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Development and Field Testing of a Neural Network

Ship Predictor System (SPS)

Prepared for

Transportation Development Centre, Transport Canada (TDC)
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Atlantic Canada Opportunities Agency (ACOA)

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CORETEC Incorporated

January 1999

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16. Abstract

The main objective of this project was to develop and field test an intelligent system that will accurately predict the position, speed and heading of large ships to improve the safety and efficiency of ship operations, particularly in rivers and confined waterways.

CORETEC has successfully developed a ship predictor system (SPS), an advanced system that uses ship control and environmental data to provide accurate prediction of the vessel's trajectory and display this prediction on the ship's electronic chart and display information system (ECDIS). The predictive component of the SPS is based on an innovative adaptive model that integrates a mathematical ship manoeuvring model with a neural network module to produce an accurate, versatile and affordable predictor.

The validity and accuracy of the adaptive model's predictions were verified during the development stage using hundreds of data sets. The real-time operations and accuracy were evaluated onboard the Canada Steamship Lines vessel MV *Nanticoke*.

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16. Résumé

L'objectif principal de ce projet était de développer et mettre à l'essai en service réel une méthode intelligente capable de prédire avec précision la position, la vitesse et le cap de grands navires, afin d'accroître la sûreté et l'efficience du transport maritime, notamment dans des voies navigables restreintes.

Le système prédictif d'aide au pilotage (SPS, pour *Ship Predictor System*) mis au point par CORETEC est une méthode d'avant-garde qui, à partir des ordres donnés aux navires et des paramètres environnementaux, estime avec précision la trajectoire du navire et affiche ces prédictions à l'écran du système de visualisation de cartes électroniques et d'information (SVCEI) du bord. La composante prédictive du SPS s'appuie sur un modèle adaptatif novateur qui conjugue un modèle mathématique des manoeuvres du navire et un module neuronal, pour produire un prédicteur précis, souple et abordable.

Pendant le développement du système, les chercheurs ont vérifié l'exactitude des prédictions générées par le modèle adaptatif à l'aide de centaines d'ensembles de données. Un essai à bord du navire NM *Nanticoke* de la Canada Steamship Lines a permis d'évaluer le fonctionnement temps-réel du système et la justesse de ses prédictions.

17. Mots clés
Prédicteur d'aide au pilotage, prédiction de la trajectoire d'un navire, aides à la navigation maritime, système de visualisation de cartes électroniques et d'information (SVCEI), pilote automatique, maintien de la trajectoire, intelligence artificielle (IA), réseau neuronal

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André Taschereau, Transportation Development Centre (TDC), Transport Canada, Montreal

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The project team gratefully acknowledges Canada Steamship Lines (CSL) Limited and Captain John D. Pace and Kirk Jones for their interest in and support of the SPS project and for making the *Nanticoke* available for the SPS field testing and data collection program. The support and advice provided by Captain Pace have been invaluable to this project. Special thanks to Captain Tim Poste and his crew for their co-operation and assistance during the field test program.

We would also like to thank the Institute for Marine Dynamics for providing CCMC with technical expertise and data acquisition equipment.

The success of the data collection program would not have been possible without the excellent work and dedication of the engineers and technical staff of CCMC who participated in the planning and execution of the field testing and data collection program.

EXECUTIVE SUMMARY

Manoeuvring large ships in rivers and confined waterways is a challenging and potentially hazardous task. Because ships are slow to respond to changes in the surrounding environment and their own rudder movements, a change in the ship's course to avoid an accident may not occur in time. Statistics show that ship accidents involving striking and grounding outnumber all other types of ship accidents in Canada. Additionally, the delay in ships' response to rudder changes causes unnecessary rudder movements that reduce speed and decrease fuel efficiency.

The main objective of the SPS project was to develop and field test a ship predictor system that would help improve the safety and operational efficiency of ships travelling in restricted waters by providing an accurate prediction of a ship's motion.

To meet the requirements and challenges of the project, CORETEC assembled a highly qualified team of experts. In addition to CORETEC's experts in hydrodynamics and numerical modelling, the team included experts in artificial intelligence (AI) and neural network (NN) technology from Applied AI Systems, Inc., and market research experts from EnterPride Professional Development Corporation. A team from CCMC carried out the data collection program and provided instrumentation for the field test.

The SPS was developed in three phases:

Phase I - Strategic planning of prototype development
Phase II - Development of working prototype
Phase III - Field testing of the prototype

At the completion of each phase CORETEC submitted to TDC and CCMC an interim report documenting the findings of that phase. This report provides an overall summary of the project findings with only non-proprietary information included.

The following sections present a summary of the key findings of the project.

The SPS is made up of three main components: data acquisition, prediction and display. Figure 1 presents a schematic of the SPS components.

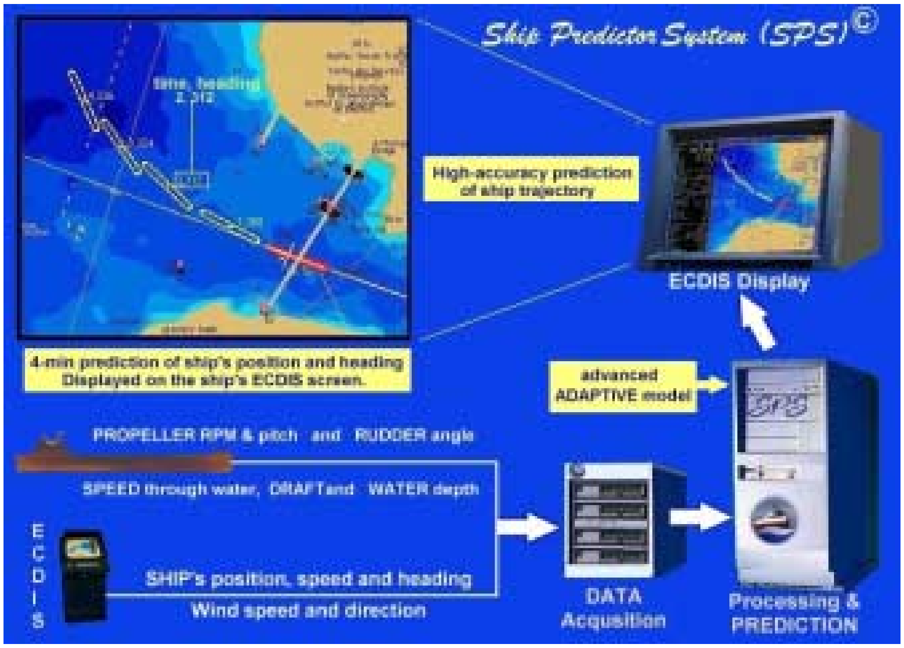

Figure 1: SPS Component Schematic

DATA ACQUISITION

The SPS uses the following parameters as input:

- Vessel’s position and speed
- Heading from ship’s gyro
- Wind speed and direction
- Vessel’s speed through water from speed log
- Propeller’s pitch and shaft RPM
- Helm indicator (rudder angle indicator)
- Water depth from depth sounder

The data acquisition system measures the values of the above parameters from the indicated ship devices and then processes this data to provide the required input for the predictive model. Data pertaining to the ship’s speed and heading are further processed to provide additional input data in the form of surge, sway and yaw rates of the ship.

PREDICTION

The predictive component of the SPS is based on an innovative adaptive model designed to provide real-time, high-precision prediction of the vessel’s position and heading. The predictor combines a state-of-the-art mathematical ship-manoeuvring model with a neural network module. This hybrid design eliminated the need for an expensive model test or additional field trials to determine a ship's hydrodynamic parameters.

The neural network module (NNM) provides the predictor with the ability to fine-tune its parameters, in real time, and to account for factors that cannot be modelled mathematically. These factors include variations in ship hydrodynamics due to changes in ambient conditions such as topography and water depth. The result is an adaptive model that combines accuracy, versatility and affordability.

The prediction period and update interval are configurable. The SPS can provide two-minute predictions of ship position, speed and heading - updated every second - and monitors the accuracy of its prediction by comparing the current ship position with the predicted position in hind-cast mode.

DISPLAY

SPS prediction (ship position, velocity and heading) is displayed as a layer on a ship's electronic chart display and information system (ECDIS). Output from the SPS is broadcast as NMEA strings similar to those of the differential global positioning system (DGPS), thereby making the SPS compatible with existing ECDIS systems. Figure 2 presents a sample display of SPS prediction.

