THE JOURNAL OF NAVIGATION (2003), **56**, 241–255. © The Royal Institute of Navigation
DOI: 10.1017/S0373463303002194 Printed in the United Kingdom

An Integrated Navigation System For Suez Canal (SCINS)

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This paper offers a designed Integrated Navigation System that will permit vessels to transit safely through the Suez Canal avoiding collision and grounding in all weather environments instead of being directed to anchor, thus keeping the Canal open at all times for ship transits. The Suez Canal Integrated Navigation System (SCINS) includes Differential Global Positioning System (DGPS), Suez Canal LORAN-C system, and Vessel Traffic Management System (VTMS). The combination of DGPS and LORAN-C systems[1,2] would provide real-time DGPS corrections that could be used to calibrate the Loran fix; this can be achieved by means of portable integrated DGPS/LORAN-C sets installed aboard the vessels. The addition of VTMS provides significant capability for preserving system accuracy during periods of GPS outages. Due to the interface between LORAN-C and VTMS systems, the SCINS will be able to solve the problem of targets that cannot be tracked by VTMS radars in the shadow areas behind the new bridges along the Canal. The SCINS automates position fixing in real-time, offers a designed algorithm to return the ship to the middle of the Canal and computes the cross-track error (XTE) and the ship squat. Kalman Filter design and system level performance predictions for the SCINS are briefly described. Simulation results show that the SCINS offers superior performance and better position accuracy than current integrated systems.

KEY WORDS

1. Integration. 2. DGPS. 3. LORAN-C. 4. VTMS.

1. INTRODUCTION. Vessels committed to a narrow channel approach need to be able to complete the operation confidently and safely in the event of total loss of the Global Positioning System (GPS) for periods of minutes to hours due to a temporary and localized jammer or source of interference. This goal can be accomplished now with LORAN-C at one level of accuracy. LORAN-C's low-frequency signal propagation has a completely different immunity profile to noise, fading, and interference to that of GPS[3]. These complementary system features form a good basis for integrated navigation systems. The integration of DGPS observations of position and velocity with LORAN-C system will produce a method to achieve very high navigation accuracy. The addition of VTMS radars, which can be fully integrated with these systems, provides significant capability for preserving continuous positioning system accuracy during periods of GPS outage. This paper presents an Integrated Navigation System for vessels to transit safely through the

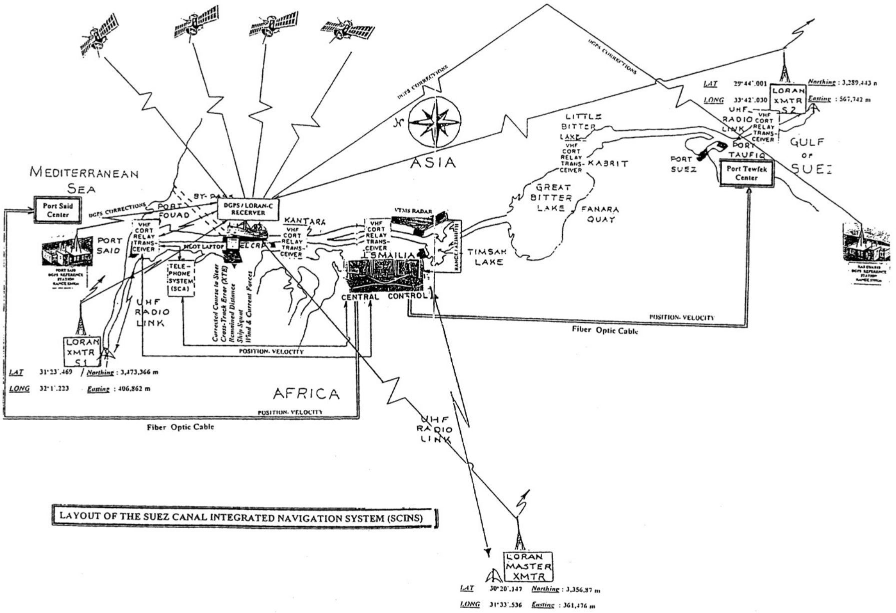

Figure 1. Layout of the Suez Canal Integrated Navigation System (SCINS).

Suez Canal avoiding grounding and collision in weather related environments such as fog, sandstorm, darkness and especially in nil visibility where the bow cannot be seen, with the varying environmental factors of wind and currents being taken into consideration. This can be achieved by use of designed software which enables calculation of the most efficient course to steer to return the ship to its ideal position in the middle of the Canal, where the pilot can expect the pressures and interaction effects to be roughly equal, and rudder effectiveness to be at its best.

A 14-state Kalman Filter[4] is designed for this fully integrated system, where the filter allows the estimation of not only the position and velocity of the moving vessel, but also of the biases that are inherent in all available sensors in the system. A dual channel high accuracy GPS/Beacon receiver GBX-PRO is used and field test results with plots are obtained from the two reference stations at Port-Said and Ras Gharib of the National Network for the Egyptian Ports and Lighthouse Authority. The Network covers the entire Suez Canal area from North to South with an accuracy acceptable for safe navigation in the Suez Canal to within a few metres.

Simulations that yield the filter performance for a given vessel trajectory through the Canal for different locations at EL-KANTARA (km25), ISMAILIA (km75), and PORT TEWFEK (km158), with a fixed satellite configuration have been used to aid the investigation. Computer simulations from the proposed Suez Canal Integrated Navigation System (SCINS) system are presented for comparison with a DGPS/LORAN-C integrated system.

