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MAXIMIZATION OF SHIP DRAFT IN THE ST.LAWRENCE SEAWAY

VOLUME 1: SQUAT STUDY

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Un sommaire français se trouve avant la table des matières.

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16. Abstract

This project entails the collection of ship sinkage (squat) data on 33 vessel transits in the St. Lawrence Seaway; the collection and analysis of hydrographic data, currents and ship descriptive parameters; and the development of squat and under-keel clearance predictors for the subject ships.

Existing hydrographic data was used to establish the bottom elevation and configuration, and to determine the canal blockage effects. Current measurements were made using an Acoustic Doppler Current Profiler to generate the current patterns necessary to determine the true vessel speed through the water. Accurate squat data was measured through the use of advanced kinematic Differential Global Positioning System (DGPS) technology. Other shipboard measurements were also made, including propeller speed and rudder angle. A number of ships-meeting situations were measured and analyzed.

Laser-based Total Station Measurement techniques were used verify the DGPS analysis.

Water surface elevations were measured using the same DGPS system to determine water surface slopes between locks.

A series of existing squat models was examined in relation to the synthesized data set and comparisons of actual and predicted squat measurements were made. Analysis of the data set identified inherent levels of uncertainty and a series of recommendations for the applicability of numerical predictions was made.

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Volume 2 – Maximization of Ship Draft in the St. Lawrence Seaway: In-Depth Analysis of Squat and UKC

16. Résumé

Ce projet comprend la collecte de données d'enfoncement (*squat*) relatives à 33 navires en transit dans la Voie maritime du Saint-Laurent; la collecte et l'analyse de données hydrographiques, de paramètres descriptifs touchant les courants et les navires; et la mise au point de prédicteurs de l'enfoncement et de la profondeur d'eau sous quille pour les navires étudiés.

Les chercheurs ont utilisé les données hydrographiques existantes pour établir la topographie du fond et déterminer les effets d'obstruction du canal. Par ailleurs, ils ont mesuré le courant à l'aide d'un profileur de courant à effet Doppler, afin de pouvoir déterminer la vitesse vraie du navire. Ils ont recueilli des données précises d'enfoncement en recourant à la nouvelle technologie du DGPS (GPS différentiel) cinématique. Ils ont également mesuré d'autres variables à bord des navires, dont la vitesse de rotation de l'hélice et l'angle de barre. Enfin, ils ont étudié des cas de croisement de navires.

Pour valider les analyses par DGPS, les chercheurs ont eu recours à des techniques métrologiques à laser utilisant des stations totales.

L'élévation de la surface de l'eau a été mesurée à l'aide du même DGPS. Le but était de déterminer la pente de la ligne d'eau entre écluses.

Les données recueillies ont été synthétisées et soumises à une série de modèles d'enfoncement existants. L'enfoncement mesuré a ensuite été comparé à l'enfoncement prévu par les modèles. Ces analyses ont mis au jour des degrés d'incertitude inhérents et des recommandations ont été formulées pour accroître la valeur des prédictions numériques.

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Enfoncement, tirant d'eau sous quille, modèle d'enfoncement, Voie maritime du Saint-Laurent

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- the operational staff of the Traffic Control Centre SLSMC Montreal, for their assistance in identifying vessels and notifying the appropriate owners and operators, as well as for the 24/7 response in facilitating the boarding of ships;
- the operational staff at each lock for their invaluable assistance in controlling traffic and setting up the data acquisition; and
- the SLSMC staff for their technical assistance in providing access to their work, including the survey data for bathymetry.

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Finally, we wish to acknowledge the Transportation Development Centre's Technical Authority and the team from the Université de Laval for their input into the planning, execution and analysis of this project.

EXECUTIVE SUMMARY

The St. Lawrence Seaway is a cost-competitive transportation route providing access to 15 major ports and 50 smaller regional ports. The Seaway opened in 1959 and the maximum operational draft was set at 6.85 m (22'6"). Over time, that draft limitation was increased and is currently limited to 8.0 m (26'3") over the area of interest in this study – the stretch between Montreal and Iroquois Lock. With changing water levels in the Seaway and a desire to "manage" the allowable loading of vessels rationally, under-keel clearance (UKC) has become a critical issue and a better understanding of the factors influencing it is needed – particularly the ship operational phenomenon known as "squat".

In 2000, a joint industry-Seaway group of stakeholders developed a two-part mandate to improve the Seaway's ability to handle traffic. The short-term objectives were to explore more fully the safety margins currently used in determining maximum operational draft and to establish that draft for all ships using the system without changing the infrastructure of the Seaway. The long-term mandate was to enhance the system through infrastructure changes and to develop a cost-benefit analysis of such changes. This mandate was further developed into a three-phase approach, of which this project is Phase 1:

- Phase 1 (Squat Study)
  Determine squat and UKC of ships through the system and formulate squat model.
- Phase 2 (Maximization of Safe Economical Draft)
  Use a risk-based methodology and the outcomes of Phase 1.
- Phase 3 (Integrated Traffic Management System)
  Manage Seaway traffic in real time, utilizing electronic systems and ship simulation models.

This project entails the following:

- the systematic collection of accurate ship sinkage (squat) data on 33 vessel transits between the Lock 1 St. Lambert and Lock 3 Beauharnois stretch of the Seaway and four extended runs between Lock 3 and Iroquois;
- the collection and analysis of hydrographic data, currents and ship descriptive parameters; and
- the development of sinkage and, therefore, UKC predictors for the subject ships.

Hydrographic data from the St. Lawrence Seaway Management Corporation (SLSMC) was used to establish the bottom elevation and configuration, and to determine the blockage effects (cross-sectional area of ship in relation to cross-sectional area of channel). Current measurements were made using an Acoustic Doppler Current Profiler to generate the current patterns necessary to determine the true vessel speed through the water.

Accurate sinkage data were measured through the use of advanced kinematic Differential Global Positioning System (DGPS) technology, using specially deployed shore base stations and four antennae on each ship. Other shipboard measurements were also made.

Multiple teams were deployed in parallel to ensure schedules were met in an effort to obtain as many meeting situations with two instrumented ships, and to maintain the lowest costs on rented equipment. Proven squat models were then used to determine whether they are applicable and whether they meet the accuracy requirements for determining UKC under operational conditions.

Independent measurement of ship movement was made using laser-based Total Station Measurement techniques to provide verification of the DGPS analysis.

Water surface elevations were measured using the same DGPS system to determine water surface slopes between locks. Analysis of SLSMC water level gauge data was made to demonstrate the fluctuation in water surface.

Reduction of all data gathered was performed and a unified set of ship position, ship characteristics, channel data and operational parameters developed. A series of existing squat models was examined in relation to the synthesis data set and comparisons of actual and predicted squat measurements were made. Analysis of the data set identified inherent levels of uncertainty and a series of recommendations for the applicability of numerical predictions is presented.

Squat model recommendations resulting from this study vary according to channel segment and ship type. For Traditional and New Lakers in the Canal section, the Tothill formulation is recommended, while the Barras 2 formulation applies to all other vessel types. Eruyuzla et al. is recommended for the Chemical Tanker class in the lake section, whereas the Tuck formulation applies to all other ship types.

Listed below are recommended areas of future analysis.

- Provide additional hydrographic surveys for more extensive channel cross-section data, including waterway outside of navigation channel, especially in the South Shore Canal Lower Pool and the extended reaches.
- Collect additional water level measurements along the channel to determine the effect of surges and fluctuations in water level surface and to more accurately define the water surface elevations along the navigation canal in the extended reaches.
- Perform further analysis of the Environment Canada data to compare these data with the SLSMC water surface levels and channel bottom values.
- Obtain more complete water surface, current and channel bottom elevation data for Lake St. Francis and the Wiley-Dondero Canal to be used in further analysis of the squat data collected during the extended runs.
- Determine the effect of ship traffic and moored vessels in the canal on squat through further investigation of videotapes, ship logs and SLSMC traffic records.
- Develop a customized formula for calculation of squat in the St. Lawrence Seaway.

SOMMAIRE

La Voie maritime du Saint-Laurent est une voie de transport qui, moyennant des droits concurrentiels, donne accès à 15 grands ports et 50 petits ports régionaux. Lors de l'inauguration de la Voie maritime, en 1959, le tirant d'eau opérationnel maximal était de 6,85 m (22 pi 6 po). Avec le temps, cette limite a été haussée pour s'établir aujourd'hui à 8,0 m (26 pi 3 po) dans le secteur qui intéresse la présente étude, soit le tronçon entre Montréal et l'écluse d'Iroquois. Étant donné les fluctuations du niveau d'eau dans la Voie maritime et le désir de l'administration de «gérer» rationnellement le chargement admissible des navires, la profondeur d'eau sous quille revêt une importance de plus en plus cruciale. D'où la nécessité de mieux comprendre les facteurs qui influent sur cette variable – en particulier le phénomène connu sous le nom d'«enfoncement» du navire, ou *squat*.