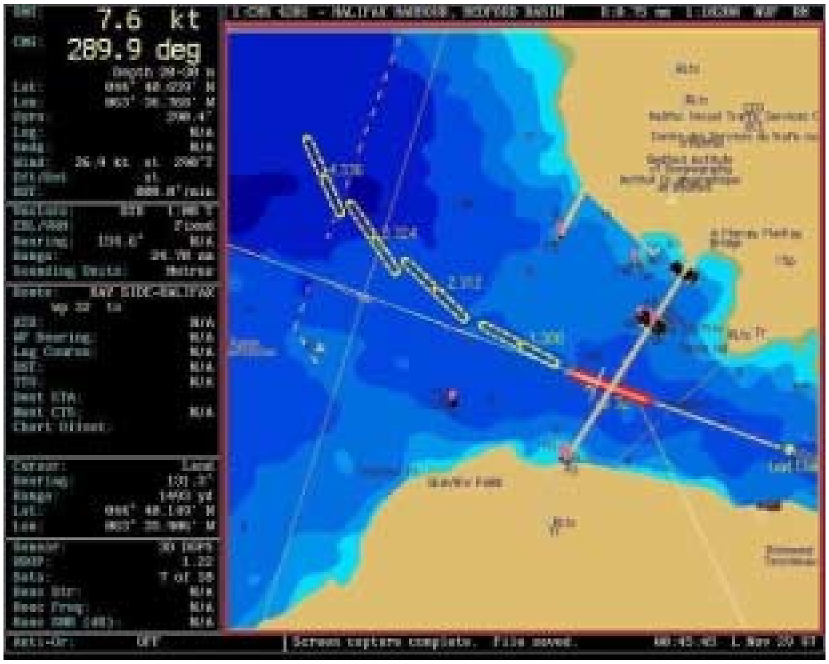

Figure 2: Sample Display of SPS Prediction

ACCURACY

According to the established performance specifications, the measure of SPS accuracy should be based on offset error in a one-minute prediction. The results of the onboard trials indicate that the offset error in the one-minute prediction was consistently less than 20 m and less than 10 m 93% of the time. The two-minute prediction error was less than 20 m 90% of the time. This confirms the accuracy of the SPS prediction.

SOMMAIRE

Il est difficile et potentiellement dangereux de manoeuvrer de grands navires dans des voies navigables restreintes. Comme les navires réagissent lentement aux changements des conditions environnementales et aux mouvements du gouvernail, il peut arriver qu'un ordre de changement de route soit donné trop tard pour empêcher un accident. Ainsi, les statistiques révèlent que les talonnages et les échouements surpassent en nombre tous les autres types d'accidents maritimes au Canada. De plus, le délai de réponse du navire aux changements d'angle de barre entraîne des mouvements de gouvernail inutiles, qui ralentissent le navire et nuisent à son efficacité énergétique.

L'objectif principal de ce projet était de développer et mettre à l'essai en mer un système prédictif d'aide au pilotage (SPS, pour *Ship Predictor System*) capable d'améliorer la sûreté et l'efficience du transport maritime dans des cours d'eau restreints, en prédisant de façon précise les mouvements d'un navire.

Pour être à la hauteur des défis posés par ce projet, CORETEC a réuni une équipe d'éminents spécialistes. C'est ainsi que des experts de l'intelligence artificielle (IA) et des réseaux neuronaux d'Applied AI Systems Inc. et des spécialistes en études de marché de EnterPride Professional Development Corporation se sont joints au personnel spécialisé en hydrodynamique et en modélisation numérique de CORETEC. Une équipe du Centre canadien des communications maritimes (CCCM) s'est chargée du programme de saisie de données et de la fourniture de l'instrumentation nécessaire aux essais en mer.

Le SPS a été développé en trois phases :

Phase I - Planification stratégique du développement d'un prototype
Phase II - Développement d'un prototype fonctionnel
Phase III - Essai en mer du prototype

Ce rapport donne un aperçu des résultats de ces travaux. Aucune information protégée par des droits de propriété intellectuelle n'est divulguée.

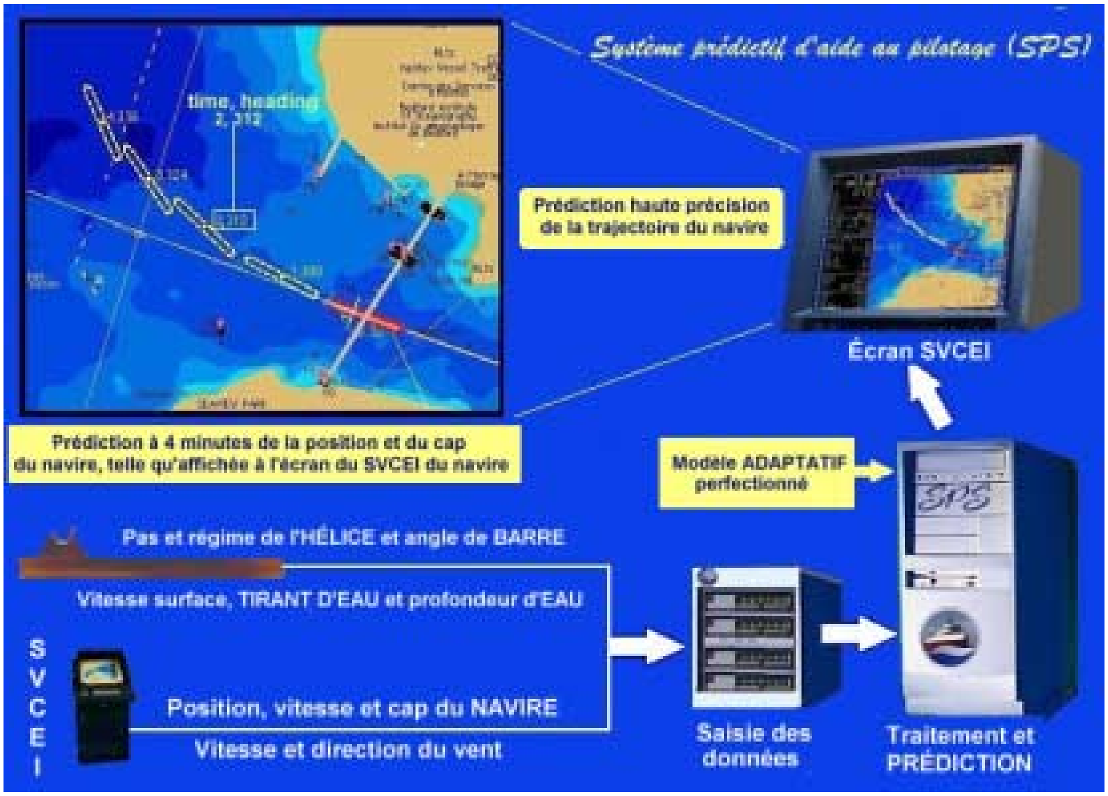

Figure 1 : Représentation schématique des composantes du SPS

Le SPS est constitué de trois composantes, responsables des fonctions suivantes : saisie des données, prédiction et affichage. La figure 1 donne une représentation schématique de ces composantes.

SAISIE DES DONNÉES

Le SPS utilise en entrée les paramètres suivants :

- la position et la vitesse du navire;
- le cap, selon le gyrocompas du navire;
- la vitesse et la direction du vent;
- la vitesse surface du navire, selon le loch;
- le pas et le régime de l'hélice (tr/min.);
- l'angle de barre, selon l'axiomètre;
- la profondeur d'eau, selon l'échosondeur.

Le module de saisie des données reçoit des divers appareils de mesure du navire les valeurs des paramètres ci-dessus et les traite de façon à fournir au prédicteur toute l'information utile. Les données qui ont trait à la vitesse et au cap du navire subissent un traitement complémentaire, au terme duquel des données d'entrée supplémentaires sont générées, concernant le cavalement, l'embardée et le lacet du navire.

PRÉDICTION

La composante prédictive du SPS se fonde sur un modèle adaptatif novateur conçu pour fournir des prédictions temps-réel exactes de la position et du cap du navire. Le prédicteur conjugue un tout récent modèle mathématique de la manoeuvre des navires et un module neuronal. Ce concept hybride a permis d'éliminer les coûteuses étapes d'essai sur maquette ou en mer normalement nécessaires pour définir les caractéristiques hydrodynamiques du navire.

Le module neuronal permet au prédicteur de revoir et préciser en temps réel ses paramètres, en prenant en compte des facteurs impossibles à modéliser mathématiquement. Parmi ces facteurs, mentionnons la variation des caractéristiques hydrodynamiques du navire sous l'effet des changements de conditions ambiantes (p. ex., topographie ou profondeur d'eau). Le résultat est un modèle adaptatif qui allie précision, souplesse et faible coût.

Il revient à l'utilisateur de déterminer le temps de prédiction et la fréquence des mises à jour. Le SPS peut prédire à deux minutes près la position, la vitesse et le cap du navire, faire des mises à jour toutes les secondes, et contrôler la valeur de ses prédictions en comparant rétrospectivement la position véritable du navire avec sa position prédite.

AFFICHAGE

Les prédictions du SPS (position, vitesse et cap du navire) sont affichées en superposition sur l'écran du système de visualisation de cartes électroniques et d'information (SVECI) du navire. Les sorties SPS ressemblent aux chaînes NMEA en sortie du Système de positionnement global différentiel, ce qui garantit la compatibilité du SPS avec les SVECI existants. La figure 2 donne un exemple d'affichage de prédiction SPS.