2. CONCEPT OF THE PROPOSED SCINS.

The concept of the proposed SCINS is illustrated in Figure 1. The ship's position and velocity will be determined by means of the on-board integrated DGPS/LORAN-C sets after applying the DGPS correction data[5] received from the reference stations at Port Said and Ras Gharib and will be updated every 0·2sec by the DGPS. The capability to detect a developing dangerous situation and the ability to give timely warning of such dangers can be achieved by integrating the DGPS/LORAN-C systems with VTMS (which has six radar stations installed along the Canal at Port Said, Kantara, Ismailia, G.B.L., Geneva, and Port Tewfik). All the radar stations are connected to the Operation Centres at Port Said, Ismailia, and Port Tewfik by fiber optic cable. The radar signals received in the Operation Centres are converted to digitized video and shown on bright displays.

The ship's position and velocity determined by VTMS radar are fed to the 14-state Kalman filter together with DGPS and LORAN-C data to estimate the ship's position and velocity with very high accuracy. These data are transmitted to the Loran data processor at the Central Control Facility at Ismailia via the dedicated telephone circuits and VHF Carry-On Receiver Transmitter (CORT) relay transceivers located along the Canal at Port Said, Kantara, Ismailia, Kabrit and Port Tewfik. The CORT DGPS/LORAN-C set polling messages are transmitted by telephone from Ismailia to the CORT relay nearest the vessel and then by VHF to the vessel-borne CORT. The CORT relay message follows the same route back to Ismailia. A CORT is permanently installed at each of the five CORT relay sites. These CORTs are polled along with those installed on vessels in the Canal. Since these CORTs are at fixed locations their Time Differences (TD's) should ideally be invariant. Any variation of the fixed CORT monitor TD's is a measure both of Loran transmitter timing drift and of time-varying propagation anomalies. The TD variation in each zone as measured by a fixed CORT monitor may be used to differentially correct the TD measurements on all vessel-borne CORTs in the same zone on the assumption that such temporal effects are nearly uniform over the relatively small extent of a CORT polling zone. Thus, position accuracy will be provided to within 5 m along the Canal. Polling messages containing CORT ID data are broadcast from the CORT relay stations along the Canal. Whenever a CORT receives a polling message containing its own ID, it responds by transmitting its data back to the relay station.

The outputs from the Kalman filter, the ship's position and velocity with high accuracy are fed directly to the pilot's Laptop, where the proposed software will instantaneously compute the corrected course to steer corrected for the ship's drift by wind and currents, to return the ship to the middle of the Canal between the buoys. In addition, the cross-track error (XTE), the remaining distance from the ship's current position to its arrival point between the buoys, the wind and current affecting the ship's manoeuvre and the ship squat are also calculated.

Due to the interface between the LORAN-C system and the VTMS, the Loran-C server will, in principal, function as a messenger that translates the messages between the Loran-C subsystem and the VTMS. The LORAN-C server will be activated immediately when the LORAN-C system starts and as long as it is operational the LORAN-C Sever will perform its tasks. As soon as the LORAN-C tracking starts, the track data from the LORAN-C subsystem will be transmitted to the VTMS, and the target will be integrated with radar track data. If a target is lost due to the shadow area between the two new bridges along over the Canal, it will be tracked by the LORAN-C system. The integration of VTMS radars with DGPS and LORAN-C systems will provide significant capability for preserving continuous positioning

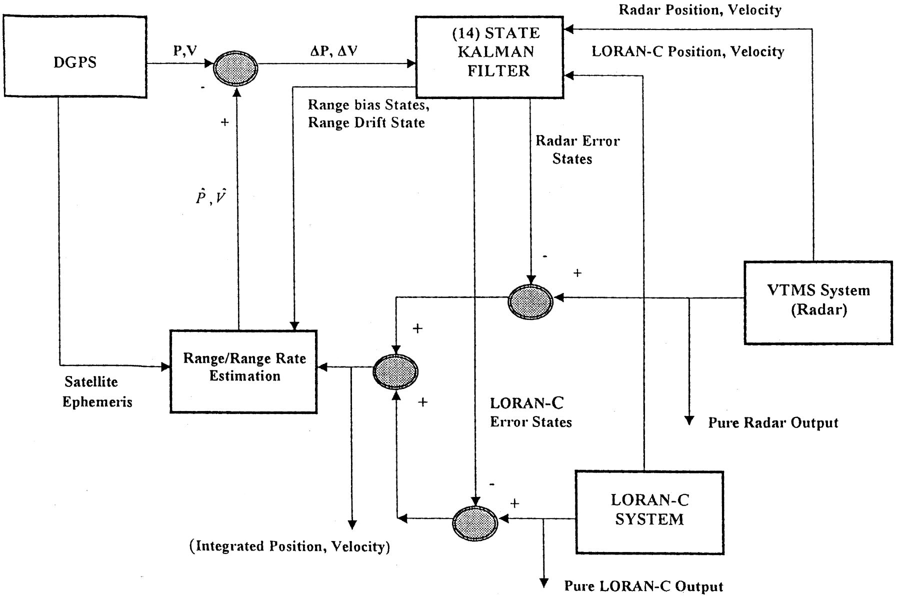

Figure 2. "DGPS/LORAN-C/VTMS" Functional Block Diagram.

system accuracy during periods of GPS outages, and will ensure more complete information on the maritime traffic situation.