En 2000, un groupe mixte réunissant des représentants de l'industrie et de la Corporation de la Voie maritime adoptait un plan d'action à court et à long terme en vue d'améliorer la capacité d'accueil de la Voie maritime. Le plan à court terme consistait à examiner plus en détail les marges de sécurité actuellement utilisées pour déterminer le tirant d'eau opérationnel maximal et à établir ce tirant d'eau pour tous les navires qui empruntent la Voie maritime, en écartant toute modification de l'infrastructure. Le plan à long terme comportait des travaux d'infrastructure visant à améliorer le canal de navigation et l'analyse des coûts et avantages associés à de tels travaux. Ce dernier plan a pris la forme d'une démarche en trois phases, dont le présent projet constitue la première :

- Phase 1 (Étude sur l'enfoncement)
  Déterminer l'enfoncement et le tirant d'eau sous quille des navires utilisant la Voie maritime et formuler un modèle d'enfoncement.
- Phase 2 (Maximisation du tirant d'eau sûr et économique)
  Appliquer une méthode fondée sur l'analyse du risque aux résultats de la phase 1.
- Phase 3 (Système intégré de gestion du trafic)
  Gérer en temps réel le trafic dans la Voie maritime, en recourant à des systèmes électroniques et des modèles de simulation de navires.

Ce projet comprend les tâches suivantes :

- collecte systématique de données d'enfoncement précises (*squat*) concernant 33 transits de navires entre l'écluse 1 (Saint-Lambert) et l'écluse 3 (Beauharnois) de la Voie maritime et quatre trajets plus longs entre l'écluse de Beauharnois et l'écluse d'Iroquois;
- collecte et analyse de données hydrographiques et de paramètres descriptifs touchant les courants et les navires;
- élaboration de prédicteurs de l'enfoncement et, partant, du tirant d'eau sous quille pour les navires étudiés.

Les données hydrographiques de la Corporation de gestion de la Voie maritime du Saint-Laurent (CGVMSL) ont été utilisées pour établir la topographie du fond et pour déterminer l'effet d'obstruction (rapport de la section transversale du navire à la section transversale du canal).

Des mesures ont été prises à l'aide d'un profileur de courant à effet Doppler, afin de produire les modèles de courants nécessaires pour déterminer la vitesse vraie du navire.

Des données précises d'enfoncement ont été obtenues à l'aide de la nouvelle technologie du DGPS (GPS différentiel) cinématique. Cette technologie a nécessité la mise en place de quatre stations de base spéciales à terre et de quatre antennes sur chaque navire. D'autres mesures ont aussi été faites à bord des navires.

Il a été convenu de déployer plusieurs équipes simultanément, afin de respecter le calendrier des travaux, d'accroître les chances que deux navires instrumentés se croisent et d'abaisser les coûts du matériel loué. Les chercheurs ont alors eu recours à des modèles d'enfoncement éprouvés pour en déterminer l'applicabilité et pour vérifier s'ils possèdent le degré de précision nécessaire pour permettre d'établir la profondeur d'eau sous quille dans des conditions opérationnelles.

Pour valider l'analyse par DGPS, des mesures indépendantes du mouvement des navires ont été effectuées à l'aide de techniques métrologiques à laser utilisant des stations totales.

Le même système DGPS a servi à mesurer l'élévation de la surface de l'eau, de façon à déterminer la pente de la ligne d'eau entre écluses. Les données des indicateurs de niveau d'eau de la CGVMSL ont été analysées, afin de démontrer les fluctuations du niveau de l'eau.

Toutes les données recueillies ont été réduites et regroupées dans un ensemble comprenant la position des navires, les caractéristiques des navires, les données sur le canal et les paramètres opérationnels. Les données ainsi synthétisées ont été soumises à une série de modèles d'enfoncement existants. L'enfoncement mesuré a ensuite été comparé à l'enfoncement prévu par les modèles. Ces analyses ont mis au jour des degrés d'incertitude inhérents et des recommandations ont été formulées pour accroître la valeur des prédictions numériques.

Les recommandations touchant le modèle d'enfoncement varient selon le tronçon de la Voie maritime et le type de navire. Dans le cas des laquiers classiques et des nouveaux laquiers naviguant dans la section du Canal, la formule Tothill est recommandée, tandis que la formule Barras 2 s'applique à tous les autres types de navires. La formule Eruyuzla et coll. est recommandée pour les navires transporteurs de produits chimiques dans la section du lac Saint-Louis, tandis que la formule Tuck s'applique à tous les autres types de navires.

Voici dans quels secteurs la recherche devrait se poursuivre, selon les auteurs de la présente étude :

- Effectuer des levés hydrographiques supplémentaires afin de disposer de données plus complètes sur la section transversale du canal. Effectuer aussi des levés dans les voies navigables à l'extérieur de la Voie maritime, en particulier dans le bassin de Laprairie du Canal de la Rive Sud, et dans les tronçons longs.

- Prendre d’autres mesures du niveau de l’eau le long du chenal afin de déterminer l’effet des hausses subites et des fluctuations du niveau de l’eau, et de définir plus précisément l’élévation de la surface de l’eau du canal de navigation dans les tronçons longs.

- Approfondir l’analyse des données d’Environnement Canada afin de les comparer aux valeurs de la CGVMSL sur le niveau de l’eau et le fond du chenal.

- Obtenir des données plus complètes sur le niveau de l’eau, les courants et l’élévation du fond du chenal dans le lac Saint-François et le Canal Wiley-Dondero, afin de pousser l’analyse des données d’enfoncement colligées durant les longs trajets.

- Déterminer l’effet du trafic maritime et des navires amarrés sur les données d’enfoncement, en examinant plus attentivement les enregistrements vidéo, les livres de bord des navires et le registre de trafic de la CGVMSL.

- Élaborer une formule spéciale pour le calcul de l’enfoncement dans la Voie maritime du Saint-Laurent.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSSARY OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

ADCP	Acoustic Data Current Profiler
BMT	British Maritime Technology
CDs	Compact Disks
DGPS	Differential Global Positioning System
EC	Environment Canada
FTL	Fleet Technology Limited
GPS	Global Positioning System
IGLD	International Great Lakes Datum
MARSIM2000	Maritime Simulation and Ship Manoeuvrability 2000
RPM	Revolutions per Minute
SLSMC	St. Lawrence Seaway Management Corporation
UKC	Under-Keel Clearance
UTM	Universal Transverse Mercator
VLCC	Very Large Crude Carriers
WST	Waterway Simulation Technology

= ship volumetric displacement (in m^3)
A_c = cross sectional channel area
A_s = ship underwater cross sectional area
A_w = net underwater channel cross sectional area = $A_c - A_s$
B = ship beam
B_{TR} = transom stern width
C_b = ship block coefficient
F_{nh} = Froude number based on the undisturbed water depth = $V/(gh)^{1/2}$
G = acceleration of gravity = 9.81 m^2/s
H = water depth (in m)
h_t = flooded bank height
K_b = width factor
$K_i = 1$ = Channel-type parameter for canal with no overbanks
L_{pp} = ship length between perpendiculars (in m)
S_2 = A_s/A_w = channel blockage
S_b = sinkage at the bow (in m)
$S_{\max}$ = squat (in m)
S_{mid} = squat amidship (in m)
T = ship draft
T_{FP} = static draft at Fore Peak
V = ship speed through the water (in m/s)
V_k = ship speed (in kn)
W = channel width

1. INTRODUCTION

The St. Lawrence Seaway is a cost-competitive transportation route providing access to 15 major ports and 50 smaller regional ports. The capacity to load Seaway-sized vessels is determined by the maximum allowable draft. The Seaway opened in 1959 and the maximum operational draft was set at 6.85 m (22'6"). Over time, that draft limitation was increased and is currently limited to 8.0 m (26'3") over the area of interest in this study – the stretch between Montreal and Iroquois Lock. This draft limitation has been set based on some earlier squat measurements taken at single positions within the system and includes margins of safety determined by experience. With changing water levels in the Seaway, and a desire to "manage" the allowable loading of vessels rationally, under-keel clearance (UKC) has become a critical issue and a better understanding is needed of the factors influencing it – particularly the ship operational phenomenon known as "squat".

In 2000, a joint industry-Seaway group of stakeholders developed a two-part mandate to improve the Seaway's ability to handle traffic. The short-term objective was to explore more fully the safety margins currently used in determining maximum operational draft and to establish that draft for all ships using the system without changing the infrastructure of the seaway. The long-term mandate was to enhance the system through infrastructure changes and to develop a cost-benefit analysis of such changes. This mandate was further developed into a three-phase approach:

- Phase 1 (Squat Study)
  Determine squat and UKC of ships through the system and formulate squat model.
- Phase 2 (Maximization of Safe Economical Draft)
  Use a risk-based methodology and the outcomes of Phase 1.
- Phase 3 (Integrated Traffic Management System)
  Manage Seaway traffic in real time, utilizing electronic systems and ship simulation models.

1.1 Project Objective

The overall objective of the project, of which this first phase is a major part, is to optimize the loading of vessels transiting the Seaway. To do this, it is necessary to understand the water levels and depths, and the true maximum draft of a transiting ship. A key aspect is to determine how the ship sinks in the water at any time as it moves through the navigation channel.