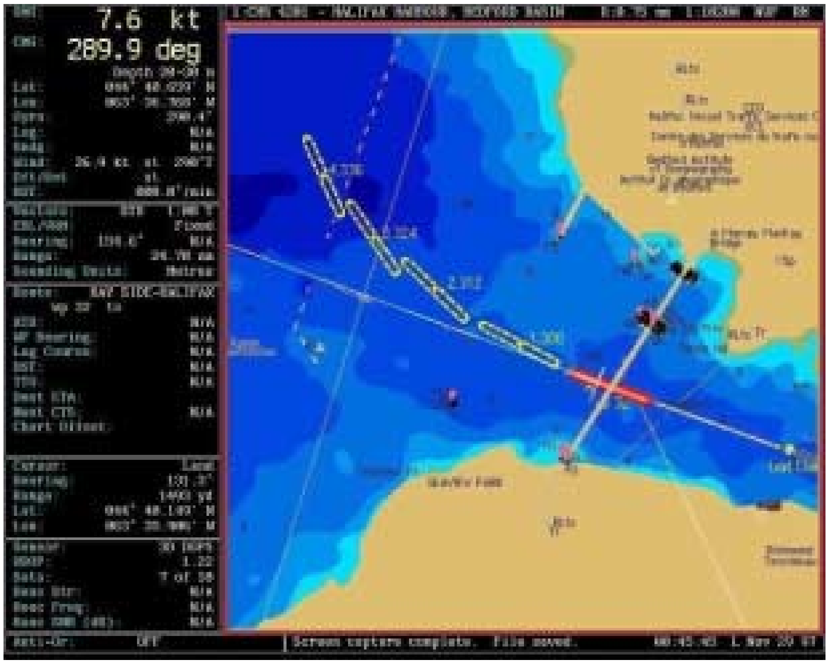

Figure 2 : Exemple d’affichage de prédiction SPS.

PRÉCISION

Selon les spécifications de performances établies, le degré de précision du SPS doit être déterminé d’après l’écart entre les valeurs réelles des paramètres et les prédictions datant d’une minute. Les résultats des essais en mer révèlent, pour un temps de prédiction d’une minute, une erreur de moins de 20 mètres dans tous les cas, et une erreur inférieure à 10 mètres dans 93 % des cas. Pour un temps de prédiction de deux minutes, l’erreur s’est révélée inférieure à 20 mètres dans 90 % des cas. Ces données confirment la précision des prédictions SPS.

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LIST OF FIGURES

1. INTRODUCTION

The ship predictor system (SPS) is an innovative marine navigational aid that will provide a significant contribution to shipping safety and higher operating efficiency. The SPS will accomplish this by providing the ship's officers with real-time information pertaining to the future behaviour of the vessel. This information would be useful to the ship’s master when manoeuvring in difficult situations, thereby helping to avoid collisions with other ships or harbour structures, particularly in restricted waters. The SPS could also be used, in real time or in simulation mode, to verify the effects of certain actions before they are taken. Ultimately, advanced versions of the SPS will serve as a key component of a track-keeping autopilot.

Realizing the marine industry’s need for an accurate, reliable system to predict the future motion of a ship as an aid to a ship’s Captain operating in difficult situations such as restricted waters and in poor visibility, the Canadian Centre for Marine Communications (CCMC) and the Transportation Development Centre (TDC) initiated the SPS project.

The main objective of the project was to develop and field test an SPS that will help improve the safety and operational efficiency of ships travelling in restricted waters by providing accurate prediction of ship motion.

The SPS was developed in three phases:

Phase I:	Strategic planning of prototype development
Phase II:	Development of working prototype
Phase III:	Field-testing of the SPS prototype

At the completion of each phase a detailed interim report documenting the findings of that phase was submitted. Due to the commercial nature of this project, all of the interim reports are confidential. This report provides an overall summary of the project findings and includes only non-proprietary information. A summary of the key findings of each phase is presented in the following sections followed by concluding remarks and recommendations.

2. PHASE I – MARKET STUDY AND STRATEGIC PLANNING

The following tasks were carried out in Phase I:

- Preparation of a work plan
- Review of current technology
- Identification of target ship
- Identification of computer hardware for prototype
- Preparation of market feasibility study and development of a strategic plan

A detailed work plan was prepared and submitted for approval at the beginning of this phase. The following sections present a brief summary of the tasks and activities concluded during this phase.

2.1 Review of Current Technology

An extensive review of relevant literature was carried out to determine the capabilities of existing ship prediction devices, hydrodynamic models for ship manoeuvring and neural networks for ship manoeuvre and control. The review also examined the various ship navigation aids that may influence the design of the SPSs such as the electronic charts and display systems (ECDIS) and the global positioning system (GPS).

The review of the related technologies indicated that initiatives to develop various forms of ship prediction devices have been reported in the United States, Japan, Germany, the United Kingdom and Italy. The most advanced of these devices is a shipboard piloting expert system developed in the United States. Very little information is available on the other efforts and there is virtually no awareness of such initiatives by users, ship industry groups and associations.

The review of hydrodynamic models for ship manoeuvring indicated that these models are based on three coupled, non-linear, ordinary differential equations describing the surge, sway and yaw motions. The hydrodynamic coefficients in these equations are usually determined from model and/or full-scale tests that are quite costly to obtain. Analysis of adaptive modeling techniques indicates that the hydrodynamic forces and coefficients in the adaptive model can best be determined using a hybrid approach that combines the use of a linear mathematical model with a parametric identification system to estimate the non-linear forces. The use of a neural network was determined to be a promising technique for parametric identification system.

The review of current research into the use of neural networks (NN) indicated that NN are excellent candidates for ship prediction and control due to their ability to process many input variables at once. The same features that make neural networks good predictors may also allow them to adopt non-linear control strategies or to mimic the subtleties of a human operator.

2.2 Market Feasibility and Strategic Planning Study

A market feasibility and strategic planning study was carried out to investigate the market opportunity for the SPS and the *true* needs of potential SPS users. In addition to personal and telephone interviews, a market survey was prepared and issued to ship owners associations and companies, research institutes and government agencies.

The following is a summary of key findings:

- The study indicated that a sufficient market exists for the SPS to warrant completion of the prototype development.

- Tankers and passenger carrying vessels (cruise ships, high-speed ferries) are believed to represent the most attractive vertical markets.

- The primary motivation for potential users were safety and cost saving. The primary obstacles were a perception of high cost, skepticism regarding system performance, and a general resistance to the technological revolution sweeping the industry.

- Innovators and skeptics alike agreed on certain features that an ideal ship predictor system must provide. The top three features are high level of accuracy, ease of use and integration with a ship's electronic chart display information system (ECDIS).

2.3 Identification of Target Ship

Two candidate vessels, one from Canada Steamship Lines (CSL) and the other from Marine Atlantic were identified. Both vessels operate in extremely confined and shallow-water conditions, making them excellent candidates for testing the SPS.

The CSL ship is the Great Lakes bulk carrier MV *Nanticoke*, a single-rudder, single-screw, vessel equipped with the latest version of the electronic chart and precise integrated navigation system (ECPINS). The selection of the ship by CSL was based on equipment, availability and the type of operations involving several scenarios in which the SPS can be particularly useful.

Marine Atlantic identified the type of ship that can be used for testing the SPS as a twin-rudder, twin-screw Ro/Ro passenger ship. A list of physical characteristics, navigational aids and propulsion equipment of the MV *Caribou* were provided by Marine Atlantic as sample characteristics of ships in the identified type.

2.4 Hardware and Software Requirements

Identification of computer hardware for the SPS prototype was the subject of detailed discussions among the team members involved in the development of the prototype models and the interface between the SPS and the ship's hardware. The preferred system was found to be a stand-alone industrial grade computer system based on two MS-DOS compatible CPUs with real-time clock cards. The first CPU would be responsible for running the SPS predictive models (the hydrodynamic model and/or the neural networks). The second machine would handle I/O operation with all hardware devices in the SPS (the serial, analogue and digital equipment), providing time-based correction to the asynchronous data, and sending and receiving data with the main CPU.

A review of available operating systems was carried out to select one capable of handling the inter-process communications between the two CPUs, operate in real time and perform with complete functionality on a PC-based system. Two multitasking kernel-based operating systems, OS-9000 and QNX, were identified as candidate systems. Both are real-time operating systems capable of running on a PC as well as other platforms. Both systems are also modular, allowing easy upgrading. The two systems can run DOS applications and have the necessary tools for creating graphical user interfaces.