3. KALMAN FILTER DESIGN FOR THE PROPOSED SCINS.

The Kalman filtering technique[6,7] is used in this proposed integrated system because its recursive structure avoids extensive calculations, allows the estimation of ship's position and velocity, and the biases inherent in all system's sensors. The technique improves accuracy, design and the operational flexibility of the proposed integrated navigation system. The combination of DGPS/LORAN-C and radar sensors can produce an integrated system capable of maintaining continuous positioning information.

The DGPS system provides measurements of position and velocity to the Kalman Filter. The Kalman Filter processes these data and provides optimal estimates not only of position and velocity errors, but also LORAN-C and DGPS errors, according to the error models. With the addition of VTMS radars, the Kalman filter updates the navigation, LORAN-C, DGPS, and radar errors. The functional block diagram of the 14-state Kalman filter which combines the DGPS/LORAN-C and radar data is shown in Figure 2. The measurements in this application will be a sequence of position fixes obtained from the LORAN-C system, and VTMS radar. Sources that are completely independent of the DGPS system. The difference between the independently determined position and the DGPS system output will yield noisy measurements of DGPS position errors, the noise in this case being the error associated with external reference providing the discrete position fix. The error will be random and independent of the W_k sequence in the DGPS error model. Once the estimates are obtained the position and corrections may be made in accordance with the estimates and the DGPS will operate unaided until another position fix becomes available. The sequence will be repeated and the system reset again and so forth. The result of this integration is a positioning system with characteristics of position continuity and reliability, rendering it suitable for safe navigation in narrow channels and in the Suez Canal.

4. KALMAN FILTER KEY PARAMETERS FOR SCINS.

The Position Velocity (PV) dynamic process can be described by the vector differential equation:-

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \\ \dot{x}_7 \\ \dot{x}_8 \\ \dot{x}_9 \\ \dot{x}_{10} \\ \dot{x}_{11} \\ \dot{x}_{12} \\ \dot{x}_{13} \\ \dot{x}_{14} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \end{bmatrix} + \begin{bmatrix} 0 \\ u_2 \\ 0 \\ u_4 \\ u_5 \\ u_6 \\ 0 \\ u_x \\ 0 \\ u_y \\ 0 \\ u'_x \\ 0 \\ u'_y \end{bmatrix} \tag{1}$$

In the form $\dot{x} = F \times x + GU$ where: F = the state coefficient matrix, G = the noise coefficient matrix, and U = the input vector whose elements are independent unity white noise. The state transition matrix (Φ), and the process noise covariance matrix (Q), can be calculated from "Kalman Filter program" with incremental step $\Delta t = 1$ sec.

For the DGPS System:-

x_1 = East position error. x_3 = North position error.
x_2 = East velocity. x_4 = North velocity.
x_5 = Range (clock) bias state. x_6 = Range (clock) drift state.

For the LORAN – C System:-

$x_7 = \Delta x$, $x_9 = \Delta y$ Incremental Positions
$x_8 = \Delta \dot{x}$, $x_{10} = \Delta \dot{y}$ Incremental velocities

For the VTMS Radar system:-

x_{11} = East position x_{13} = North position
x_{12} = East velocity x_{14} = North velocity

and, u_2, u_4, u_5, u_6, u_x, u_y, u'_x, u'_y, are white noise driving functions.

5. MEASUREMENT EQUATIONS.

5.1. *For the LORAN-C System.*

$$TD_{12} = \left(\frac{b_{12} - r_1 + r_2}{c} \right) + CD_2 \tag{2}$$

$$\mathrm{TD}_{13}=\left(\frac{b_{13}-r_1+r_3}{c}\right)+\mathrm{CD}_3 \tag{3}$$

where: CD_2 is the coding delay of station S_2, CD_3 is the coding delay of station S_3.
TD_{ij} = the time difference observation for stations i and j.
c = the speed of propagation of the radio waves (3×10^8 m/s)
b_{ij} = the geometric distance between the two stations.
r_i and r_j are obtained from the relation:

$$r_i=\sqrt{(x-x_i)^2+(y-y_i)^2} \tag{4}$$

where (x, y) are ship's position, and (x_i, y_i) are station's position coordinates.

We assume that an approximate nominal position is known at the time of the measurement, and that the locations of the stations are known exactly.

We now need to form the $\frac{\delta h}{\delta x}$ matrix as specified by the equation:

$$\frac{\delta h}{\delta x}=\begin{bmatrix}\frac{\delta h_1}{\delta x_1} & \frac{\delta h_1}{\delta x_2} & \frac{\delta h_1}{\delta x_3} & \frac{\delta h_1}{\delta x_4}\\ \frac{\delta h_2}{\delta x_1} & \frac{\delta h_2}{\delta x_2} & \frac{\delta h_2}{\delta x_3} & \frac{\delta h_2}{\delta x_4}\end{bmatrix} \tag{5}$$

where:

$$\frac{\delta h_1}{\delta x_1}=\frac{(x_1-a_2)}{\sqrt{(x_1-a_2)^2+(x_3-b_2)^2}}-\frac{(x_1-a_1)}{\sqrt{(x_1-a_1)^2+(x_3-b_1)^2}} \tag{6}$$

$$\frac{\delta h_1}{\delta x_3}=\frac{(x_3-b_2)}{\sqrt{(x_1-a_2)^2+(x_3-b_2)^2}}-\frac{(x_3-b_1)}{\sqrt{(x_1-a_1)^2+(x_3-b_1)^2}} \tag{7}$$

$$\frac{\delta h_2}{\delta x_1}=\frac{(x_1-a_3)}{\sqrt{(x_1-a_3)^2+(x_3-b_3)^2}}-\frac{(x_1-a_1)}{\sqrt{(x_1-a_1)^2+(x_3-b_1)^2}} \tag{8}$$

$$\frac{\delta h_2}{\delta x_3}=\frac{(x_3-b_3)}{\sqrt{(x_1-a_3)^2+(x_3-b_3)^2}}-\frac{(x_3-b_1)}{\sqrt{(x_1-a_1)^2+(x_3-b_1)^2}} \tag{9}$$

Where: (a_1, b_1), (a_2, b_2), and (a_3, b_3) are master and secondary stations coordinates.

