Low-cost radar surveillance of inland waterways for homeland security applications[1]

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Abstract- **Low-cost radar systems have been developed for homeland security missions. These detect and track small maneuvering craft in the water. The systems consist of a conventional marine radar, a capture card that digitizes the radar signals, and a computer that processes them. We have an experimental system that can monitor western Lake Ontario. It runs in real time, with operator controls, and can store captured radar video. The achieved detection and tracking is demonstrated with recorded datasets. The combination of lower thresholds plus a sophisticated multi-target tracker gives excellent performance.**

I. INTRODUCTION

Low-cost radar surveillance systems have been developed for international border security and critical infrastructure protection missions. The systems are potentially significant aids for countering terrorism and smuggling operations. The radar systems provide all-weather, day-night, wide-area situational awareness with automated detection, localization and warnings of threats.

Homeland terrorist attacks occur infrequently at unpredictable locations. To be effective, security must be widely deployed for long periods of time. Although sophisticated military systems could provide such protection, their size and cost precludes them from being employed on small, agile police and border security vessels. The systems described here are small, inexpensive and readily available.

II. MISSIONS

The Great Lakes St. Lawrence Seaway System is shown in Fig. 1(a). It not only is the border between Canada and the United States, but also encompasses cities, ports, manufacturing and power plants, bridges, shipping lanes and countless pleasure craft. There are two challenging problems with this large open border:

- Protecting the assets and populations from terrorists.
- Preventing the illegal crossing of the border.

All of the following potential homeland security missions require the detection and tracking of small maneuvering craft:

- Protection of a sensitive site (e.g. a power plant) from attack via the water.
- Interception of smugglers or illegal entrants crossing a water border.
- Protection of ships, either in harbors or in transit.

Fig. 1(b), (c) and (d) illustrate some of these missions.

In addition to these security missions, underwater archeological sites (e.g. shipwrecks) can also be protected from scavenging divers using the low-cost radar solutions proposed herein. The Great Lakes and inland rivers such as the Hudson contain numerous underwater sites having need of such protection.

III. CONCEPT

Our system concept is based on using small, low-cost, commercial off-the-shelf (COTS) marine radars. These can be mounted either on fixed or transportable land-based platforms, or on mobile vessels or vehicles. To the radar, we add:

- Capability for digitizing the return signal.
- Low-threshold target detection processing.
- High-performance multi-target tracking software.
- Scenario-dependent threat recognition and alert response.

All of these added features run in real time on a conventional personal computer (PC).

Small non-cooperative targets have low (and fluctuating) radar cross-sections (RCS), and compete with lake clutter. Recreational marine radars have low small-target detection sensitivity. The presence of many friendly targets further complicates matters. Because of these issues, surveillance operators need to observe many consecutive radar scans in order to properly assess the situation at hand.

To mitigate these problems, we have modified the signal processing after digitizing. We set lower detection thresholds (with higher false alarm rates) than conventional processors, and are thus able to detect smaller craft. We then depend on a sophisticated tracking algorithm to extract real targets and reduce the false alarms to a manageable level.

At any instant in time, the track histories provide situational awareness of recent activity. Any suspicious behavior (e.g. perimeter crossings) is recognized, and communicated to authorities. Systems can be connected to a network to distribute information to remote users. Plots and tracks can be archived for longer-term investigations. We customize the target detection, tracking and threat recognition algorithms for specific threats and scenarios.