2.5 Documentation

An interim report entitled, *PHASE I - Market Study and Strategic Planning*, was submitted at the end of phase I. The report is made up of three volumes:

Volume I: Interim report
Volume II: Market feasibility study and strategic plan
Volume III: Review of current neural networks technology

3. PHASE II – DEVELOPMENT OF WORKING PROTOTYPE

The main objective of this phase was to develop and factory-test a working prototype of an advanced ship predictor. To ensure that at least one *working* predictor would be completed, three types of ship prediction models were investigated simultaneously. The first is a mathematical model based on conventional ship manoeuvring equations; the second is a conventional adaptive model; and the third is based on neural network technology.

CORETEC investigated the mathematical model and conventional adaptive model concepts while the neural network model was investigated by Applied AI Systems. The result was the development of two predictors: an innovative adaptive model and a neural network model.

3.1 Adaptive Model

3.1.1 Input and Output of the Adaptive Model

The adaptive model utilizes the following input parameters:

- Vessel mass, length, beam and draft
- Vessel position (longitude and latitude)
- Vessel speed (surge and sway)
- Vessel's heading and yaw rate
- Wind speed and wind direction
- Water currents velocity
- Shaft thrust
- Rudder angle
- Water depth

The adaptive model provides the following output at an interval of 1 second for the duration of the prediction period:

- Vessel position
- Vessel's heading
- Surge velocity
- Sway velocity
- Yaw rate

3.1.2 Adaptive Model Development

Manoeuvring equations reflecting ships' motions are composed of a large number of linear and non-linear terms. Some of the hydrodynamic coefficients can be calculated (mathematical coefficients) while the others (empirical coefficients) must be determined either from physical model tests or from field trials of a particular ship. Both model tests and field trials involve significant expenses and have inherent limitations including scale effects in model testing and an inability to cover all possible varying conditions in one field trial.

To overcome the above limitations in determining the hydrodynamic forces and coefficients, an innovative adaptive model that combines mathematical modelling with neural network technology was proposed. The mathematical model would incorporate the "mathematical coefficient" terms while the neural network module would utilise non-linear functions to account for the remaining terms. Preliminary evaluation of the proposed concept indicated that the adaptive model would run efficiently enough, both in the parametric identification (learning) mode and the prediction mode and is capable of providing prediction with high accuracy. This established the adaptive model as the basis of the hydrodynamic predictor due to the adaptive model's superiority to any conventional (mathematical) model in many ways.

The next step was to develop the adaptive model and evaluate its convergence using hundreds of data sets of simulated manoeuvres. The non-linear functions, identified by the neural network component of the adaptive model, did not converge to the required level of accuracy. To overcome this problem, a new technique had to be developed to facilitate the conversion of these functions during the parametric identification (learning) mode.

The difficulty of conversion seemed to be caused by the fact that the non-linear functions are embedded into the coupled differential equations of motion. Extensive analyses of the non-linear functions and their characteristics resulted in the development of a methodology to isolate the non-linear functions and to identify them separately. This technique was successful and resulted in fast conversion of the non-linear functions during the neural network learning process.

The neural network module provides the adaptive predictor with a unique ability to fine-tune its parameters, in real time, in order to optimize its predictions and maintain a high level of accuracy. The fine-tuning of model parameters accounts for variations in ship hydrodynamics due to changes in ambient conditions such as topography and water depth and also updates a built-in function that accounts for the effects of other unknown factors such as water currents. This enables the SPS to predict with unprecedented accuracy while substantially reducing its cost (due to the elimination of the need for expensive model testing and field trials).

Vol. I of the interim report for this phase presents a detailed description of the adaptive model covering the following topics:

- Determination of Hydrodynamic Coefficients
- Development of the Parametric Identification Component of the Adaptive Model
- Equations of Motion
- Formulas for the Determination of Linear Hydrodynamic Coefficients
- Determination of Non-linear Functions
- Mathematical Model for Wind Forces

This information is not presented herein because of its proprietary nature.

3.1.3 Factory Testing of the Adaptive Model

The adaptive model was first tested using hundreds of data sets of simulated ship manoeuvres that were specified by the project team. CCMC generated 876 sets of simulation data at the Centre for Marine Simulation (CMS) for the *Québécois*, a bulk carrier, and the *Dronning Ingrid*, a ferry.

The results indicated that the system identification technique was capable of deducing the non-linear functions with a very high degree of accuracy. The predictions of the adaptive model were found to be almost identical to the simulated manoeuvres, which provided a strong indication of success for the adaptive model concept.

The second stage of factory testing involved the evaluation of the adaptive model using field data. Extensive research of existing field data failed to produce any complete data sets that could be used in the factory testing of the adaptive model. Consequently, it was determined that a field program was required to collect appropriate data for factory testing. The field program was implemented and data were collected on board the CSL *Nanticoke* as it traveled from Sept Isles, Quebec to Thunder Bay, Ontario, in September of 1995. Figure 3.1 presents the route of the *Nanticoke* during the data collection program.

Figure 3.1: Route of the Nanticoke – Data Collection Program

While the field program was a success, the data derived from it had unexpected limitations. The time stamp of the records was erratic and the chain used to measure the shaft RPM was loose. Also, due to time limitations, not all standard manoeuvres required to appropriately train the neural network were carried out. To overcome these limitations, special data processing and refinements of the adaptive model were required. This processing and refinement of data proved effective and the training of the neural network was completed quickly, converging within approximately 10,000 iterations.

A quantitative assessment of the accuracy of model prediction was carried out using 9,255 predicted trajectories with each trajectory lasting two minutes. Analysis of the prediction error indicated that the offset error was within one ship beam (23 m) in almost 75 percent of the cases. The results, presented in Figures 3.2 and 3.3, provided strong evidence of the validity and accuracy of the adaptive model's predictions and that the adaptive model is ready for real-time field testing.