The measurement connection matrix $H=\frac{\delta h}{\delta x}|$ at the approximate trajectory.

5.2. *For the DGPS System.* The four satellite measurement equations are given by:-

$$\begin{bmatrix}Z_1\\Z_2\\Z_3\\Z_4\end{bmatrix}=\begin{bmatrix}hx^{(1)} & 0 & hy^{(1)} & 0 & 1 & 0\\ hx^{(2)} & 0 & hy^{(2)} & 0 & 1 & 0\\ hx^{(3)} & 0 & hy^{(3)} & 0 & 1 & 0\\ hx^{(4)} & 0 & hy^{(4)} & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}x_1\\x_2\\x_3\\x_4\\x_5\\x_6\end{bmatrix}+\begin{bmatrix}vp_1\\vp_2\\vp_3\\vp_4\end{bmatrix}. \tag{10}$$

This equation can be written in a vector form as:-

$$Z_p = p - \hat{p}(x_0) = H_p x + vp \tag{11}$$

Where: Z_i = measurement residuals = measured minus predicted pseudorange. vp_i = pseudorange measurement noise sequence.

$$hx^{(i)} = \frac{\delta\psi_i}{\delta\chi}, \quad hy^{(i)} = \frac{\delta\psi_i}{\delta y} \quad \text{for } i = 1, \ldots\ldots, 4.$$

Where: ψ is the noiseless pseudorange.
From this equation, $\frac{\delta\psi}{\delta\chi}$ becomes the filter parameter H.

The computer simulations for the DGPS scenarios used equations that analitically described typical satellite orbits and, for simplicity, these orbits are assumed to be perfectly circular with a radius (R = 26 560 km) and inclined 55 degrees to the equatorial plane[6]. The Earth-Centered Earth-Fixed coordinates for the satellite position in the orbital model are given by:-

$$x = R(\cos\theta \cos\Omega - \sin\theta \cos 55^\circ) \tag{12}$$

$$y = R(\cos\theta \sin\Omega + \sin\theta \cos\Omega \cos 55^\circ) \tag{13}$$

$$z = R \sin\theta \sin 55^\circ \tag{14}$$

Where:-

$$\theta = \theta_0 + (t - t_0) * \frac{360}{43\,082} \text{ deg} \tag{15}$$

$$\Omega = \Omega_0 - (t - t_0) * \frac{360}{86\,164} \text{ deg} \tag{16}$$

Ω is the right ascension, θ represents the location of the satellite as the angular phase in the circular orbit using the right ascension as the reference point.

The satellite positions in the locally level coordinate frame can be written as functions of time as follows:-

$$x'(t) = R(\cos\theta(t) \sin\Omega(t) + \sin\theta(t) \cos\Omega(t) \cos 55^\circ) \tag{17}$$

$$y'(t) = R \sin\theta(t) \sin 55^\circ \tag{18}$$

$$z'(t) = R(\cos\theta(t) \cos\Omega(t) - \sin\theta(t) \sin\Omega(t) \cos 55^\circ) - r \tag{19}$$

Where: r is the Earth radius of 6380 km.

The components of the unit direction vector can be written as functions of time (t) as follows:-

$$hx = \frac{-x'(t)}{\sqrt{x'^2(t) + y'^2(t) + z'^2(t)}} \tag{20}$$

$$hy = \frac{-y'(t)}{\sqrt{x'^2(t) + y'^2(t) + z'^2(t)}} \tag{21}$$

$$hz = \frac{-z'(t)}{\sqrt{x'^2(t)+y'^2(t)+z'^2(t)}} \tag{22}$$

The recommended satellite visibility window runs from $t=0$ to $t=3600$, a total of 60 min in duration.

5.3. *For the VTMS System.* The measurement equation is described by the following nonlinear discrete equation:-

$$Z_k = H*(x_k)+V_k = \begin{bmatrix} \sqrt{x_k^2+y_k^2} \\ \tan^{-1}\left(\frac{y_k}{x_k}\right) \end{bmatrix} + \begin{bmatrix} V_r \\ V_\theta \end{bmatrix} \tag{23}$$

Where: V_r and V_θ are measurement noise and are assumed to be white, Gaussian, mutually uncorrelated, and zero-mean with variances σ_r^2, σ_θ^2 respectively. Thus the measurement noise covariance can be written as: $R_k = \mathrm{diag}[\sigma_r^2, \sigma_\theta^2]$.

It is assumed that Wk and V_k are mutually independent with each other and have the initial state X_0. All matrices describing the system and covariance's Q_k and R_k are assumed known.

The basic task is to estimate as accurately as possible the true state of the vessel from the radar observations. In the converted measurement Kalman filter (CMKF) approach[8] which is particularly appropriate for the radar tracking problem, the polar measurements range and line-of-sight angle of the vessel are transformed to a Cartesian coordinate frame so that the resulting measurements may be modelled as linear in the transformed state and the filter parameter H can be determined.