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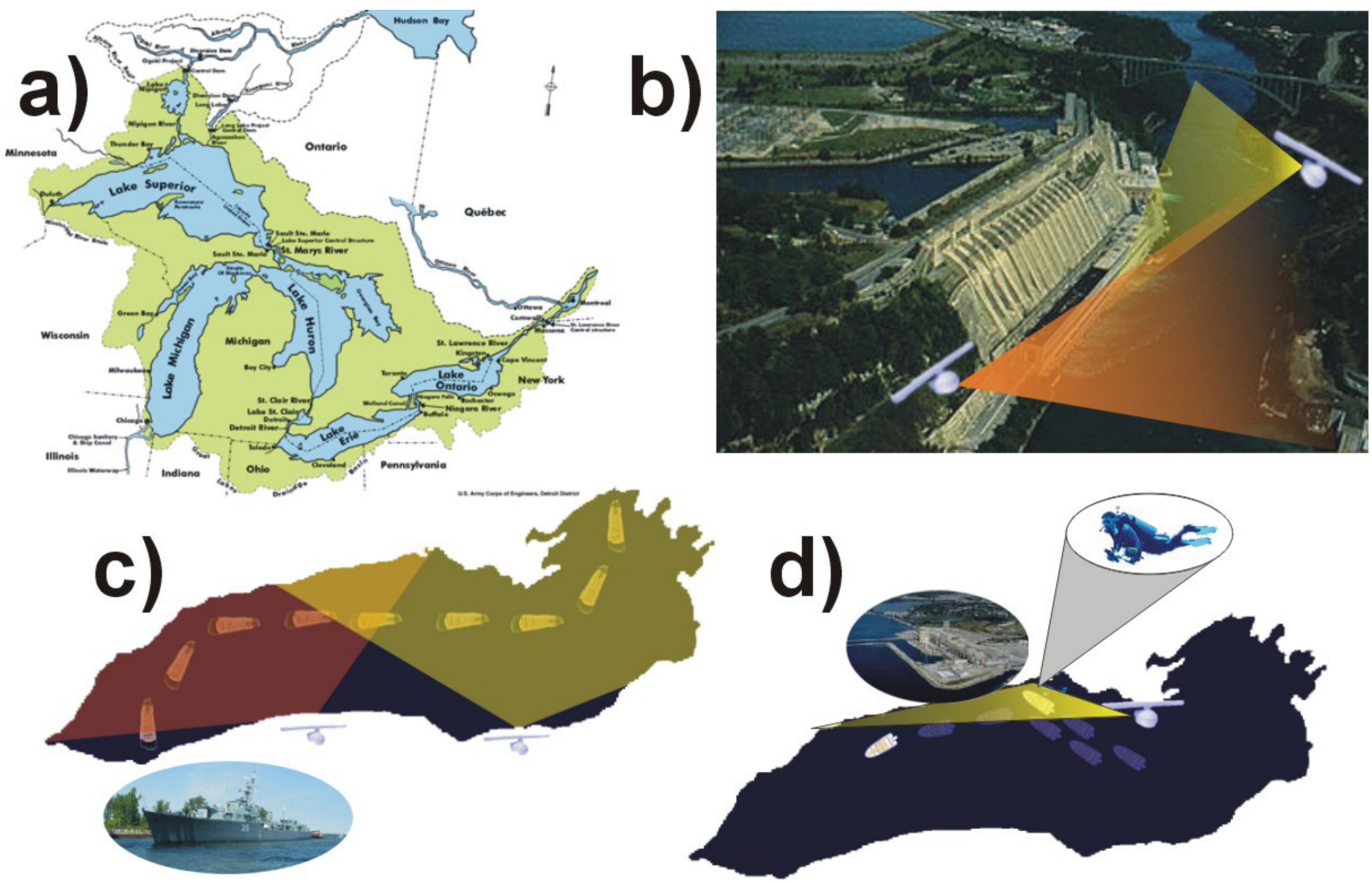

Fig. 1. Great Lakes St. Lawrence Seaway and Homeland Security Missions

A single system is suitable for monitoring a geographically close group of sites or even a fairly large waterway. Multiple systems can be networked together to provide integrated coverage of extended routes or border regions. Mobile systems are appropriate for monitoring regions needing more intermittent coverage.

IV. System

A block diagram of the surveillance system is shown in Fig. 2. Characteristics of each block are as follows.