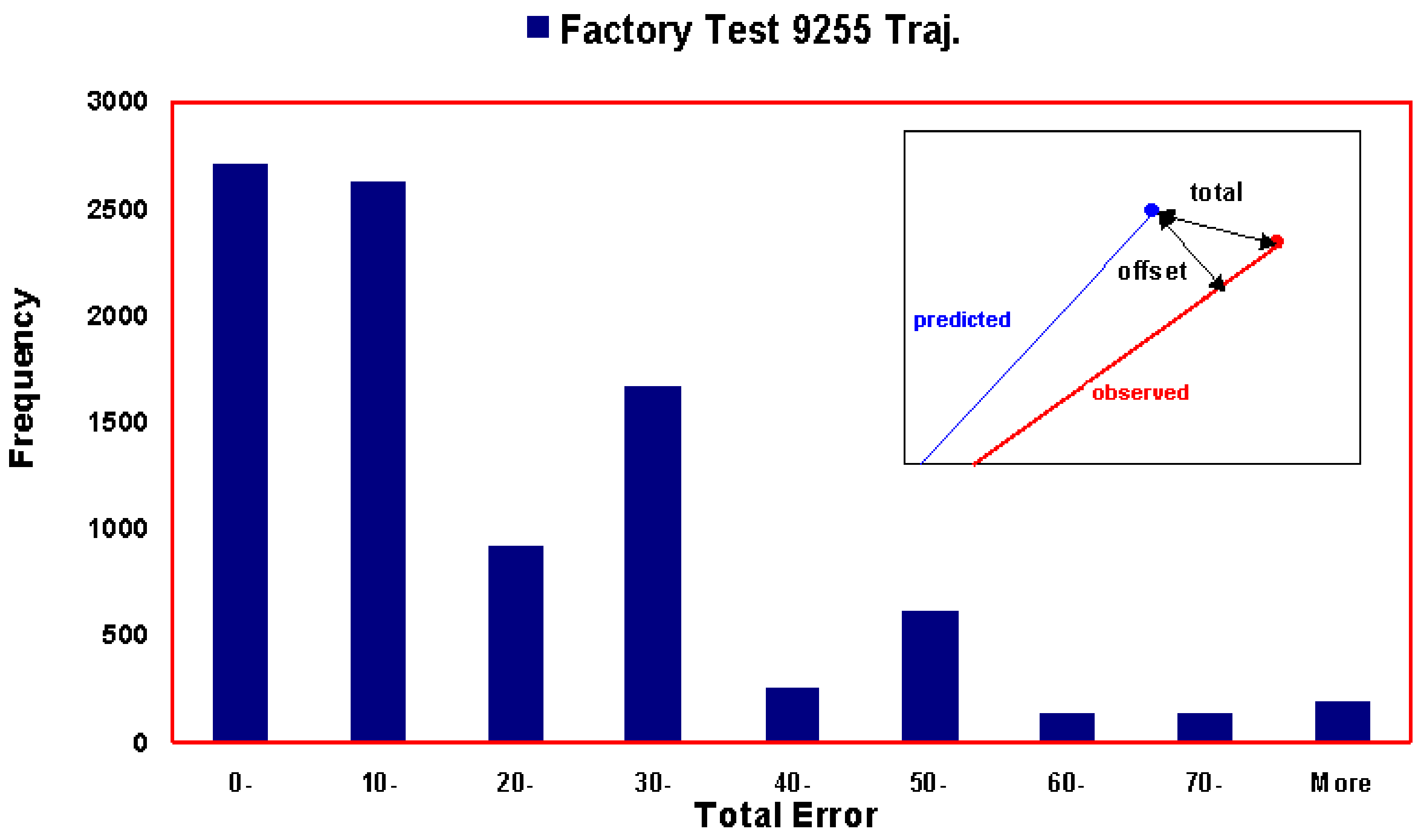

Figure 3.2: Total Prediction Error for the *Nanticoke*

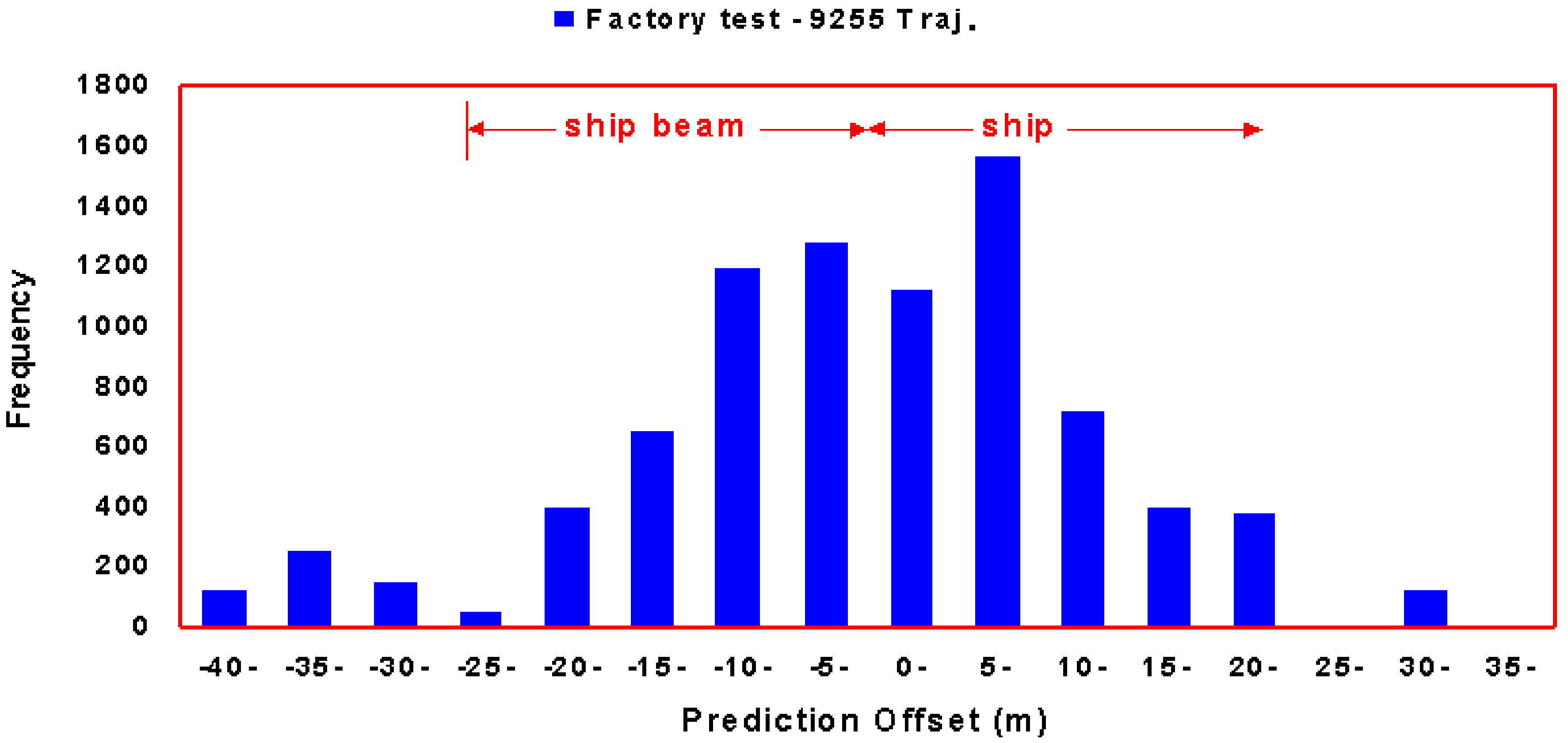

Figure 3.3: Offset Error for the *Nanticoke* Predictions

3.2 Development and Evaluation of the Neural Network Model

3.2.1 Input and Output of the Neural Network Model

The neural network model input parameters are:

- wind speed and wind direction
- current speed and current direction
- water depth
- cosine of the yaw and sine of the yaw
- yaw rate
- velocity over ground in x-direction and in y-direction
- acceleration in x-direction and acceleration in y-direction
- yaw acceleration
- propeller speed (RPM)
- rudder angle
- an integer offset

The output consists of two nodes designating the predicted position in two-dimensional space.

3.2.2 Network Topology: The Elman Net

After considerable study and experimentation, the Applied AI (AAI) team concluded that a feedforward network that explicitly factored in the past with the present offered the best avenue for capturing the underlying dynamics and kinematics represented in the simulated data. Recirculating networks reflect the long lag times in the movement of large ships. Therefore, the Elman architecture, in which the entire hidden layer of a feedforward network is returned into the input layer during backproprogated training, was adopted.

In order to predict an entire trajectory with the required accuracy, AAI created a twelve-network system. Each of the networks specialized in a ten-second-prediction segment. The data to develop and test the neural networks came from extensive simulations specified by AAI and provided by 876 sets of simulation data specified by CCMC.

Learning proceeded by repeatedly showing the network all the training data until the predicted output converged, within a pre-set error margin, to the correct simulated output. The repetitive process was on the order of a million iterations.

One of the important limitations of the training was the fact that one neural network was unable to learn the dynamics of ship movement in different depths. Unable to discern whether this problem is due to an inadequate amount of training data or to a very high sensitivity of the hydrodynamic equations to jumps in the value of the depth, AAI confined all of its training and testing to depths of 10 m.

3.2.3 Factory Testing of the Neural Network Model

The neural network model was first evaluated using the simulation data. The neural network average and RMS errors could be kept under 2 m, and the maximum error never exceeded 10 m on any portion of the two minute predicted trajectory. A closer look at the network's ability to generalize as a function of the number of training iterations reveals that optimal results occurred somewhere between 2,000,000 and 3,000,000 training iterations. Of course there are important limitations in the above results since the network can only predict in those dynamic regimes that it was trained on. The above results were based on limiting the network to the non-transition portions of the manoeuvre. When efforts were made to teach the network both the transition and non-transition portions of the zig-zag manoeuvre, the maximum error climbed closer to the maximum permissible, though the average errors still remained relatively low. Clearly, far more training is needed to induce the network to "understand" the dynamics of transition. The issue here is not one of the network's capabilities, but rather the need for a sufficiently rich training set that incorporates many examples of transitions.

The neural network model was then evaluated using the data collected on board the CSL *Nanticoke* during the data collection program. However, it was found that there was only a limited amount of data that was of use in training and testing the neural networks. The neural network predictor used for the real data case resembled the one used for the simulated case. Efforts to train these networks to predict within the accuracy required were not completely successful. Test results on the network trained for 3,500,000 iterations indicated that the maximum errors were completely unacceptable.

Better results were obtained when the topology of the Elman network was changed to accentuate further the principle of incorporating memory into the network. Rather than input data from T_0 to predict position at time T_0 +10, the input nodes were added to include data from T_0-20, T_0-40, and T_0-60. As a result, each of the twelve Elman networks contain forty-four inputs to the network (11 input parameters times 4 time steps). The test results for the network trained for 3,500,000 iterations indicated that the average error for the full 2-minute prediction was 3.5 m in latitude and 2.5 m in longitude. The maximum error was 18.7064 m in latitude and 18.2946 m in longitude. A separate network was made just to predict the change in heading. The network contained 44 inputs, 20 hidden and 20 context neurons, and one output (the change in heading 2 minutes in the future). The average error for predicting the change in heading was about 1.2^o.

Despite these encouraging results, AAI feels that field-testing of the current networks on the *Nanticoke* is still problematic. The neural networks could predict well within the restricted test data extracted from the *Nanticoke*. If the networks are shown input parameters significantly different from the training set, which will probably be the case, the network's ability to generalise will be limited. However, AAI remains confident that if given a sufficiently rich training set, the neural predictor would respond with acceptable accuracy to any range of inputs.

3.3 Documentation

This report presents the results and findings of the work carried out in Phase II, Development of Working Prototype. The report consists of three volumes:

Volume I: Interim report covering the development and evaluation of the adaptive model
Volume II: Market feasibility study and strategic plan
Volume III: Development of the neural network model

Additionally, a user's manual documenting the adaptive model computer program, SPS_ADAP was prepared and submitted. The source code along with sample data and an executable version of the program were also submitted.