6. SIMULATION RESULTS AND PERFORMANCE COMPARISON.

Computer simulations using the *Kalman Filter Program* for three different ship positions at km25, km75, and km158 along the Canal, provided the East and North position and velocity errors used for comparison between the DGPS/LORAN/VTMS and the DGPS/LORAN-C systems. The standard deviations for the three system errors are taken to be; DGPS $\sigma=2$m, LORAN-C $\sigma=5$m, VTMS radar $\sigma=20$m (range), $\sigma=0{\cdot}02^\circ$ (bearing). Fifty runs for each case were obtained and the Root Mean Square (RMS) values of the estimated position and velocity errors were computed and plotted. Figures 3, 4 and 5 present the RMS errors in the East position of the DGPS/LORAN/VTMS system compared with DGPS/LORAN-C system when the ship's position is at km25, km75 and km158 respectively. Figures 6, 7 and 8 show the North position RMS errors for the two systems at the same locations. As expected, the presence of VTMS radar has held the growth of position error, while the DGPS/LORAN-C system has grown to a RMS of 1·3m in East position, and to a RMS of 1·1m in North position. As can be seen from these plots, the addition of the VTMS radar has significantly improved the position errors.

This is a very important result because our proposed SCINS depends mainly on a highly accurate current ship's position in order to compute the corrected course to steer to return to the middle of the Canal. It may be sufficient to use the VTMS radar only when GPS is not available. The reason for this is that the GPS will calibrate the LORAN-C system when it is available. When the GPS becomes unavailable after the

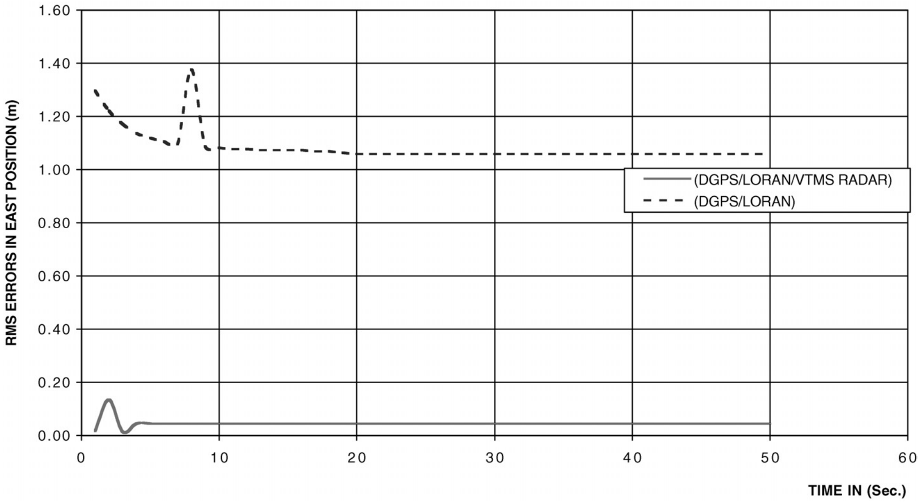

Figure 3. East position RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 25).

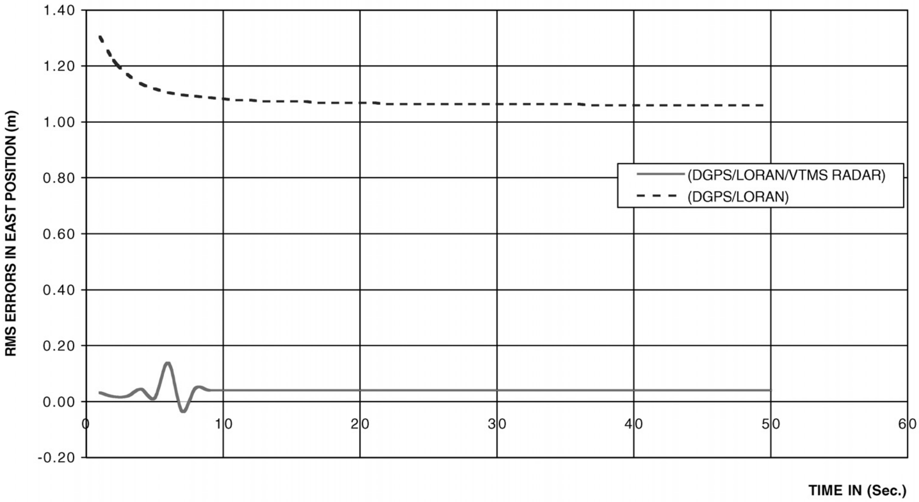

Figure 4. East position RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 75).

use of VTMS radar has started, the LORAN-C performance during the early portion of the outage remains good. This allows the LORAN-C system to calibrate the VTMS radar before the noise sources in the LORAN-C system degrade its unaided performance. The VTMS radar is therefore rapidly calibrated by the LORAN-C system, and by the time the LORAN-C system performance begins to degrade, the