A typical marine *radar* is noncoherent, transmits at X-band with pulse repetition frequency (PRF) between 1 and 2 kHz and with pulse width between 0.1 and 1 µs. It has a 2 m antenna, rotates at 24 RPM, and has up to 165 km range.

The *capture card* collects radar video samples from each pulse, at sampling rates and over range intervals appropriate for the operational mode. The card is mounted on the PCI bus of the *computer*, which is a high-end (but COTS) Pentium©4 with conventional video card, memory, monitor, etc.

The *detector* (plot-extractor) and multi-target *tracker* are implemented in real-time software. The detector declares the presence and location of targets on each radar scan. The tracker sorts the time-series of detections (plots) into either tracks (confirmed targets with estimated dynamics) or false alarms.

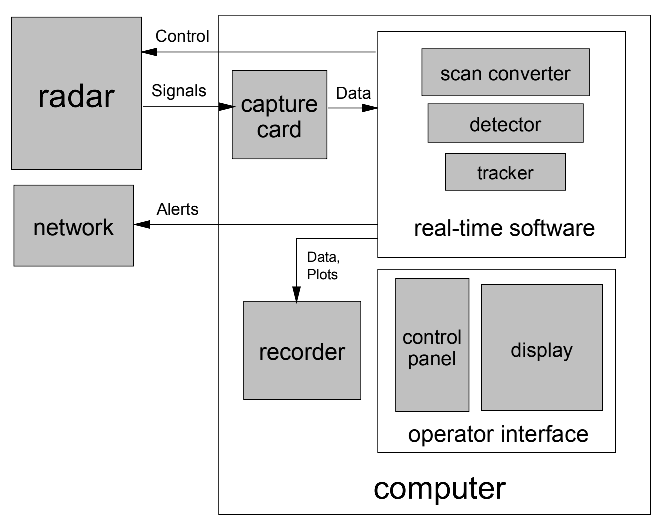

Fig. 2. Surveillance system block diagram

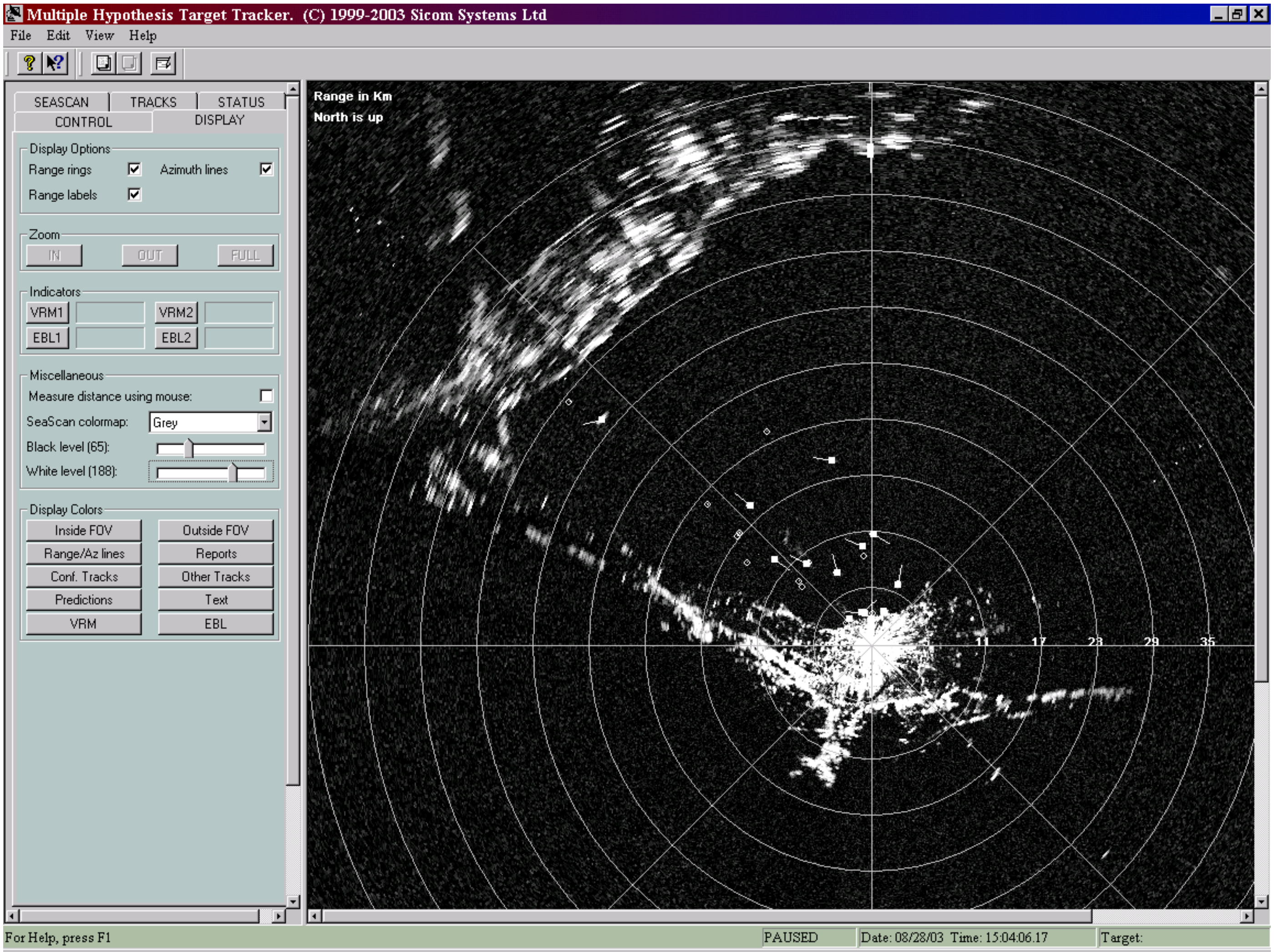

Fig. 3. PPI display and control panel

The *scan-converted* radar video signal is presented on a plan-position indicator (PPI) *display* (see Fig. 3). Tracks and plots are overlaid; plots appear as circles and tracks as filled squares with tails. Note the *operator controls* in the window panel to the left of the PPI image.

With an automated monitoring system, security perimeters are defined. The software determines when targets approach and cross these perimeters, and issues appropriate *alert responses* (e.g. an audible alarm, or a transmitted message). Thus the surveillance can be 24-hours, without a full-time operator.

The *recorder* stores the received radar video samples onto disk or tape. Track and plot histories can also be recorded; this is a more compact and convenient alternative. The files (in either format) can subsequently be played back through any computer having the surveillance software; it is not necessary that it be connected to a radar. This feature is useful for off-line analysis, investigations, evidence, etc.