3.4 Summary

In summary, two predictors, one based on adaptive modelling and the other based entirely on neural networks were developed and factory tested. The adaptive predictor, developed by CORETEC Inc., combines a state-of-the-art mathematical ship-manoeuvring model with a neural network module. The neural network module provides the adaptive predictor with a unique ability to fine-tune its parameters, in real-time, in order to optimise its predictions and maintain a high level of accuracy.

A quantitative assessment of the accuracy of the adaptive model prediction was carried out using 9,255 predicted trajectories using real data collected onboard the Nanticoke. The results provided strong evidence of the validity and accuracy of the adaptive model's predictions and that the adaptive model is ready for real time field-testing.

The neural network model, developed by Applied AI (AAI), is based on the Elman network architecture and is made up of a twelve-network system, each of the networks specialised in a ten-second prediction segment. This model was evaluated using 440 real data sets. Despite the encouraging results, AAI feels that "field-testing of the current networks on the *Nanticoke* is still problematic". The neural networks could predict well within the restricted test data extracted from the *Nanticoke*. If the networks are shown input parameters very different from the training set, which will probably be the case, the network's ability to generalise will be limited. However, AAI remains "confident that if given a sufficiently rich training set, the neural predictor would respond with acceptable accuracy to any range of inputs".

4. PHASE III – FIELD TESTING OF WORKING PROTOTYPE

Having developed and successfully factory tested the adaptive predictor, the next step was field testing the entire system. The main objective of this field test was to assess the real-time operations of the SPS and evaluate the accuracy of the SPS predictive model during a routine voyage of the *Nanticoke* in the St. Lawrence Seaway.

Field testing of the prototype SPS was carried out during the period from 23 November 1997 to 8 December 1997, by a team of engineers and technicians from CORETEC Incorporated and the Canadian Centre for Marine Communications (CCMC). Figure 4.1 presents *Nanticoke*'s route during the 1997 field-testing program.

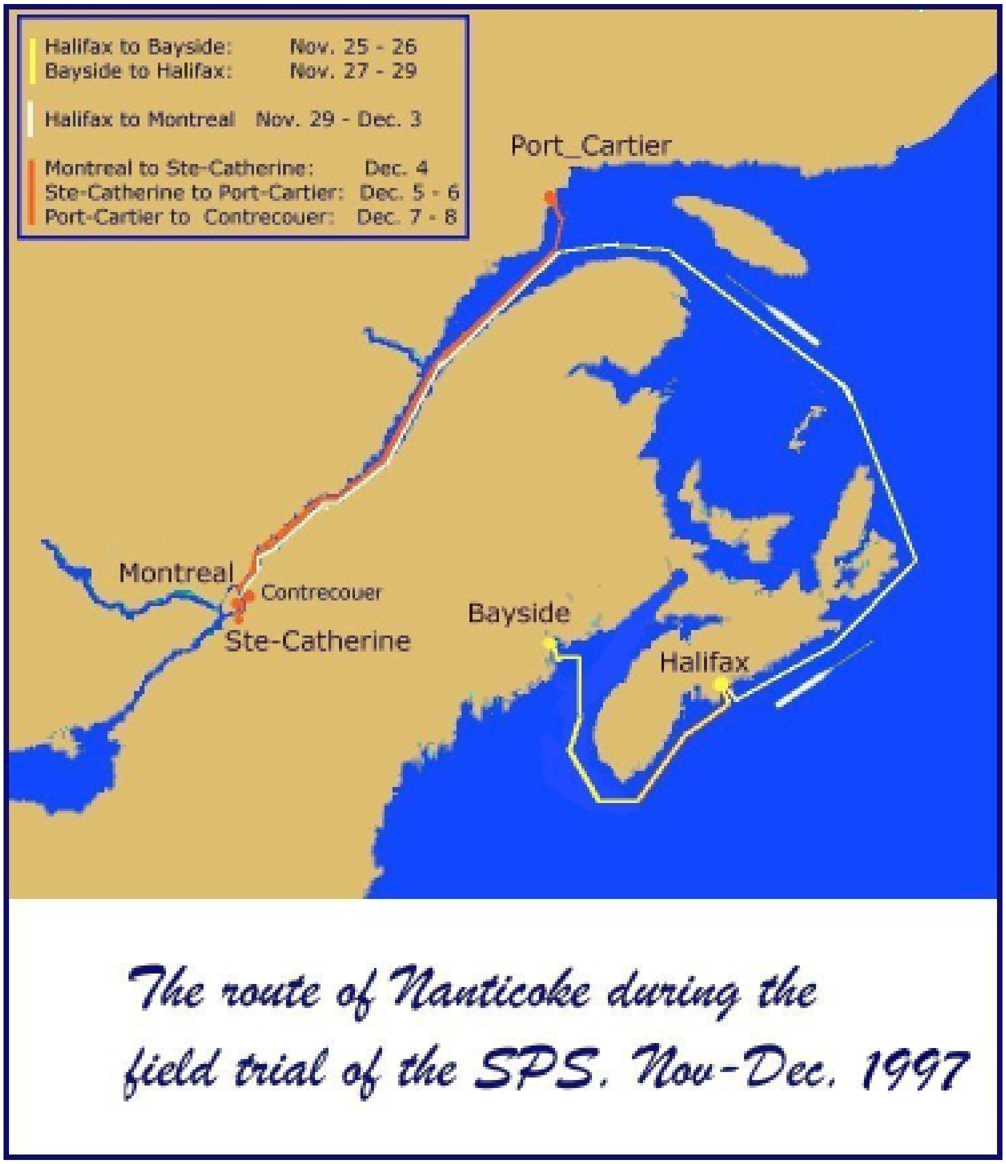

Figure 4.1 : SPS Field Trials Route of the MV Nanticoke

A thorough analysis and evaluation of the SPS and the general conduct of the field testing program were carried out at the conclusion of the trials and a report documenting the trials was prepared and presented to CCMC and the Transportation Development Centre (TDC). The report, entitled "Field Testing of Working Prototype – Final Report", includes a detailed account of the field test preparations, interface development, systems installation and configuration on the *Nanticoke*, SPS operations during the test and the results of a quantitative assessment of the SPS prediction accuracy.

The following sections present a detailed description of the finalized version of the SPS, its input requirements and performance specifications.

4.1 SPS Components and Operations

As shown in Figure 1 of the executive summary, the SPS is made up of three main components: data acquisition, prediction and display. All the SPS software components, including data acquisition, processing modules and the SPS predictor run on a single Pentium computer.

A key feature of the SPS is its integration with the ship's electronic chart display and information system (ECDIS). SPS prediction (ship position, velocity and heading) is displayed on the ship's ECDIS. The SPS also gets many of its input parameters, such as the speed, position and heading of the ship from ECDIS. All data transfer between the SPS and the ship's ECDIS are made via serial port communications using NMEA strings.

4.1.1 Input Parameters

The SPS uses the following 15 input parameters. The meaning of the letters and numbers in the square brackets is given at the end of the list.

- Vessel position (longitude and latitude) from the differential globalpPositioning system (DGPS) through ECDIS.
- The magnitude and direction of ship's speed (speed made good and course made good) from ECDIS [1]
- Time stamp (UTC) from ECDIS
- Heading from ship's gyro
- Wind speed and wind direction from the anemometer [2]
- Vessel's speed through water from speed log [3]

- Propeller pitch and shaft RPM
- Helm indicator (rudder angle indicator)
- Water depth from depth sounder [4]
- Bow thruster power and pitch [5]

Notes:

[1] Can be deduced from longitude, latitude and heading data.
[2] Prediction accuracy will suffer greatly in its absence
[3] Critical for training but system should still work without it
[4] Important for shallow water effects. User can manually set a shallow water flag in case of device failure.
[5] Needed for berthing, and manoeuvring at very low speeds

4.1.2 Prediction

The data acquisition system measures the values of the input parameters from the respective ship devices and then processes this data to provide the required input for the predictive model. As soon as the input data becomes available, the adaptive model produces a prediction of ship position, speed and heading. The prediction period and update interval are configurable. The default prediction period is two minutes and the default update rate is one Hertz. During the field trials, the entire cycle of acquiring the data, preparing the SPS input, generating two-minute or four-minute predictions, and sending the output to the ECPINS™ unit for display took less than one second.

4.1.3 Display

SPS prediction (ship position, velocity and heading) is displayed as an overlay on the ship's ECDIS. The SPS prediction is broadcast as NMEA strings similar to those of the DGPS, thereby making the SPS compatible with existing ECDIS systems. Icons of the ship, plotted to scale and oriented along the predicted heading, will be used to represent the predicted position and heading of the ship. Figure 2 of the Executive Summary shows a sample screen capture of the proposed SPS prediction displayed format.

