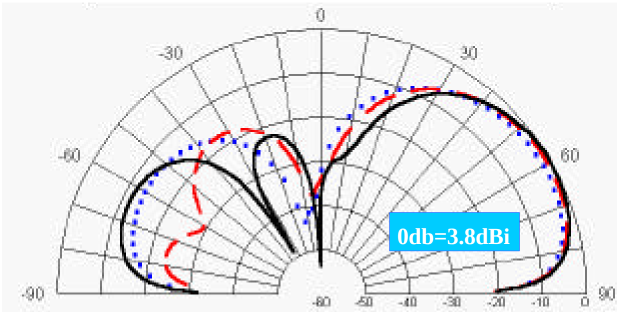

Fig.7: Vertical radiation pattern of the quadlet channel with the 16-element radials (dots: 3.5MHz, dashed: 4.5MHz, solid: 5.5MHz)

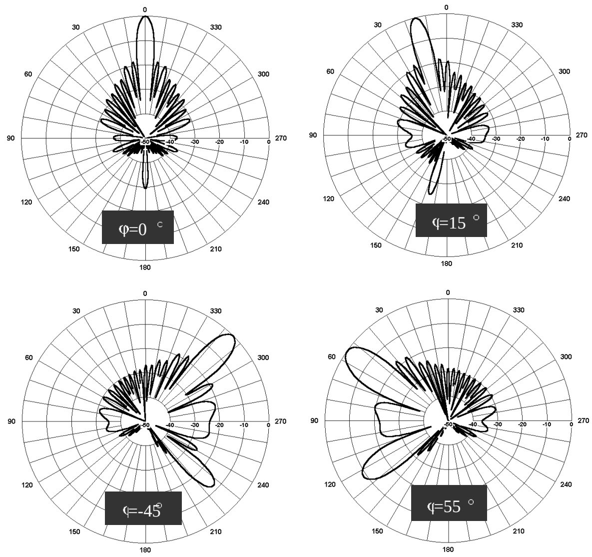

Fig.8: Digital beam synthesis in the HFSWR receive array

4.4 HF Spectrum Occupancy

HFSWR for long range surveillance operates at the lower end of the HF band. This band is crowded by other users. An HF radar must operate without causing interference to, or be interfered with these other users of the HF band. Finding a suitable operating frequency in these frequencies requires continuous spectrum monitoring. A typical measured spectrum is pictured in Fig.9.

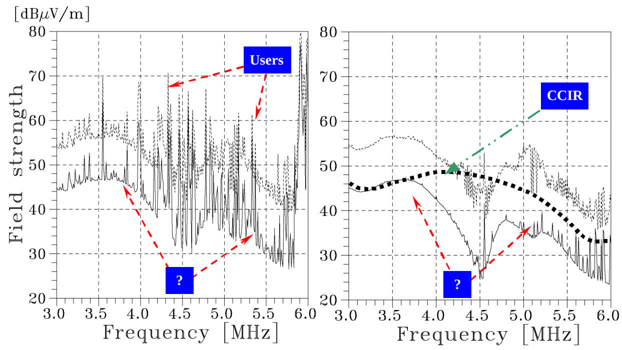

Fig.9: Typical measured HF spectra (a) night-time (b) day-time

As can be seen from the picture, there are narrow band users as well as broad band occupiers, either locally or globally. These need to be explained and accounted for.

4.5 HFSWR Signal Environment

Deterministic and stochastic behaviour of the noise and the sea clutter, possible interference sources and their spatial as well as temporal characteristics have been investigated. This has resulted in the development of techniques to mitigate against their undesired effects.

Maintaining system performance requires powerful and adaptive algorithms at each detection, tracking and identification step. Understanding the signal environment, where the decisions for detection are given, is very important. The detection decision is based on the Constant False Alarm Rate (CFAR) technique in Doppler domain (i.e., target velocity). Stochastic techniques are used to model typical signal environment [3], an example for the Doppler domain is plotted in Fig.10.

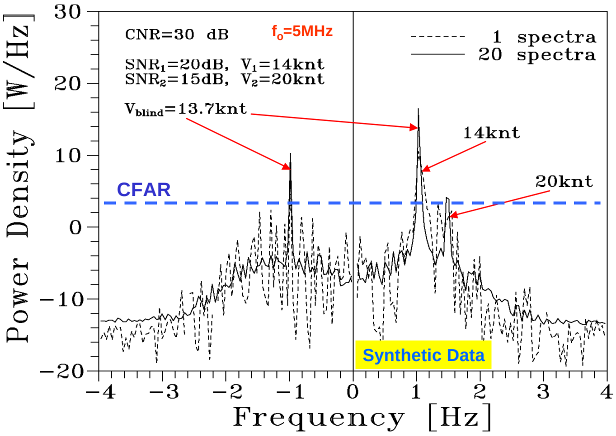

Fig.10: Typical Doppler spectrum of HFSWR

Here, non-coherent Gaussian noise, coherent sea clutter with two dominant Bragg clutter peaks as well as Gaussian clutter power spectrum are used. Two targets with different radial velocities have also been included in the total signal spectrum. The radial velocity of one of the targets falls within the blind velocity zone (i.e., positive first order Bragg zone) and is masked. Changing the radar operating frequency makes the detection possible, because Bragg lines and target's Doppler dependence on the radar frequency are different [3].