V. SOFTWARE

The main surveillance application controls the capture card and alerts, and runs the real-time processing, display, and graphical user interface. It runs on a generic PC using the Windows© operating system, and is written in C++.

The software is composed of six major components: control, scan conversion, recording, plot-extraction, tracking and display. The control software allows the operator to set parameters, handles the transfer of data from the capture card, and co-ordinates the overall flow of execution. Recording can be enabled without compromising real-time surveillance operation.

The scan conversion software transforms the received radar video samples into the raster PPI image. The operator can select the options of scan-to-scan and/or pulse-to-pulse integration, presenting a less noisy image. The 1K-by-1K 8-bit image data are updated in real-time.

The plot-extraction software detects targets in the water using a CFAR algorithm with operator-selectable parameters (reference cell window size, threshold, etc.). Regions can be designated where targets are to be searched within, thus allowing the tracker to concentrate its resources.

The multi-target tracker is designed to manage many dynamic fluctuating targets with a high false-alarm rate. It employs a multiple-hypothesis-testing (MHT) plot-to-track association algorithm. MHT easily handles many false alarms and missed detections in a dense target environment. The tracker uses an interacting-multiple-models (IMM) tracking filter to deal with varying target dynamics (i.e. maneuvers). The operator can control parameters for these algorithms, in order to optimize for specific surveillance scenarios.