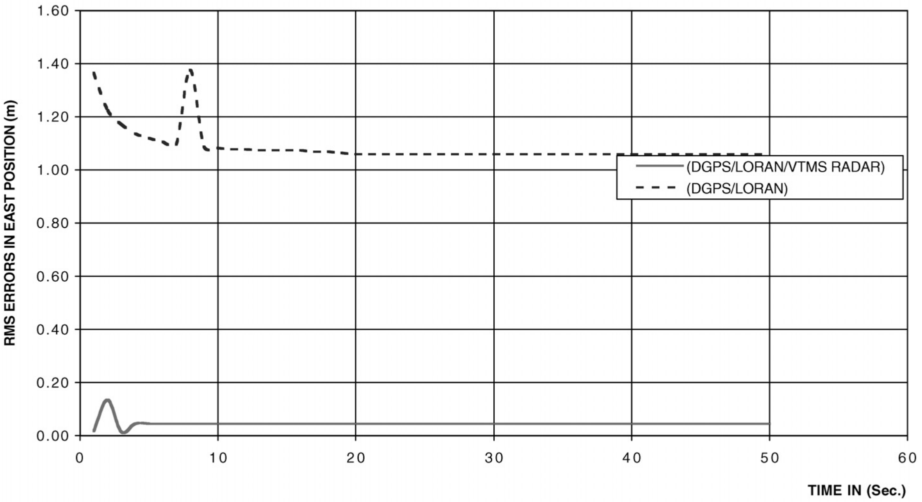

Figure 5. East position RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 158).

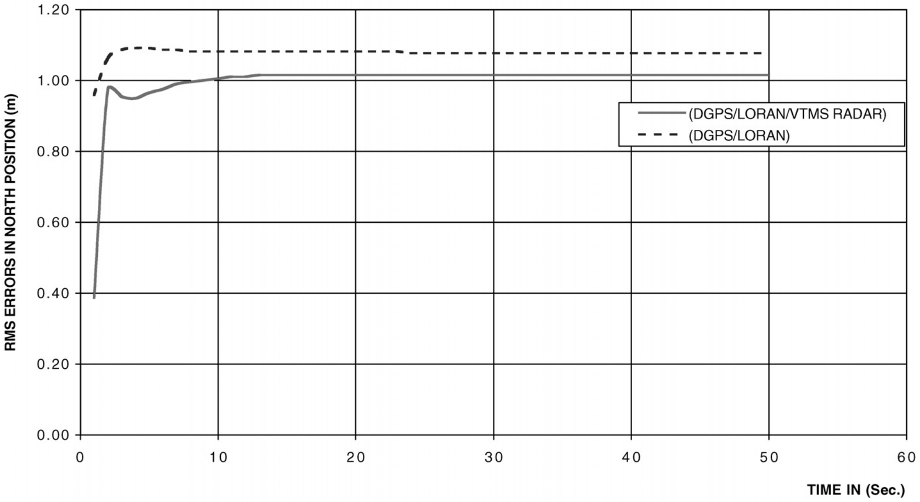

Figure 6. North position RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 25).

VTMS radar is sufficiently calibrated to maintain the system performance. The RMS error in East and North velocities are shown in figures 9, 10, 11 and 12, 13, and 14, for the same locations at km25, km75, and km158 respectively. As can be seen from these figures, the DGPS/LORAN-C/VTMS system performs better for the position estimates, but performs slightly less well in the velocity estimates. This is due to a bias

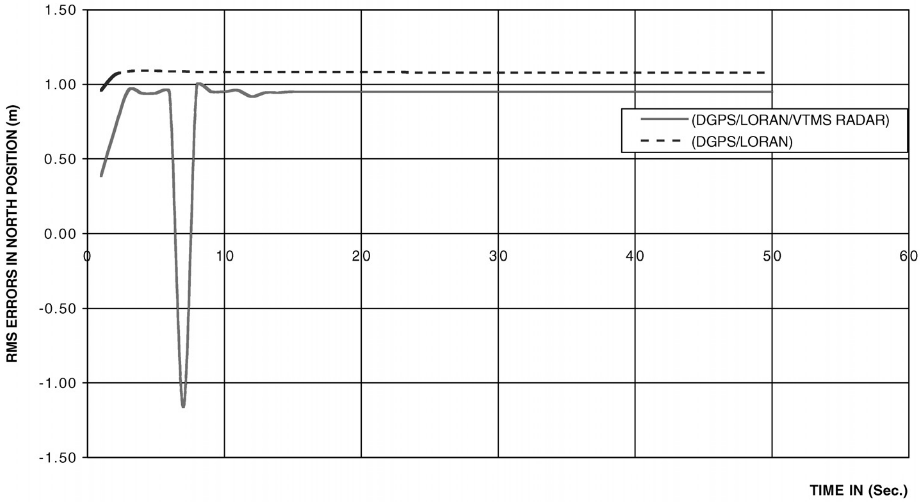

Figure 7. North position RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 75).

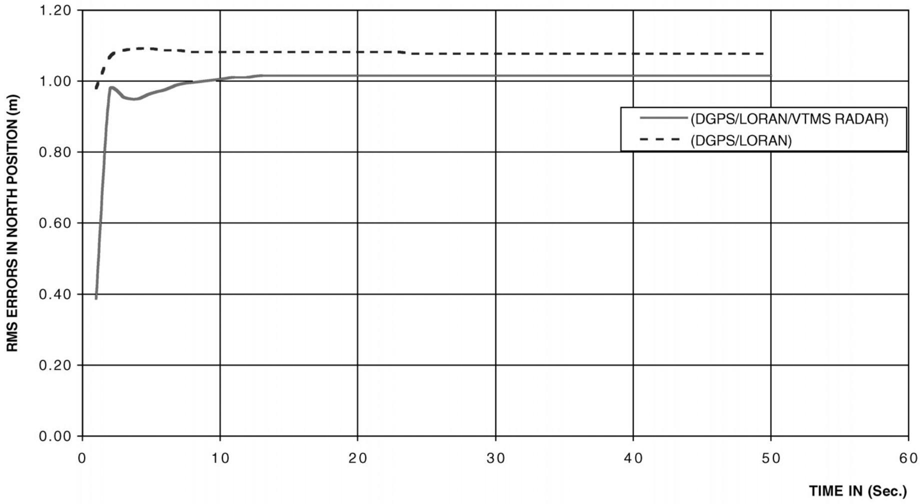

Figure 8. North position RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 158).

in radar range measurement, which will result in a transient error in the estimates of speed as the target passes through Closest Point of Approach (CPA).