The situation in a real signal environment is not as clear as shown in Fig.10. For example, a typical range variation of the radar signal is pictured in Fig.11 in the Doppler domain. Here, range variation of data gathered along the bore-sight is plotted at two Doppler frequencies, 0.0Hz and 0.9Hz respectively. At 0Hz, the two peaks correspond to a strong ionospheric reflection and Hibernia. At 0.9Hz, only the ionospheric interference occurs. In the East Coast IMS system, strong reflections from the F2 layer appear most of the time at ranges between 200km to 250km. E layer reflections are also supported for a few hours in the afternoons [2] resulting in strong interferences at ranges 100km to 120km. Because of all these interference effects it is difficult to select a fixed CFAR threshold. Adaptive CFAR techniques are required in the detection algorithms, since clutter, noise and interference levels may differ from time to time as well as from cell to cell.

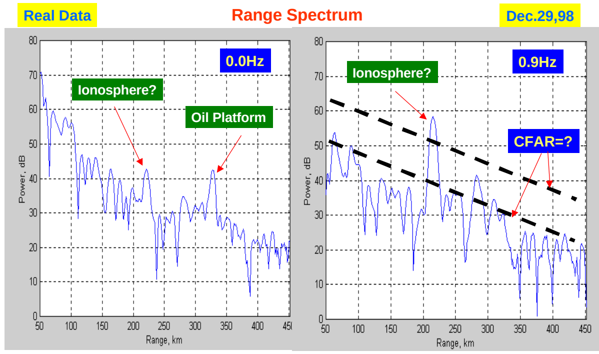

Fig.11: Range variation of HFSWR data

The last example in this section belongs to a typical system output for surface targets. Fig.12 illustrates a typical display from one of the radars in the Canadian East Coast system.

When the two HFSWR outputs are fused together with the ADS reports and all other gathered information, a clearer picture of all surface and air activities appears on screens at the OCC.

5 Conclusion

This paper describes the physics behind an HF radar based Integrated Maritime Surveillance system. The IMS provides countries and governments with the capability to collect and analyse information from a number of different sources and sensors.

The non-linear, in-homogeneous, time-varying nature of the ionosphere and sea surface makes the detection problem extremely complex. Significant effort has been given in stochastic modelling and application of new techniques, such as neural network and chaos theories, to overcome these problems [10].

The IMS system discussed here may be extended to include different sensors beside HFSWR, such as

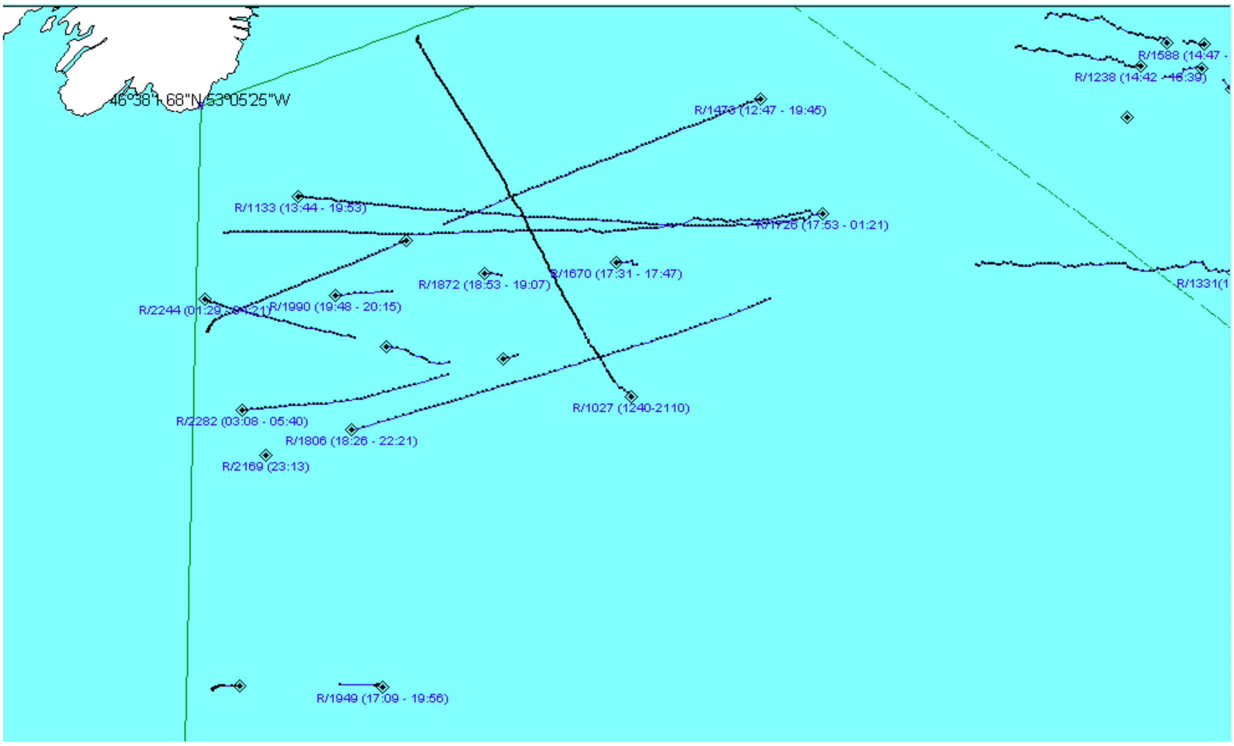

Fig.12: A typical HFSWR display

microwave radars, satellite imagery, infrared and/or thermal cameras, etc. Some of these sensors may be fix-located and others may be mobile (located on moving vehicles such as trucks or aircraft). Each sensor has its unique physical character. The challenge is to fuse these qualitatively and quantitatively different information sets in such a way as to obtain a comprehensive picture of activities in the covered area [11-12].

Acknowledgement

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