4.1.4 Self Evaluation

The SPS monitors the accuracy of its prediction by comparing the current position of the ship with the predicted position in a hind-cast mode. This provides feedback in real time to the user on the accuracy of its performance. The SPS can be configured to provide warning when its accuracy deteriorates below a certain level.

4.2 Detailed Performance Specifications

Performance specifications for the SPS predictor were arrived at based on the survey carried out in the market feasibility study (Phase I), talks with ship owners and ship captains and discussions among project team members. Criteria to evaluate the real-time performance of the SPS and the prediction accuracy were established as follows:

- Prediction should be steady and stable and does not change erratically with erratic rudder movements.

- The SPS should be able to provide a minimum of 2-minute prediction to be updated every 10 seconds or less.

- Maximum offset (off-track) error should not exceed ship's beam (23 m) in 90 percent of the time.

- The measure of SPS accuracy should be based on a one-minute prediction because first, it could take up to 30 seconds for a prediction error to be noticed (ship would be off intended track). If a corrective action was initiated at that time, the ship would take another 30 seconds (at most) to respond. This means that the maximum error in ship position would be equivalent to the error at the end of a one-minute prediction.

- The system should be steady and run unattended for a long time, with only minimum or occasional user input, if any. It should be compatible with most ECDIS systems. Interfacing between different system components, e.g., data acquisition, predictor, display should be limited to standard input/output operations (i. e. through files and standard NMEA strings).

- The system should still run and function properly if some secondary source of data (e.g. speed log) were lost. Minimize or eliminate the dependency on unreliable devices (such as speed log).

- The system should perform self-evaluation continuously and provide feedback to the user on the accuracy of its performance. It should also provide warning when its accuracy deteriorates below a certain level.

4.3 Evaluation of the SPS Performance

The SPS performance met or exceeded the detailed performance specifications. For example, it was able to provide two-minute and four-minute prediction every second. Figure 4.2 presents a sample plot presenting a comparison between the observed and predicted trajectories.

A quantitative assessment of the prediction accuracy was carried out using more than 5,000 trajectories that included significant turns. The field prediction errors were compared to those obtained during the factory tests. The results, presented in Figures 4.3 and 4.4, clearly indicated that the accuracy of the SPS predictions in the field trials was significantly higher that that of the factory tests.

The results in Figure 4.5 indicate that the offset error in the one-minute prediction was less than 20 m all of the time and less than 10 m 93% of the time. The two-minute prediction error was less than 20 m 90% of the time.

The above results showed that the SPS performed according to the target specifications and in many aspects actually exceeded them.