The specific objective of this phase is to produce a model for predicting the squat of vessels transiting critical sections of the St. Lawrence Seaway and to predict ship speed and behaviour. This will be achieved by measuring accurately, and developing a true understanding of, the parameters affecting the sinkage of the vessel due to motion (squat), and relating this to true water depths.

1.2 Project Overview

Phase I involves the systematic collection of accurate ship sinkage (squat) data on a number of vessels operating over defined stretches of the Seaway; the collection and analysis of hydrographic data, currents, and ship descriptive parameters; and the development of sinkage and, therefore, UKC predictors for the subject ships.

Hydrographic data from St. Lawrence Seaway Management Corporation (SLSMC) was used to establish the bottom elevation and configuration, and to determine the blockage effects (cross-sectional area of ship in relation to cross-sectional area of the channel). Current measurements were made to generate the current patterns necessary to determine the true vessel speed through the water. Accurate sinkage data were measured through the use of advanced kinematic Differential Global Positioning System (DGPS) technology, using specially deployed shore base stations and four antennae on each ship. Other shipboard measurements were also made.

Multiple teams were deployed in parallel to ensure schedules were met in an effort to obtain as many meeting situations with two instrumented ships, and to maintain the lowest costs on rented equipment. Proven squat models were then used to determine whether they are applicable and whether they meet the accuracy requirements for determining the UKC under operational conditions.

Reduction of all data gathered was performed and a unified set of ship position, ship characteristics, channel data and operational parameters developed. A series of existing squat models was examined in relation to the synthesis data set and comparisons of actual and predicted squat measurements were made. Analysis of the data set identified inherent levels of uncertainty and a series of recommendations for the applicability of numerical squat predictions is presented.

1.3 Squat

Squat is a phenomenon that occurs when a vessel is moving through water and is caused by the change in pressure on the ship's hull due to the acceleration of water as it flows past the ship. This is especially accentuated when the ship moves through relatively shallow or confined waters. The term "squat" has traditionally denoted the increase in draft due to both overall sinkage and trim caused by the forward motion of a ship. This sinkage is usually defined at amidships and then the lowest point of the ship is defined at the bow or stern by applying the trim.

The degree of sinkage is generally known to be a function of the hull shape, ship speed and the "channel blockage". Much of the early understanding was based on the work of Tuck,[1] and a milestone paper on the subject was by Dand.[2] Most predictor equations were based on ship model test results.

The problems with measuring squat are significant. Model tests have problems with scale effects. With model and full-scale measurements, issues arise concerning the limited conditions tested, measurement techniques and accuracy, and the establishment or recreation of the appropriate bottom and water flow conditions. The water level around the vessel is depressed, and thus any measurement data must be taken remotely and referred back to the ship. Other factors affecting squat and the elevation of the lowest part of the ship include static draft, waves, roll and pitch, propeller revolutions per minute (rpm), rudder movements, the presence of other vessels, channel width, and the nature of the channel banks, bottom, etc.

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[1] Tuck, E.O., Taylor, P.J., "Shallow Water Problems in Ship Hydrodynamics", *Proceedings 8th Symposium on Naval Hydrodynamics*, Pasadena, California, 1970.

[2] Dand, I.W., Fereguson, A.M., "The Squat of Full Ships in Shallow Water", *The Naval Architect*, No. 4, Oct. 1973, pp. 237-255.

2. STUDY APPROACH

The ship squat study approach was to focus on the comparison of measured squat values, obtained from shipboard DGPS three-dimensional position data, and predicted squat values obtained from several published parametric formulations. The comparison was to yield the best fit between the predicted and measured squat values. During the study, information was gathered concerning parameters used in the formulations, including ship particulars, details on navigation channel conditions (e.g., currents, depth, width and cross sectional area), and derived quantities from the DPGS data itself, such as ship speed. Measured squat values, derived from the recorded shipboard DGPS data, spatially coincided with recorded Seaway channel geometry data; therefore, comparison of actual and predicted squat values for study analysis was carried out on an along-the-channel basis.

2.1 Data Collection Operations

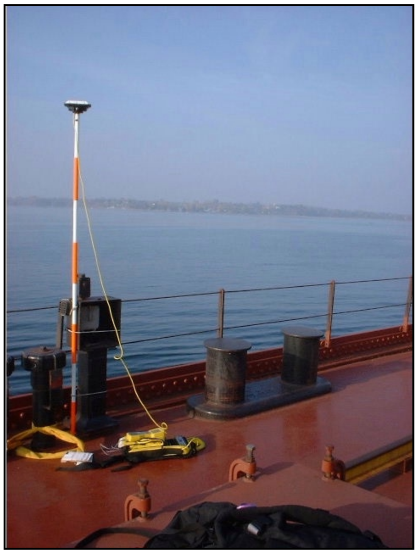
During the study, two three-man teams carried out rotating operations aboard vessels. At times, the two teams operated simultaneously on ships transiting in opposite directions, thus affording the opportunity to record Global Positioning System (GPS) data during meeting/passing operations in the Seaway. Each shipboard team consisted of a team leader, a GPS technician and an engine room instrumentation technician. The team leader was responsible for setting up GPS units on the port and starboard wings of the bridge as well as a video camera either on the bridge or outside on the deck for visual documentation of the transit. The GPS technician was responsible for setting up and monitoring the units on the bow and the portside midship. The engine room technician’s task was to set up an optical device and “yo-yo” potentiometer for recording shaft rpm and rudder movement, respectively. All three team members participated in the collection of vessel information ranging from scale drawings to pictures and tables of ship particulars. The team members were also responsible for keeping written notes of events during the transits, including vessel meetings, special manoeuvres and time of passing for specific notable points along the way. Figure 2.1 shows scenes of data collection operations and antenna setups.

The shipboard teams normally embarked and disembarked the ships in the locks via ladders or portable gangways. Upbound transits normally originated in St. Lambert Lock and terminated at either Lower or Upper Beauharnois Lock. After a team switch, the extended runs in the upbound direction continued from Beauharnois, finally terminating at Iroquois Lock. Downbound runs were carried out in the opposite sequence. Antenna elevations during static conditions (“zeros”) were obtained in the upper level of St. Lambert Lock, the upper level of Cote St. Catherine Lock, the lower level of Lower Beauharnois Lock, the lower level of Snell Lock, and the upper level of Eisenhower Lock.

The zero in Cote St. Catherine Lock was added after a few initial transits because it was discovered that antenna blockage in the lower level of Beauharnois caused poor GPS results, especially for the midship antenna. The zeros served to establish the static antenna elevations that provided the reference level for calculation of squat. The zeroing was accomplished by allowing the ships to remain stationary in the locks for a ten-minute period while the GPS units were recording. If possible, cables and lines were slacked during this time. Six-point draft readings (Figure 2.2) were taken while the ships were stationary in the locks.

Antenna on Bow

Team Prepares to Embark Ship
(Beauharnois Lock)



Antenna at Portside Midship

Antenna on Starboard Bridge Wing
(Looking Aft on Traditional Laker)

Figure 2.1: Antenna Placement and Ship Access

Figure 2.2: Sample Draft Readings in Locks

2.2 DGPS

Trimble 4700 dual-frequency (L1/L2) GPS units were used at four locations on each instrumented ship. Two units were placed on either side of the bridge on the wings, one was placed on the port side at midship and one was placed at the bow. For traditional lakers whose bridge is located at the bow, the fourth unit was placed at the stern. Every effort was made to position shipboard units so as to minimize antenna blockage by the surrounding structure. Figure 2.3 shows a plan view of typical positions of the shipboard instruments on the two basic deck arrangements encountered during the study. This arrangement of the GPS antennae made possible the calculation of ship motion in all six-degrees-of-freedom.

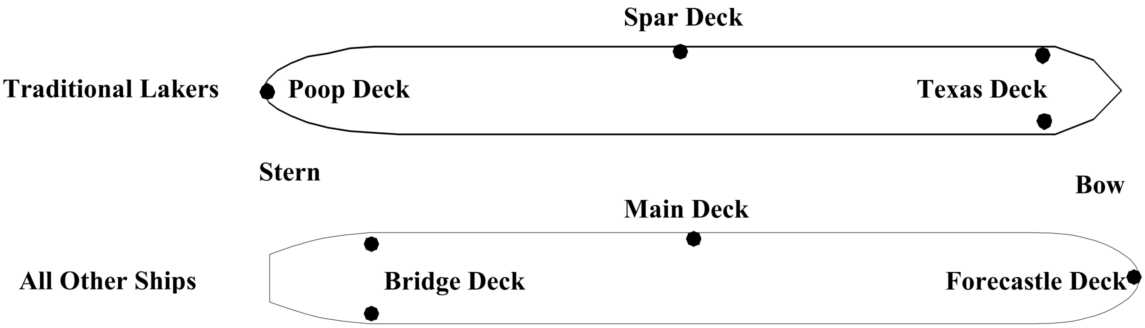


Figure 2.3: Typical Placement of GPS Antenna

The same type of GPS unit was used for the four base stations on shore, which provided the differential component for the post-processing needed to obtain the level of data resolution required for the study. For optimum accuracy of the mobile shipboard DGPS positions, the shore-based data could not be more than 16 km away; therefore, different base stations were used during post-processing, depending on the recorded position of the mobile units.