The display software manages the image data, the plots and the tracks. It combines them to form a real-time situational awareness picture tailored to the operator's preferences. Items under control include display range, markers, brightness, contrast, colors, track labels, track and plot histories, covariances, track info, etc.

VI. Experimental System, Collected Datasets and Results

We have set up an experimental surveillance system in St. Catharines, Ontario (Fig. 4). The radar antenna is mounted on an inland 24-meter tower. It can monitor the western half of Lake Ontario. The radar is connected to a PC (with capture card and surveillance software) in a building below the tower. The system runs in real time, monitoring operator-selectable regions (e.g. above the shipwrecks) on the lake. At the same time, we can store captured radar video (covering the entire scene) in data files for subsequent playback. This feature allows experimentation with different detection and tracking algorithms and parameters, and the optimizing of settings for given scenarios. It also provides authentic demonstrations of system operation at meetings and conferences.

We have captured a series of data files that recorded the last voyage of the HMCS Haida (a destroyer which served in both WW2 and the Korean war). It was towed from Port Weller to Hamilton Harbour across western Lake Ontario in August 2003. Along with the ship itself, many other small craft (and airborne targets) have been captured by the radar and recorded. The datasets span over 6 hours. The Haida and some of its accompanying vessels were also recorded on video camera, in order to provide ground truth. We also have many more files from other experimental trials. These have differing levels of ship activity, clutter, weather, propagation, interference, etc.

The following figures demonstrate the achieved detection and tracking performance with some of these datasets. Fig. 8 shows the tracks and plots (with plot-history of 30 scans) of the Haida, our ASI Surveyor vessel following it, a speedboat that happened by, and two undetermined boats. Range rings are separated by 2 km, and the range to the closer ring is 10 km. Figs. 5 to 7 show pictures of the known vessels. In Fig. 5, the Haida is shown. The ASI Surveyor, a 25' aluminum boat is shown in Fig. 6. The 25' fiberglass speedboat is shown in Fig. 7. The detection threshold for this example is set low enough that the smaller boats can be tracked. Thus the false alarm rate is relatively high.

If the threshold is set too high, we cannot track the smaller craft. Fig. 9 shows tracks and plots with a higher threshold. Such a threshold is typical of a conventional detection setting that tries to minimize false alarms, in order to not overload the operator or an automated tracker. There are now fewer false alarms, but poorer situational awareness results. This emphasizes the key point of our system concept: having low detection thresholds followed by high-performance tracking is the best design approach.

Our surveillance application has many research and development tools built in. These include track history and track covariance displays. Fig. 10 shows the plot and track history (length 120 scans) for the Haida and a small airplane that flew around it, a few minutes before the scene shown in Figs. 8 and 9. Note that the tracker was able to follow the maneuvering plane. Fig. 11 shows tracks with their covariance ellipses, for three targets in the scene at further (17 km) ranges.

Fig. 4. Sicom Experimental Surveillance System

Fig.5. HMCS Haida (track 7 and 75 in Fig.8 and 9, respectively)

Fig. 6. 25’ ASI Aluminum Boat (track 100 in Fig.8)

Fig. 7. 25’ Fiberglass Speed Boat (track 2213 in Fig.8)