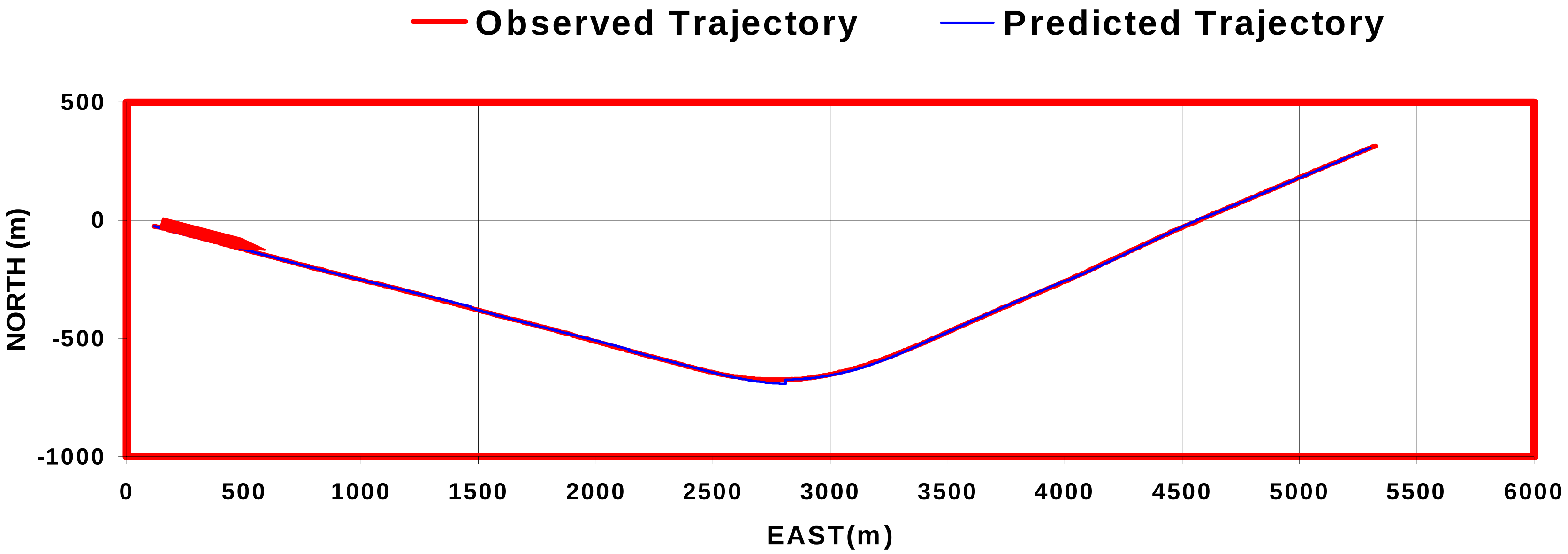

Figure 4.2: Sample Observed and Predicted Trajectories

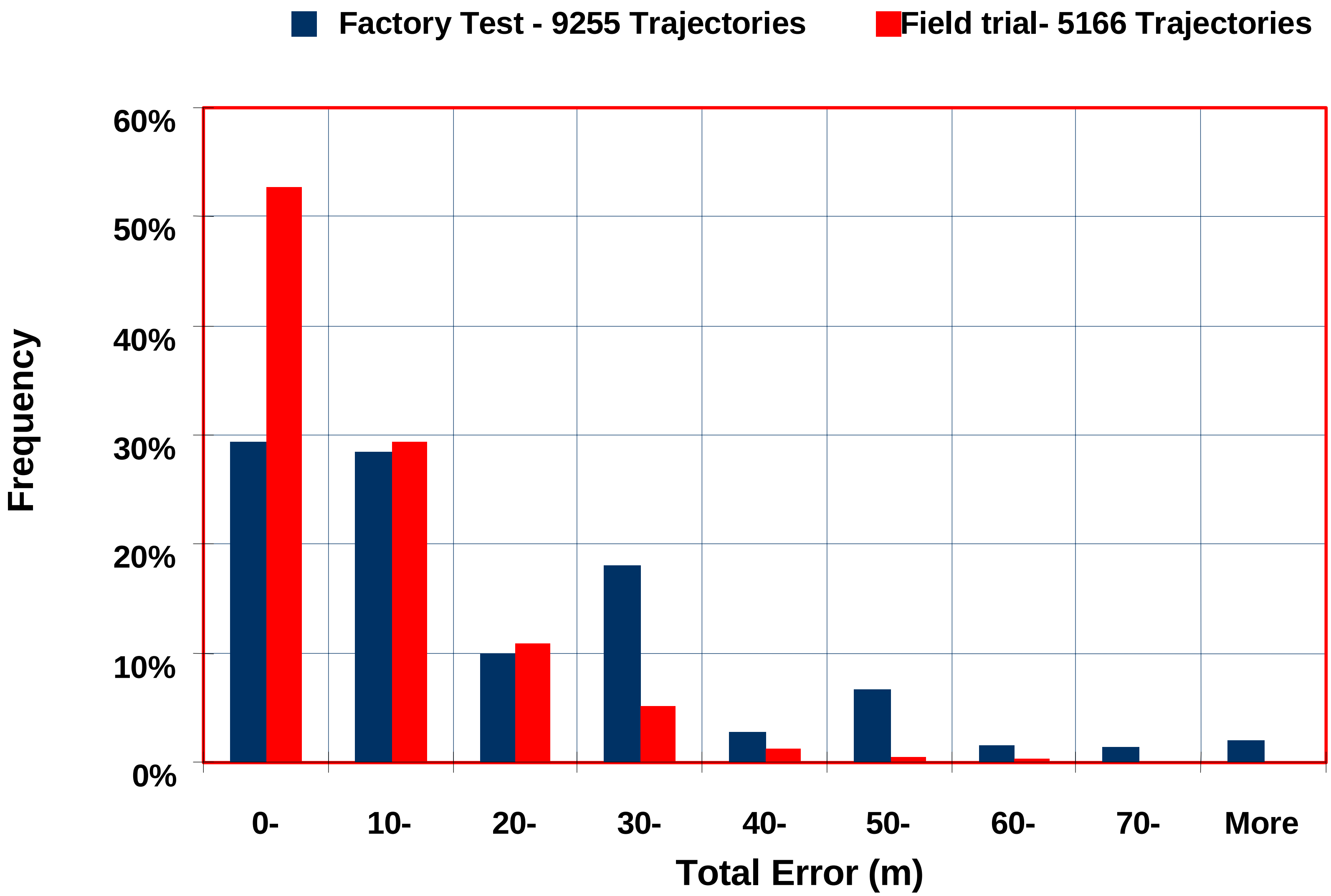

Figure 4.3: Total Prediction Error for the *Nanticoke*

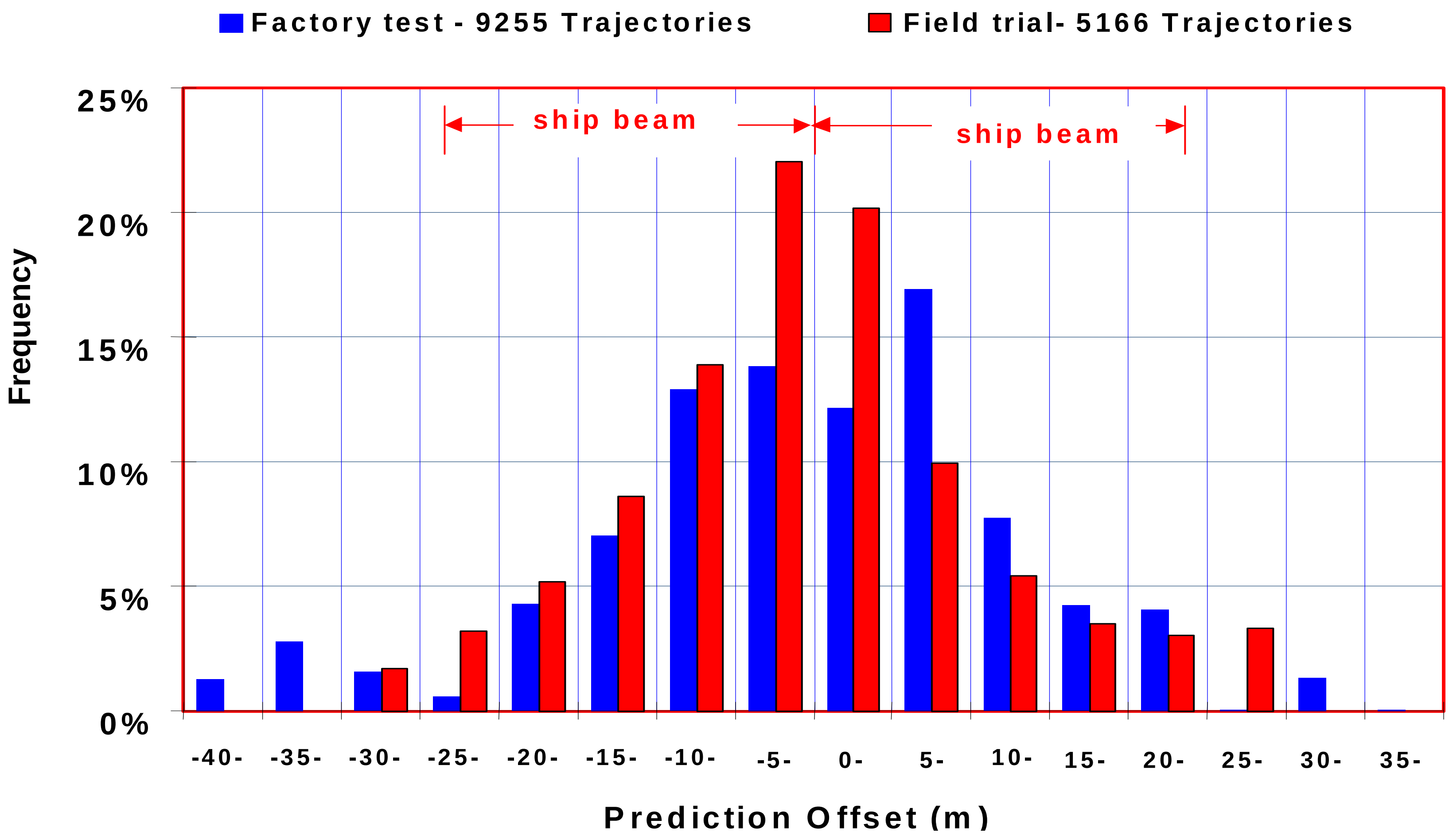

Figure 4.4: Offset Error for the *Nanticoke* Predictions

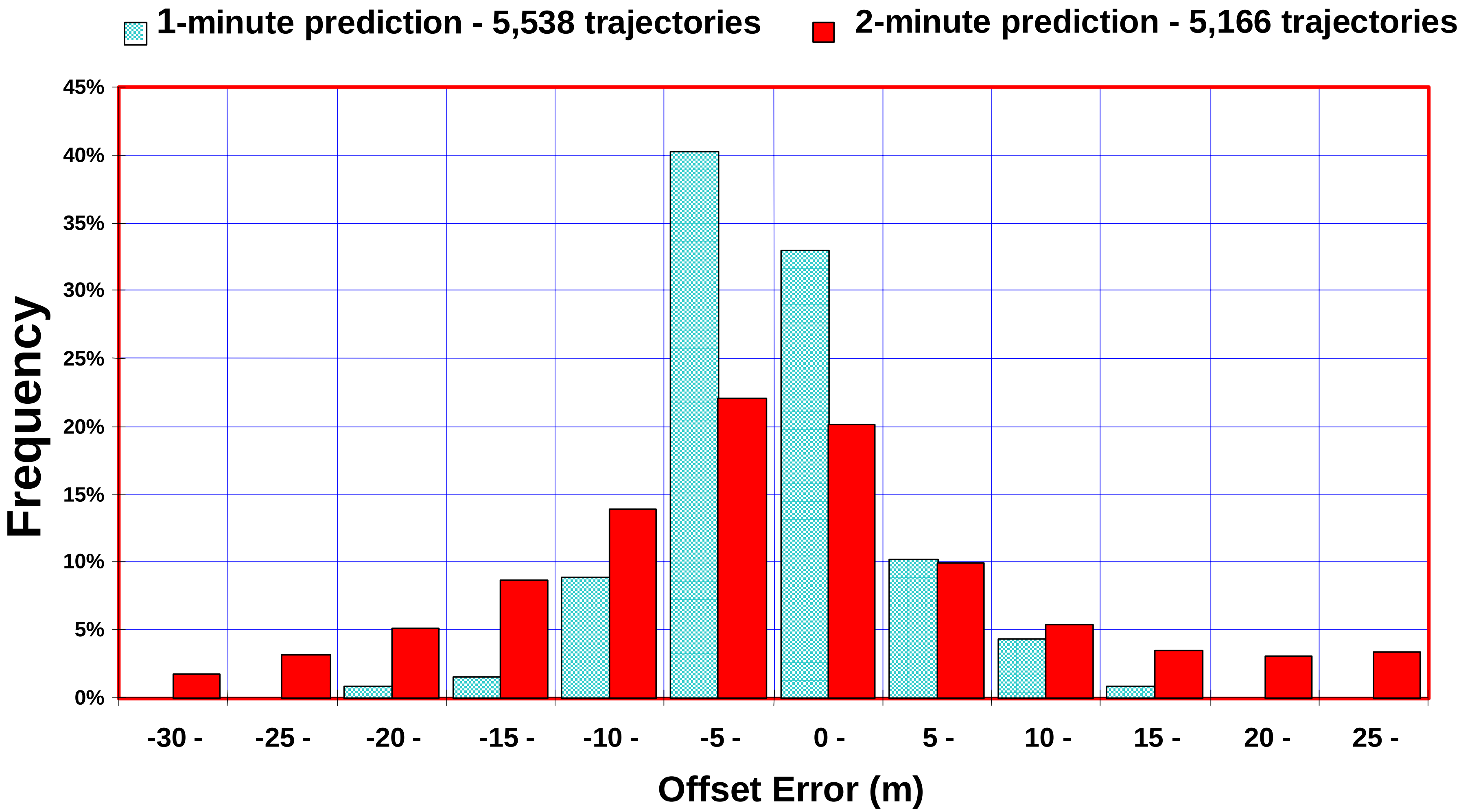

Figure 4.5: Offset Error for 1-minute and 2-minute predictions

5. CONCLUDING REMARKS

CORETEC has successfully developed and field tested the ship predictor system.

The predictive component of the SPS is based on an innovative adaptive model designed to provide real-time, high-precision prediction of the vessel's position and heading. The predictor combines a state-of-the-art mathematical ship-manoeuvring model with a neural network module. This hybrid design eliminated the need for an expensive model test or additional field trials to determine a ship's hydrodynamic parameters.

The neural network module (NNM) provides the predictor with the ability to fine-tune its parameters, in real time, and to account for factors that cannot be modelled mathematically. These factors include variations in ship hydrodynamics due to changes in ambient conditions such as topography and water depth. The result is an adaptive model that combines accuracy, versatility and affordability.

The success of this project led to the development of an advanced ship autopilot system (ASAS) for navigating in restricted waterways. The SPS is the key component of the ASAS.