During extended run transits, one GPS unit was used in a "leapfrog" approach for positioning the base stations so that shore-based data were available all along the channel. Figure 2.4 shows the base stations used during the study, with their locations at the centre of each of the 16 km diameter circles. Information about each base station is provided in Table 2.1. The software used for post-processing was GPSurvey, developed by Trimble.

Table 2.1: Base and Other Key Survey Locations

Station Name	Location	WGS 84 Coordinates Zone 18		GSC CGVD83	Std. Dev.		
		North	East	Elevation	North	East	Elevation
		(m)	(m)	(m)	(m)	(m)	(m)
Primary Base Stations							
STCAT002	Cote St. Catherine Lock (Lock 2)	5029254.394	612265.221	29.817	0.003	0.002	0.003
POLY	Chateauguay City Hall Building	5024103.373	599192.394	41.228	0.003	0.002	0.004
BEAUH003	Lower Beauharnois Lock	5018702.178	584730.439	40.130	0.003	0.002	0.004
BMCORN1	Cornwall Benchmark	4984624.066	522754.840	48.742	0.004	0.004	0.000
MACS0001	Mac's Marina	4996564.530	539022.300	49.596	0.002	0.002	0.008
Total Station							
COTEST01	Cote St. Catherine Lock Upper App. Wall	5029293.374	611993.169	23.699	0.003	0.002	0.002
JETEE001	End of Outer Jetty	5029374.286	600713.845	21.777	0.004	0.003	0.018
JETEE002	End of Outer Jetty	5029389.604	600737.082	24.082	0.007	0.005	0.010
Temporary Points (used early in study)							
1		5022194.759	600072.633	38.685	0.003	0.002	0.008
INT2		5022194.988	600076.113	38.672	0.003	0.002	0.007
68U395B		4982525.718	506296.410	80.914	0.011	0.008	0.024
68U395C		4982525.596	506295.161	79.675	0.005	0.005	0.013

The post-processed output from the mobile units was in a four-column format. The first column contained GPS time in seconds from the beginning of the week, which by convention is midnight Sunday morning. The next three columns contained x, y and z data, respectively. The z value was the vertical coordinate in metres relative to the Geodetic Survey of Canada Mean Sea Level CGVD28 datum. These data are only slightly different from the International Great Lakes (vertical) Datum (IGLD). Information provided by SLSMC shows that there was no more than 2.5 cm between the published elevation at each datum of the existing benchmarks located along the seaway between St. Lambert and Cornwall. The differences are 2.5 cm in the Lock 1 and Lock 2 area, 1.5 cm near the end of the jetties, and 1 cm in all other areas of the trials, including the extended reaches. The undulation model used was GSD95E; typical corrections are shown in Figure 2.5. The x and y values were in metres from the Universal Transverse Mercator projection (Zone 18) relative to the North Atlantic (horizontal) Datum.

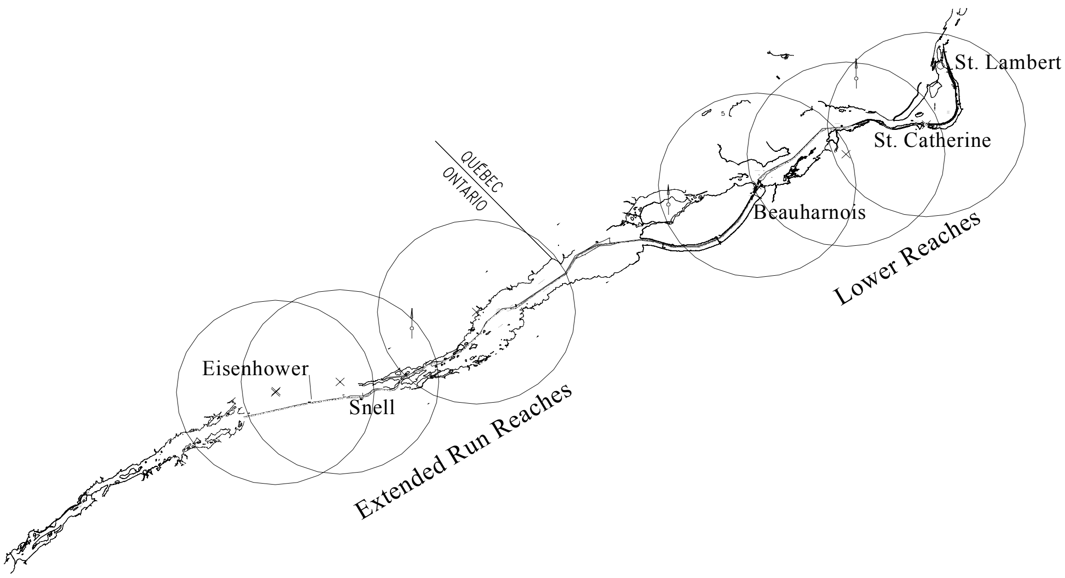


Figure 2.4: GPS Base Station Coverage

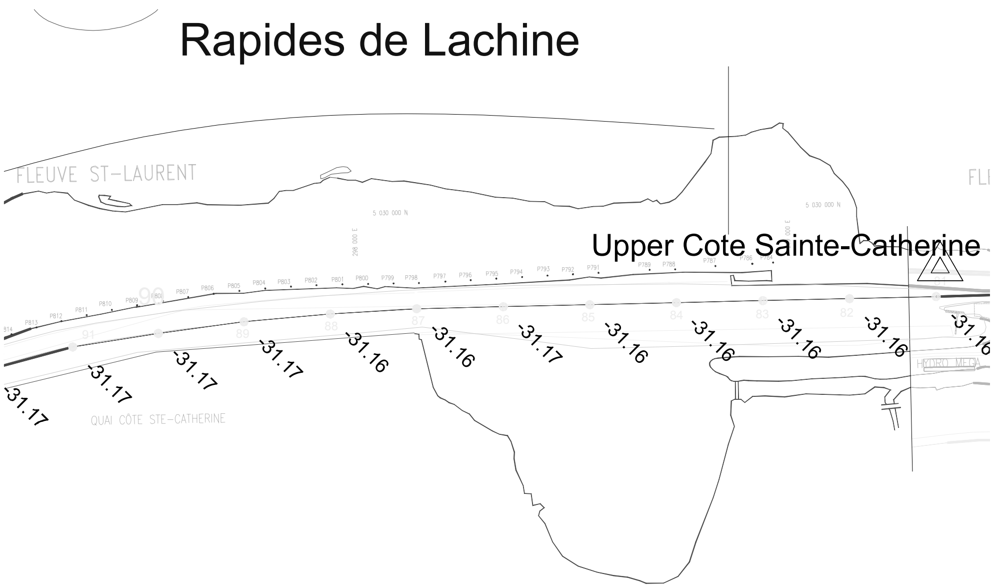


Figure 2.5: Corrections from Geoid Model – GSD95E

2.3 Adjusting for Seaway Conditions

Measured squat values were relative to antenna elevations obtained during static “zeroing” procedures in the locks at the end of the test reaches; therefore, if any water surface slope existed in a specific reach, a correction to the direct squat measurements had to be applied. Furthermore, the published numerical formulations for prediction of squat used ship speed relative to the water as their primary parameter; therefore, the ground speed of the ships derived from the DGPS data required adjustment for current speed.

Water level, water surface slope and current speed were quantified using two sources: water level recording gauges located along the waterway and operated by SLSMC (at the locks) and Environment Canada (EC); and water surface profile and current speed measurements carried out by EC personnel during the data collection period. The water surface profiles were recorded aboard a hydrographic survey boat using GPS receivers similar to those used for the land-based and shipboard stations.

2.4 Water Level in Lower Reaches

Waterway conditions in the study test reaches varied from a pooled canal to a flowing river. The water surface slope in the South Shore Canal between St. Lambert and Cote St. Catherine Locks was negligible and the waterway therefore had no current. However, the reach between Cote St. Catherine and Beauharnois Locks consisted of two distinct regions: one inside the South Shore Canal embankments with negligible water surface slope and the other in Lake St. Louis, outside the restricted canal, with surface slope and currents.

Figure 2.6 shows the plotted results of the EC water surface profile measurements (for the lower reaches) obtained from transits made in the survey boat. These data served to identify the channel station at which the water surface began to slope in the test reach between Cote St. Catherine and Beauharnois Locks. The slope transition occurred upstream of the end of the South Shore Canal jetties adjacent to the mouth of the Chateauguay River. A correction for slope was applied to the calculated squat values only in this section of the channel. From the point of slope transition downstream to Cote St. Catherine Lock, the water surface slope was considered negligible, as was the slope between Cote St. Catherine and St. Lambert Locks.

In the lower test reaches, the time variation of water surface elevation during the data collection period was recorded by SLSMC gauges located in the upper pools at both St. Lambert and Cote St. Catherine Locks, the Laprairie Basin between St. Lambert and Cote St. Catherine Locks, and the lower level of Lower Beauharnois Lock. These data were recorded at six-minute intervals. Figure 2.7 shows the water level recorded by these gauges during the four weeks of data collection. It indicates little variation (in time or space) in the water surface slope for the lower pool and a small slope (in space) in the upper pool between Cote St. Catherine and Beauharnois Locks (see preceding paragraph). Figure 2.8 shows the difference between the gauges at the ends of both pools during the data collection period for the lower study reaches. It indicates little change over time in the water surface slope of either pool.