7. CONCLUSIONS.

Radar has physical limitations that will always affect the performance and will cause some lost tracks particularly in the shadow area

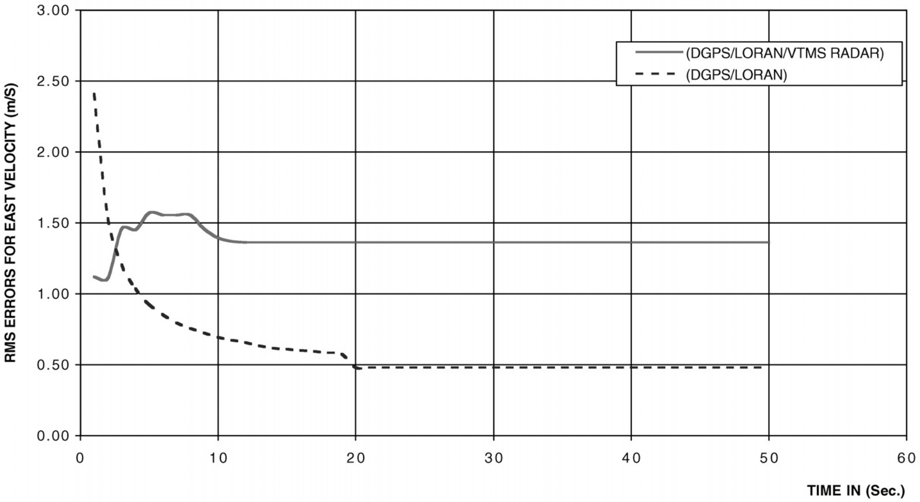

Figure 9. East velocity RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 25).

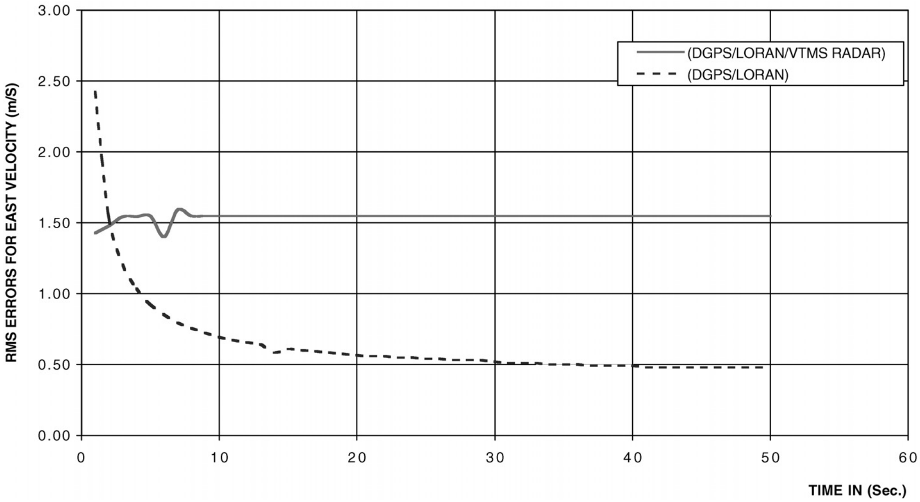

Figure 10. East velocity RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 75).

between the two new bridges at EL-Kantara and EL-Ferdan. Implementation of the DGPS system provides a solution to this problem, which will eliminate the position uncertainty in the vicinity of the bridges. DGPS will give a more accurate ship's position than radar, because the problem of different radar aspects is eliminated. The DGPS solution is the best solution as long as there is general radar coverage in the Canal. This will give Suez Canal Authority (SCA) two independent target sensors

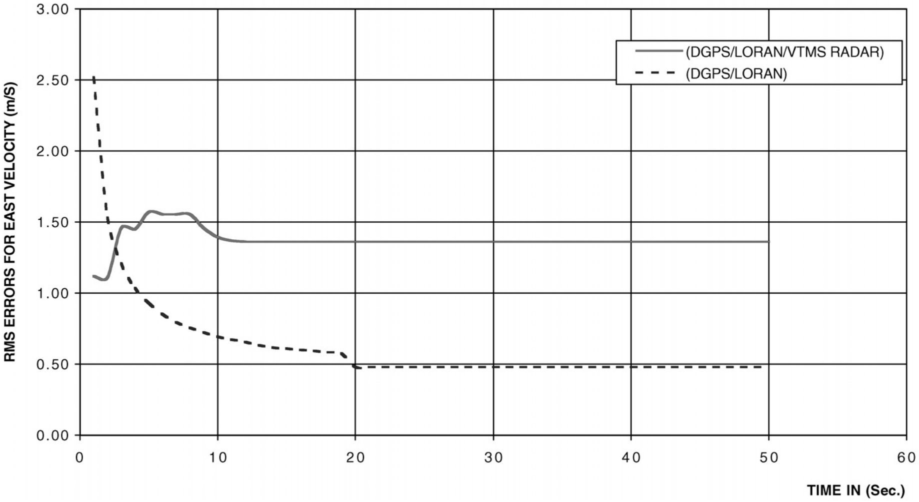

Figure 11. East velocity RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 158).