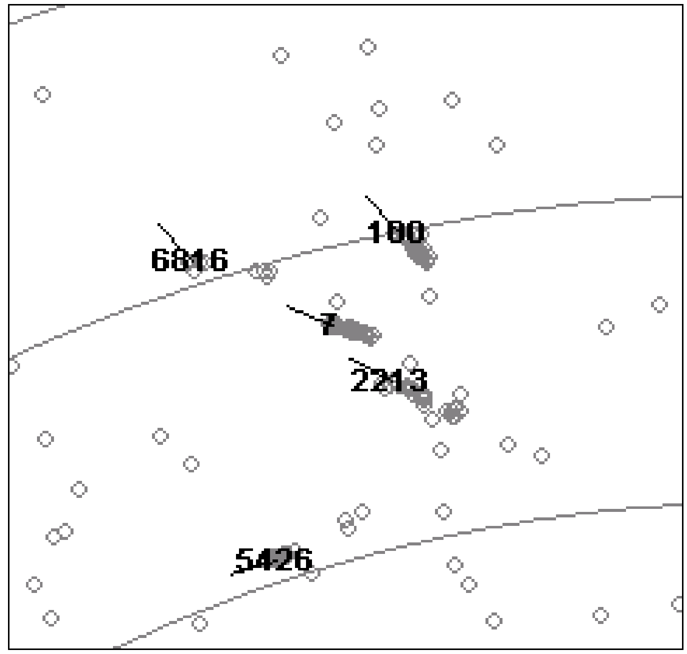

Fig. 8. Plots (circles) and tracks (indicated by a track symbol and ID number) for the vessels

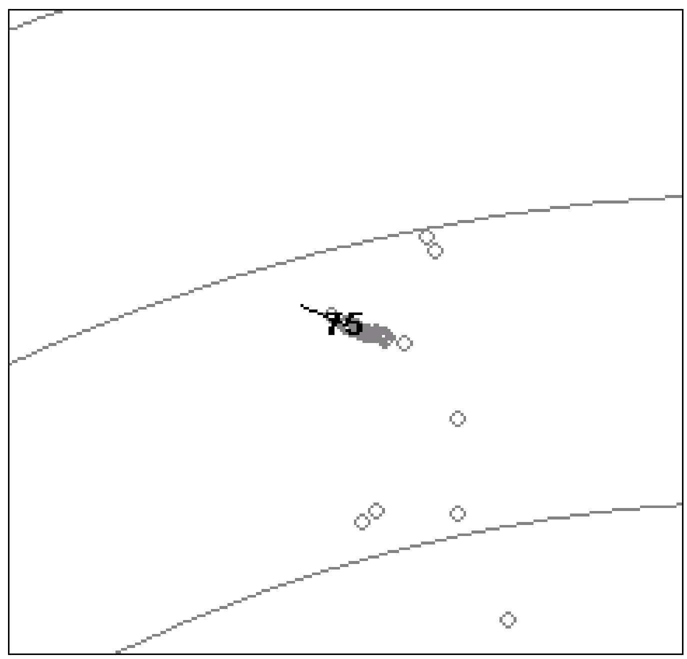

Fig. 9. Plots and Haida track with lower false-alarm rate

Being able to record raw radar data, and then replay that data in real-time through the application using different detection and tracking algorithms or settings (as was done to generate Figs. 8 and 9) has proven to be an invaluable feature of this system. This not only allows efficient optimization to be carried out for a particular application or mission, it also supports post-analysis of situations alerted by either the system or other intelligence.

VII. SUMMARY

Affordable surveillance systems have been developed for homeland security applications. These can assist in the protection of borders and infrastructure. The systems are able to detect intruders on inland waterways. They are inexpensive enough to be fielded by border patrollers or police and law enforcement agencies.

A major challenge of continuous, wide-area surveillance is the high cost of human effort to monitor sensor displays. The track data produced by this system contains detailed (but compact) long-term behavior data on individual targets. For any given scenario, these data can be automatically tested for suspicious activity, in order to generate alerts to security personnel. Because the information is detailed, alerts can signify complex behavior, such as collision predictions, origins and destinations of vessels, perimeter approaches or violations, etc. The low-bandwidth track and alert information can be easily sent to central locations, providing economical, effective monitoring.

The novel system concept described herein is to digitize the signals from a low-cost, COTS marine radar, detect small targets with a low threshold, and use a high-performance tracking algorithm to remove unwanted false alarms. This permits the detection and tracking of smaller craft than competing systems.