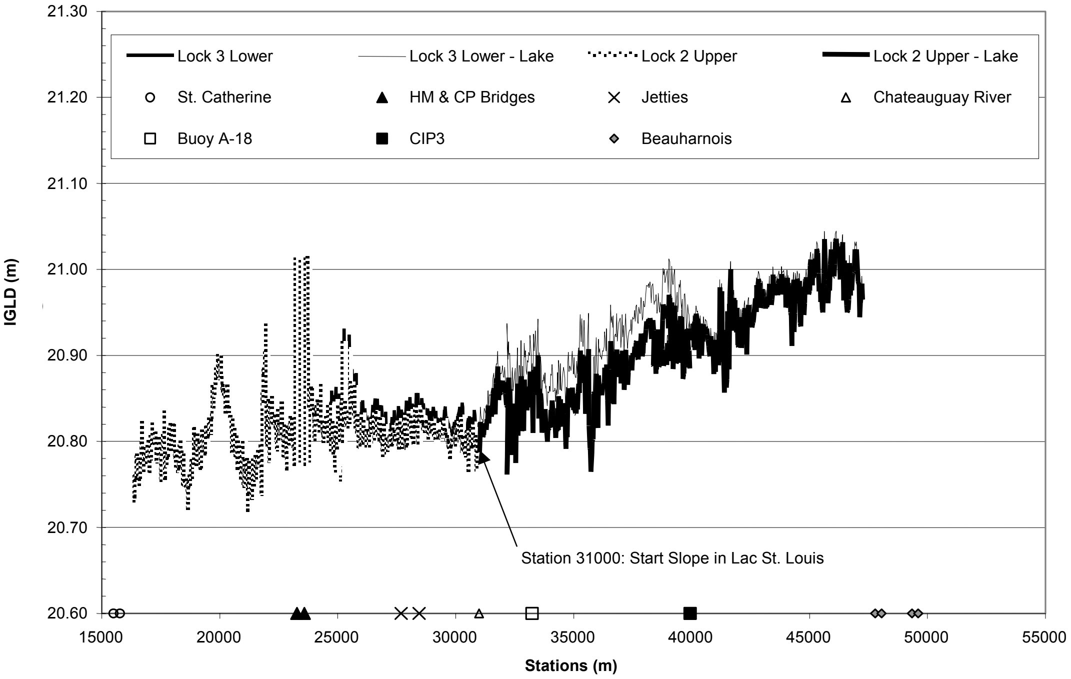


Figure 2.6: EC Water Surface Profile

The recorded DGPS antennae elevations in the channel between Lower Beauharnois Lock and the Chateauguay River mouth required adjustment as a result of a water level change. Instead of the relatively long-term average water level difference between the gauges at these two locations (Figure 2.8 upper thin line), during data analysis the difference between SLSMC average water level readings at Cote St. Catherine and Lower Beauharnois Locks recorded during the transit periods was used to establish the water surface slope for each ship transiting the reach. This difference was not the same as the average difference recorded from the SLSMC gauges over the entire ship trial period, which was approximately 16 cm or 0.9×10^{-5} m/m. The elevation difference between the water level readings at the two locks was used to derive the water surface slope only over the channel segment from the Chateauguay River to Beauharnois Lock. The remainder of the channel between the Chateauguay River and Cote St. Catherine Lock had negligible water surface slope and the calculated squat values through this section were not modified.

EC also recorded water current speed and direction in several sections of the lower reaches. The current speed was measured aboard the survey boat at the same time as the surface profile using an Acoustic Doppler Current Profiler. For the squat analysis described in this report, the current direction in the lower reaches was assumed to be universally parallel to the channel alignment.

Using this assumption, ship ground speed derived from the time-wise GPS positional data was adjusted for current speed, yielding the vessel's speed through the water. The adjustment was made algebraically depending on the direction of travel of the ship.

2.5 Water Level in Upper Reaches (Extended Runs)

The waterway reaches traversed during the extended runs upstream of Beauharnois Lock were unrestricted sections of the St. Lawrence River with surface slope and currents. The water level analysis in these reaches used water level gauges located at the upper level of Upper Beauharnois Lock, the upper level of Eisenhower Lock and at three locations along the Ontario side of the St. Lawrence River – Summerstown, Cornwall and Morrisburg. Figures 2.9 and 2.10 show the data available from the test period for these gauges. These data were used to determine estimated water surface slopes for the two upper reaches: between Buoy D-34 and Snell Lock, and the Wiley-Dondero channel between Eisenhower Lock and CIP 9.

For the extended runs, the water surface slopes had to be roughly estimated using the available water level gauge data because static conditions for the ships were only attained in a lock chamber at one end of each of the reaches. For these estimations, channel stationing was calculated for each of the water elevation gauges to determine horizontal distances for slope calculation. Using these data, the average water surface slope between the upper level of Upper Beauharnois Lock and the lower level of Snell Lock (using either Summerstown or Cornwall gauges) was calculated to be 1×10^{-5} m/m. The average water surface slope in the Wiley-Dondero channel between the upper level of Eisenhower Lock and the Morrisburg, Ontario water level gauges was 0.6×10^{-5} m/m.

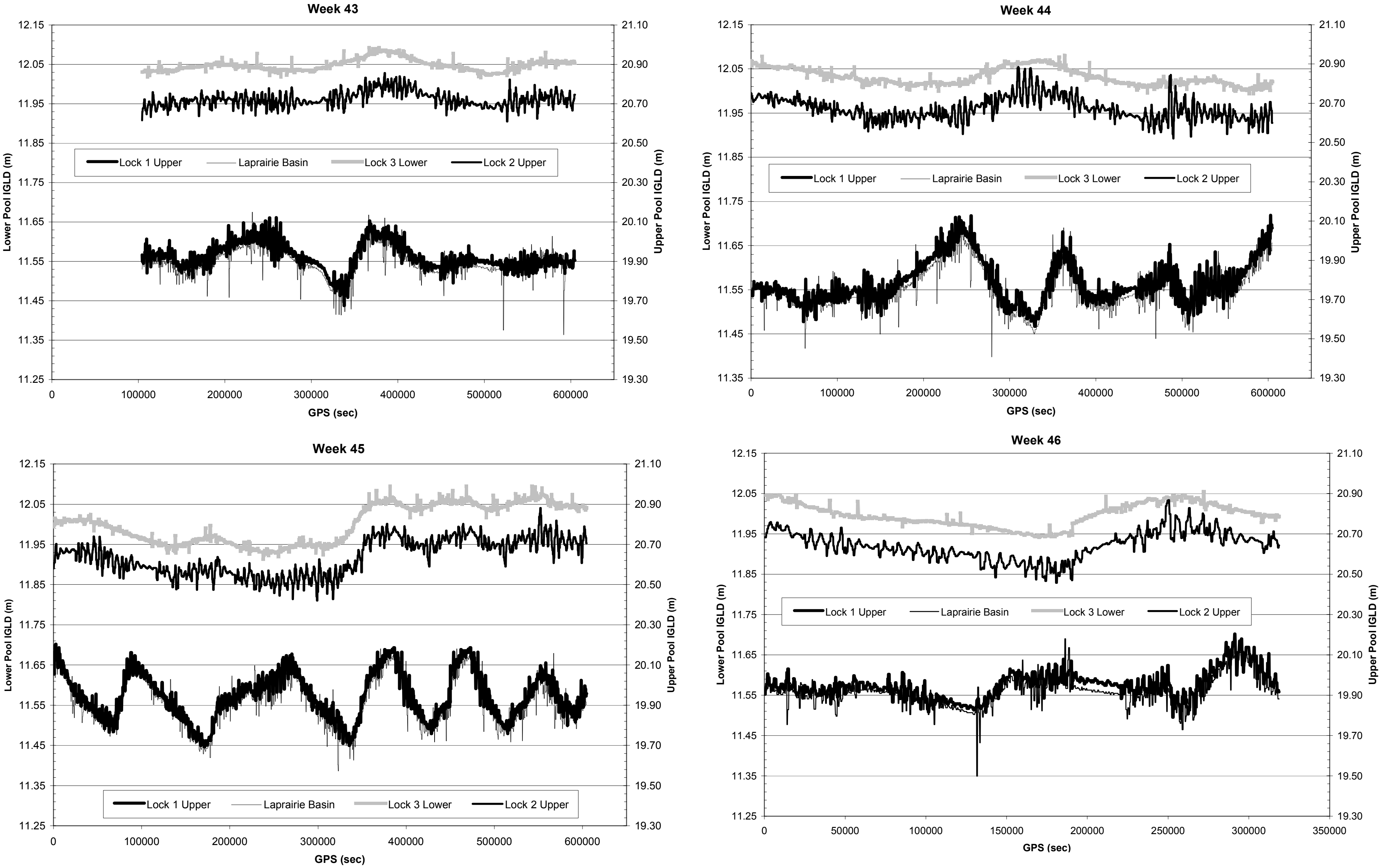


Figure 2.7: Water Surface Elevations During Study for South Shore Canal and Lake St. Louis