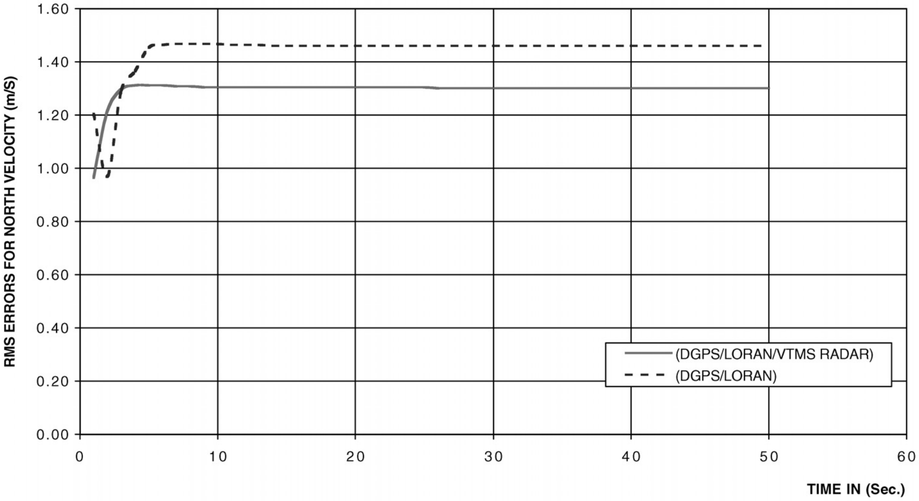

Figure 12. North velocity RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 25).

and will provide the required system redundancy. The previous problems associated with a slow position update-rate will no longer exist. The integration of LORAN-C system in the proposed systems as a backup to the DGPS system will result in adding a third target sensor to provide three independent target sensors to the SCA and will enhance the effectiveness and efficiency of the proposed integrated navigation system to Suez Canal. Thus, the proposed SCINS will provide a high

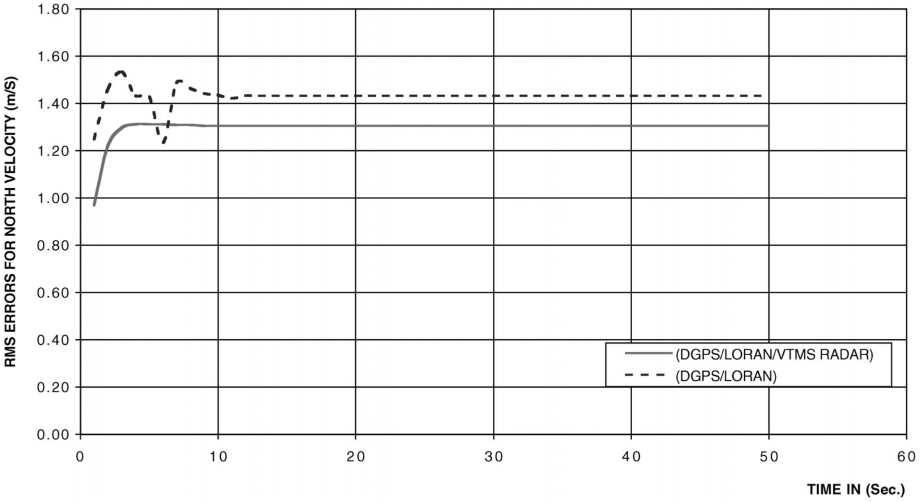

Figure 13. North velocity RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 75).

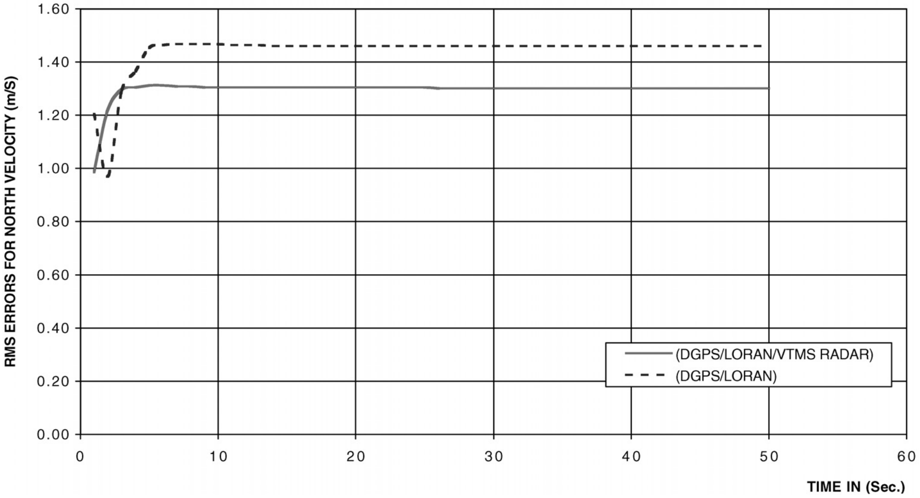

Figure 14. North velocity RMS error for (DGPS/LORAN) and (proposed system DGPS/LORAN/VTMS Radar) (Ship at km 158).

performance, accurate and rapid position update of targets with 100% coverage throughout the Canal.

ACKNOWLEDGEMENTS

We sincerely appreciate and thank the Maritime Training and Simulation Centre Staff for their help, and support for realizing all the simulations associated with this work.

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