ACKNOWLEDGEMENTS

Sicom wishes to acknowledge the assistance of Parks Canada and ASI Group in carrying out the Haida experimental trial. Parks Canada, the owner of the Haida, helped Sicom coordinate its radar surveillance trial with the scheduling of Haida's voyage. ASI Group, a St. Catharines, Ontario-based Aquatics Engineering firm, provided direct logistics support in the form of ground truthing and communications. Furthermore, the radar equipment was operated from their facility, which provided ideal coverage of the Haida's voyage. Their contribution is greatly appreciated.

Credit is also given for a few of the images used herein. Fig. 1(a) is courtesy of the U.S. Army Corps of Engineers Detroit District, Fig. 1(b) and 1(d) include photographs which are courtesy of Ontario Power Generation Corporation, and Fig. 6 is courtesy of ASI Group.

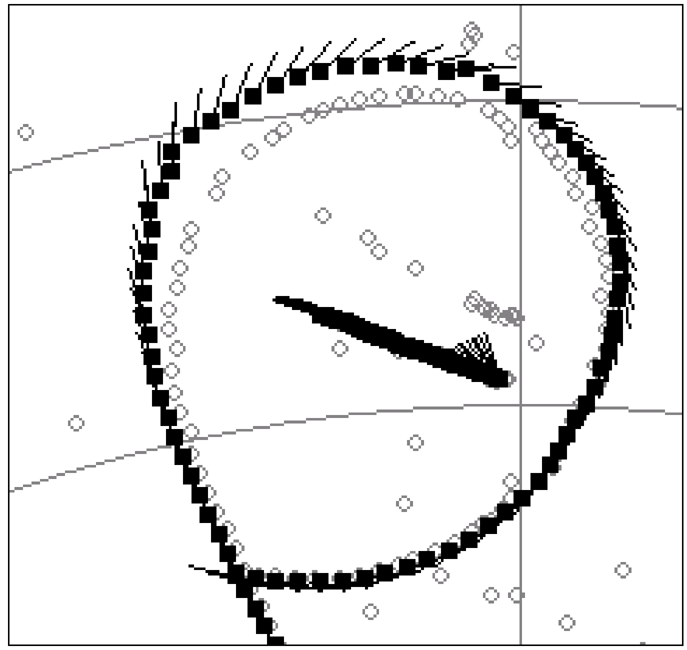

Fig. 10. Track History, airborne target and Haida

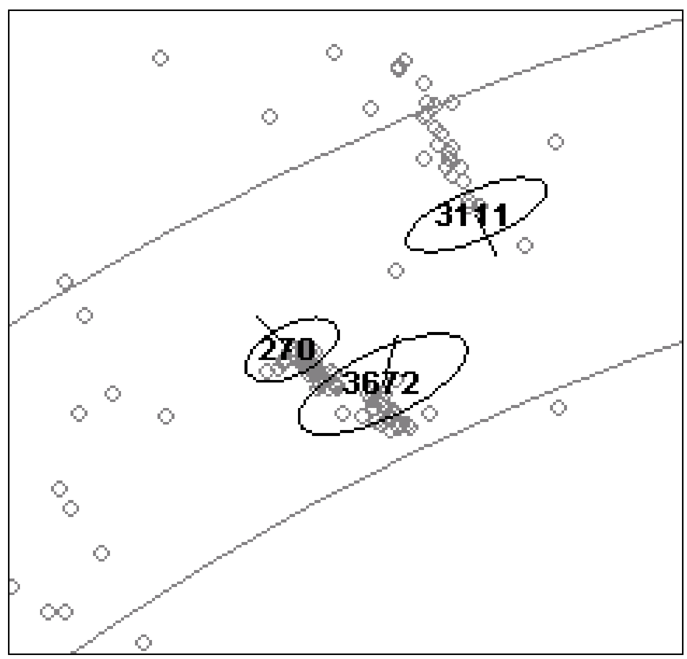

Fig. 11. Track covariances indicated by ellipses