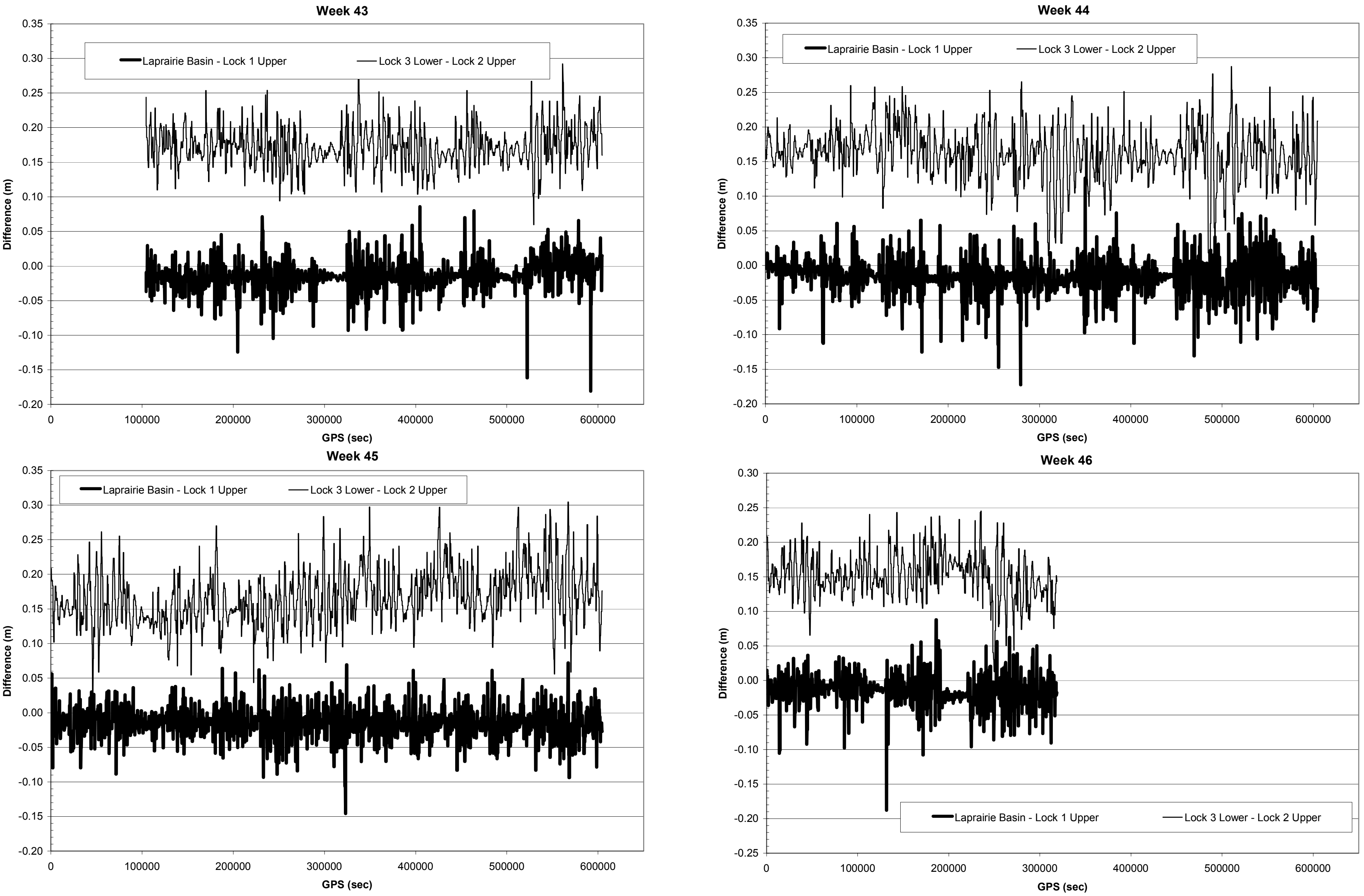


Figure 2.8: Differences of Gauge Water Surface Elevations for South Shore Canal and Lake St. Louis

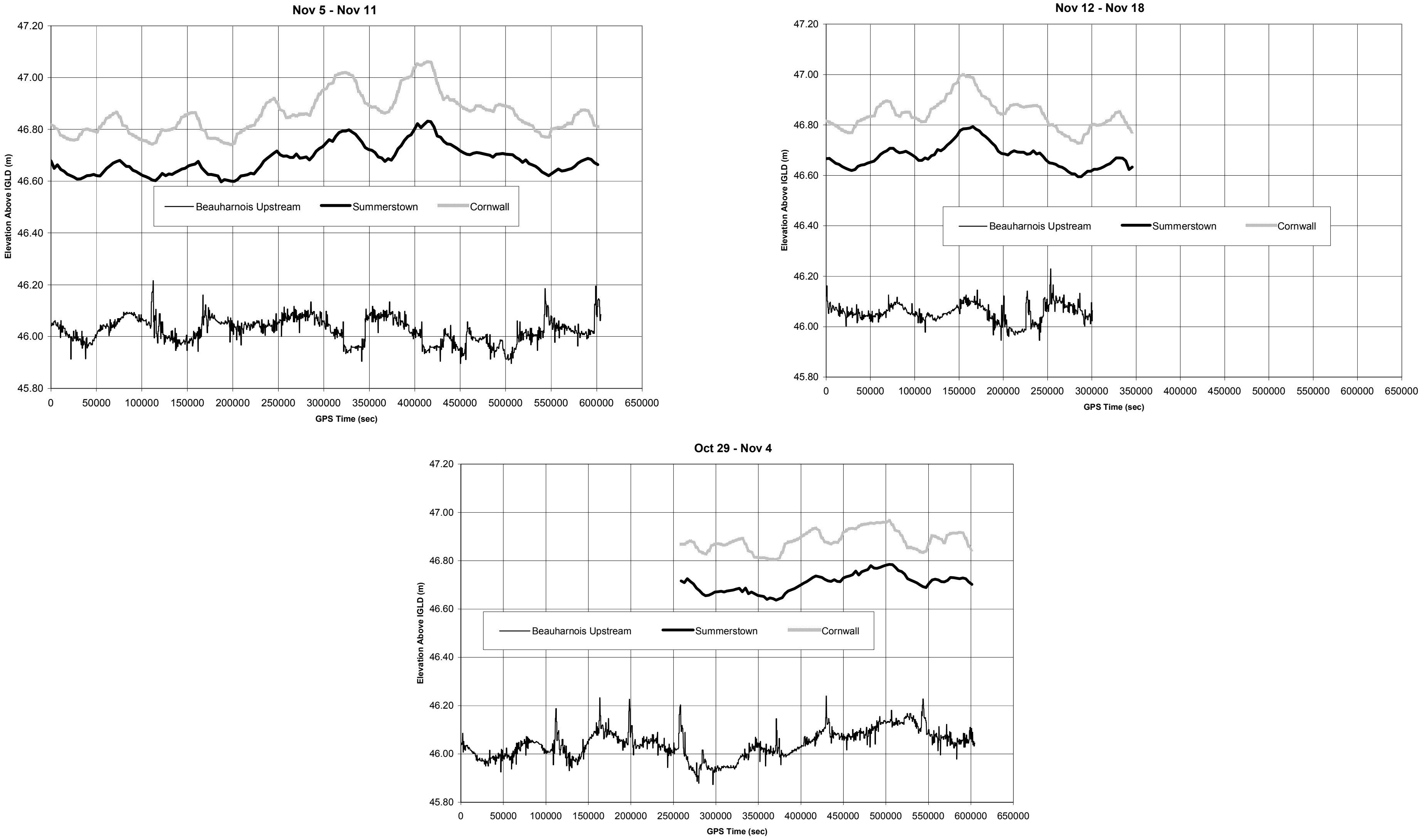


Figure 2.9: Gauge Water Surface Elevation Below Snell Lock

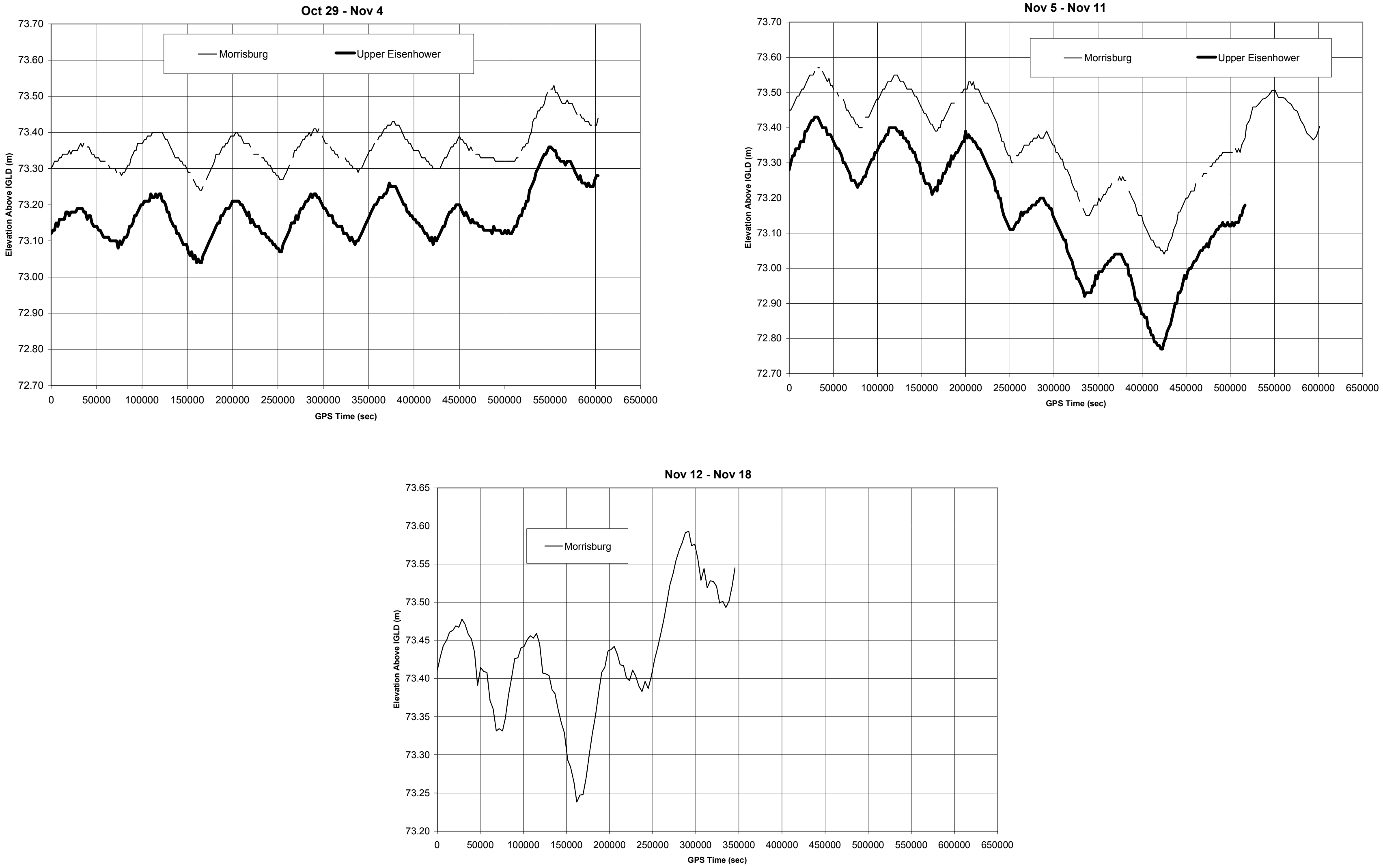


Figure 2.10: Gauge Water Surface Elevation Above Eisenhower Lock

2.6 Squat Numerical Models

The primary approach of the squat study was to compare measured squat values against predicted squat values obtained from several published formulations. Some of these methods are widely used by mariners for the prediction of squat, especially the Barrass 3 formula. Values of the parameters in the formulations were obtained from ship and channel data collected during the study. The 12 formulas are shown below.

Barrass 2

$$S_{\max} = \frac{C_b S_2^{2/3} V_k^{2.08}}{30}$$

Where: $S_{\max}$= squat (m), C_b = ship block coefficient, S_2 = A_s/A_w = channel blockage
A_s = ship underwater cross sectional area, A_c = cross sectional channel area
A_w = net underwater channel cross sectional area = A_c - A_s
V_k = ship speed (kn)

Barrass 3

$$S_{\max} = \frac{C_b V_k^2}{50} \text{ for confined water} \qquad \textbf{or} \qquad S_{\max} = \frac{C_b V_k^2}{100} \text{ for open water}$$

Tuck

$$S_b = 1.46 \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} K_S + 0.5 L_{pp} \sin\left(\frac{\nabla}{L_{pp}^3} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} K_S\right)$$

Where:
S_b = sinkage at the bow (m),
= ship volumetric displacement (m^3)
L_{pp} = ship length between perpendiculars (m)
F_{nh} = Froude number based on the undisturbed water depth = $V/(gh)^{1/2}$
V = ship speed through the water (m/s)
H = water depth (m)
g = acceleration of gravity = 9.81 m^2/s
K_S = $7.45 S_i + 0.76$ *for* $S_i > 0.03$
K_S = 1 *for* $S_i \leq 0.03$
S_i = $A_S / A_C / K_i$
K_i = 1 (channel-type parameter for canal with no overbanks)

Tuck/Huuska

$$S_b = 2.4 \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} K_S$$

Eryuzlu et al.

$$S_b = 0.298 \frac{h^2}{T} F_{nh}^{2.289} \left(\frac{h}{T}\right)^{-2.972} K_b \qquad \text{where} \qquad 1.1 < h/T < 2.5$$

$$K_b = \frac{3.1}{\sqrt{W/B}} \quad \text{when} \quad \frac{W}{B} < 9.61 \qquad \text{or} \qquad K_b = 1 \quad \text{when} \quad \frac{W}{B} \geq 9.61$$

Where: h = water depth, T = ship draft, V = ship speed, K_b = width factor
B = ship beam, W = channel width

Eryuzlu & Hausser

For fully loaded tankers in unrestricted shallow water:

$$S_b = 0.113 \left[\frac{T}{h}\right]^2 B F_{nh}^{1.8} \qquad 1.08 < h/T < 2.75$$

MARSIM 2000

For squat per unit ship length at vessel midpoint in shallow water:

$$S_{mid} = \left(1 + K_P^S\right) * PAR\_HULLs * PAR_{+}h/T * PAR\_F_{nh} * CH1 - F_{nh}^{10} * \left[\frac{0.005(1 - C_b)\left(\frac{L_{pp}}{B}\right)}{(1 - 0.95F_{nh}^{10})}\right]$$

Propeller effect:

$K_P^S = 0.15$ for single propeller **or** $K_P^S = 0.13$ for twin propellers

Hull effect: $PAR\_HULLs = 2C_b * \frac{BT}{L_{pp}^2} + 0.003$

Water depth effect: $PAR_{+}h/T = 1.0 + 0.35\left(\frac{T}{h}\right)^2$

Channel effect: $CH1 = 1.0 + 10S_h - 1.5(1.0 + S_h)S_h^{0.5}$,

for canal $S_h = S_h^c = \frac{\mathrm{A}_s T}{\mathrm{A}_c h} * C_b$

for flooded bank $S_h = S_h^c * (\frac{h_t}{h})$, where h_t = flooded bank height

(for surface piercing banks $\frac{h_t}{h} = 1$)

Furthermore, for a ship sailing off channel centre $S_h = (S_h^{port} + S_h^{stbd})/2$ based on A$_S$/2 and the area of the channel from the longitudinal symmetry plane of the ship. Thus, $\mathrm{A}_C = \mathrm{A}_C^{port} + \mathrm{A}_C^{stdb}$ where S_h^{port} and S_h^{stbd} are channel corrections for port and starboard channel sections.

Forward speed effect:

$$PAR\_F_{nh} = F_{nh}^{(1.8+0.4F_{nh})} + 0.5F_{nh}^4 + 0.7F_{nh}^6 + 0.9F_{nh}^8$$

For vessel trim in shallow water:

$$\begin{aligned} Trim = &-2.5 * PAR\_HULLs * PAR\_F_{nh} * K\_TRIM * PAR\_h/T \\ &+ 0.005 * F_{nh}^{10}\left[(1-C_b) * \frac{L_{pp}}{B} * \frac{PAR_{+}h/T}{(1-0.95F_{nh}^{10})}\right] \end{aligned}$$

Where: $K\_TRIM = C_b^n - 0.15 * K_P^S - K_P^T - K_b^T - K_{TR}^T - K_{in}^T$, where $n = 2 + 0.8 * \dfrac{CH1}{C_b}$

Propeller effect: $K_P^T = 0.15$ for single propellers **or** $K_P^T = 0.2$ for twin propellers

Bulb effect: $K_b^T = 0.1$ for bow bulb **or** $K_b^T = 0$ for no bulb

Transom stern effect: $K_{TR}^T = 0.1 * B_{TR}/B$ where B_{TR} = transom stern width

Initial trim effect: $K_{in}^T = \dfrac{(T_{AP} - T_{FP})}{(T_{AP} + T_{FP})}$ where T_{AP} = static draft at AP, T_{FP} = static draft at FP

Trim reduction due to propeller effect in shallow water: $PAR\_h/T = 1 - e^{\left[\frac{2.5(1-h/T)}{F_{nh}}\right]}$

Then, maximum squat $= S_{\max} = L_{pp} * (S_{mid} + 0.5 * |Trim|)$

SLS Trial Formula

$$S_b = L_{pp} * \left[SHF * \left(1 + 0.35\left(\frac{T}{h}\right)^2\right) * CH_S + 0.5 * 2.5SHF(C_b^2 - 0.3CH_S)PAR\_h/T \right]$$

$$SHF = \left[1.5\frac{\nabla}{L_{pp}^3} + 0.044 * C_b^2\right] * Par\_F \qquad\qquad Par\_F = F_{nh}^{(1.8+0.4F_{nh})}$$

$$CH_s = 1 + 10\left(\frac{\mathrm{A}_S T}{\mathrm{A}_C h}\right) - 1.5\left(1 + \frac{\mathrm{A}_S T}{\mathrm{A}_C h}\right)\left(\frac{\mathrm{A}_S T}{\mathrm{A}_C h}\right)^{0.5}$$

Tothill

$$S_b = S_m + 0.5(Trim) \qquad S_m = 1.25C_b\left(\frac{V^2}{2g}\left(PAR\_A - 1\right)\right)$$

$$PAR\_A = \left[\frac{\mathrm{A}_c}{\mathrm{A}_c - BT - W\left(\frac{V^2}{2g}\right)\left(\left(\frac{\mathrm{A}_c}{\mathrm{A}_c\text{-}BT}\right)^2 - 1\right)}\right]^2$$

$$Trim = 2S_m(PAR_{ch})(PAR\_h/T)$$

$$PAR_{ch} = (C_b^{(2+PAR\_A)} - 0.15(1 + PAR\_A^2) - K_b^T - K_{TR}^T - K_{in}^T) * PAR\_h/T$$

Note: Undefined parameters are same as for MARSIM2000 formulation.

Römisch

$S = C_v C_F K_{\Delta \mathrm{T}} T$ (dimensional terms in metres) $1.19 < h/T < 2.25$

Where:

$$C_v = 8\left(\frac{V}{V_{cr}}\right)^2\left[\left(\frac{V}{V_{cr}} - 0.5\right)^4 + 0.0625\right]$$

$C_F = \left(\frac{10C_b B}{L_{pp}}\right)^2$ for bow squat **or** $C_F = 1$ for stern squat

$$K_{\Delta T} = 0.155\sqrt{\frac{h}{T}}$$

$V_{cr} = K_c\sqrt{gh}$ for a canal with rectangular or trapeziform cross section

K_c defined below

A_c/A_S	1	6	10	20	30	∞
K_c	0.0	0.52	0.62	0.73	0.78	1.0

VLCC

$$S_b = 1.06hF_{nh}^2 \frac{\left(\frac{A_c}{A_s}\right)\left(1-\frac{A_c}{A_s}\right)\left(1-0.5\frac{A_c}{A_s}\right)}{\left(1-\frac{A_c}{A_s}\right)^3 - 1.16F_{nh}^2}$$

VLCC Unrestricted

$$S_b = 0.28T\frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}}$$

2.7 Computation Procedures

The data collected and processed during the field operations for each transit were entered into Excel workbooks, one for each transit, with the extended runs placed into separate workbooks. Each transit workbook was designed to be self-contained and was named using an abbreviated ship name and the Julian date of the beginning of the transit. Each workbook contained a worksheet for ship particulars, data on the antennae arrangements, waypoint data, benchmarks that indicate the progress of the transit in time and location along the channel, and the water levels recorded during the transit. Information in these worksheets was used in the computations contained in the DGPS worksheet. The DGPS worksheet was the primary worksheet of each workbook. In addition to these worksheets, there were charts containing various plots of the gauge elevations and squat versus time and position along the channel. If a total station survey was recorded for the ship transit described in the workbook, then additional worksheets were included in the workbook that contained the total station data and processing, and charts that plot the total station data versus the GPS elevations. The primary data processing was performed in the GPS worksheet. The data were organized in ascending time below a heading area that contained master computations and parameters. Each gauge was time synchronized so that the rows contained common time information. For each time step, the time, Northing, Easting, and elevation data were recorded for each gauge when available. The elevation data were computed for each gauge during the period of static zeroing, which took place in the lock chambers, and the average elevation and standard deviation were presented in the upper left of the heading area. If there were problems with any gauge record, an alternative computation was required to determine the zero elevation to be used for computing the squat values later. These values were recorded in red. The difference between the gauge zero elevations between Lock 2 and Lock 3 was computed and compared to the water level differences recorded during the pool transit by the SLSMC water level gauges. The difference in the water level gauges between Lock 2 and Lock 3 during the upper pool transit was used later in the computation procedure to determine the water level slope adjustments for data in Lake St. Louis.

The position of the GPS gauge on the ship along the channel in terms of channel station distances was computed in an external FORTRAN program for each transit and entered with the GPS data. The location of the midpoint of the ship was determined by computing the weighted station position based on the bow, port and starboard gauges. The ship ground speed was computed as the difference in distance between gauge positions divided by the time step of two seconds. The speed station is the location of the gauge being used to compute the speed.

Normally the speed was computed using the bow gauge unless it was unavailable, in which case either the port or starboard gauge was used.

The three-dimensional distances between each gauge on the ship were listed in the worksheets and the average, maximum, minimum, standard deviation, and min/max average were computed for each distance over the entire transit. Because the distance between gauges was not expected to change once the gauges were set up and operating, this measure was used as a sensitive measure of the validity of the GPS data. These distances were examined and when the distances deviated from the overall average, the data for the common gauge were examined to determine whether the data from that gauge were valid. If the data were suspect, then those data were removed from further processing during the time steps for which they were determined to be invalid. These data were also used later as a measure of the accuracy of the GPS measurements.

The squat value was then computed for each gauge at each time step. This value was determined by subtracting the static zero elevation from the gauge elevation. For transits in the Lock 1 pool, the static zero recorded at Lock 1 was used. For transits in the canal above Lock 2 and Lake St. Louis, the static zero at Lock 3 was used for upbound ships and the static zero at Lock 2 was used for downbound ships. This was done to minimize the impact of surging in the locks during the zeroing process. For the extended transits, the static zero recorded in Snell Lock was used during the period the ship was in Lake St. Francis and the static zero in Eisenhower Lock was used when the ship was in the Wiley-Dondero Canal.

After the initial squat computation was performed, an adjustment was applied to those GPS gauge readings in Lake St. Louis above the Chateauguay River and to the readings in Lake St. Francis and the Wiley-Dondero Canal for the extended transits. For the Lake St. Louis data, the squat was adjusted proportionately according to the distance along the channel between the Chateauguay River and the lower sill at Lock 3 based on the average water level difference between the SLSMC gauges at Lock 2 upper pool and Lock 3 lower pool during the transit times. Similarly, the squat was adjusted for the transit times through Lake St. Francis based on water slope computed from the average water levels recorded at the SLSMC Lock 4 upper gauge and either the EC water level gauge at Summerstown or Cornwall during the transit time. The nearest water level gauge above the Eisenhower Lock is the EC gauge at Morristown, which is 22 km upstream. The recorded water levels at this gauge and the upper gauge at Eisenhower Lock were used to make the slope adjustment to the computed ship squat for the Wiley-Dondero reach. For the transits below the Chateauguay River, the water level was considered to be flat and no water level adjustment was made to the GPS squat measurements since the canal has very little flow in it because of the presence of the locks. Naturally this approach did not account for time- and space-dependent variations in water level that occurred during a ship transit through these reaches as a result of lock filling and emptying events and the small hydropower flows that were present in the canal.

The next few columns in the worksheets determined the north and east positions and the elevations at the ship bow, stern, and midpoint on the keel plane (a plane defining the ship bottom in three dimensions). These computations were based on the ship's geometry and gauge locations. Most of this information was contained in the ship particulars and antennae worksheets. The computations were basic geometric calculations.

Once these points were determined, the keel plane was defined and absolute and dynamic heel and trim were computed about the ship's midpoint. This yielded the sinkage and the minimum keel elevation at the bow and stern for that time. The midpoint sinkage is the squat at the middle of the ship, often the value referred to in the literature as the ship squat. An estimate of ship hogging and sagging was calculated by comparing the elevations of the keel plane at the location of the mid-side gauge and the ship bottom elevation computed directly from the mid-side gauge elevation.

The next data recorded in the DGPS worksheet were the rudder angle, shaft rpm and the percentage of full speed rpm. These data were time synchronized with the GPS and derived data following calibration computations performed external to the ship workbooks. The calibration and computations of the rpm and rudder data were contained in the RPM-Rudder Angle worksheets for each ship. These computations were basically a linear fit of the recorded voltages from the gauges based on a calibration reading taken in the locks after the instrumentation was mounted and connected to the recording devices.

Likewise, external computations were performed to determine the channel bottom elevations, width and area at the ship midpoint cross section for each time step. Two sources of data were available for determining these data: the SLSMC hydrographic survey data and the EC survey data. Since the EC primarily performed profile measurements along the length of the channel, the channel geometry was only available in those locations where there was SLSMC data. The method developed for determining the channel data used extracted data from the ship transit records. The time, north and east coordinates, station location and heading of the ship were provided for each time step. Using these data, the nearest bottom elevation for each of five points across the ship midpoint cross section was located and recorded for the SLSMC and EC data. The five points in the cross section were at the ship's centreline and at 5 m and 10 m starboard and port of the centreline. These distances were selected since most of the ships had beams of slightly over 20 m.

If SLSMC hydrographic data were available, then the channel width and area were determined from the nearest cross section. The channel width and area were dependent on the determination of where the edge of the channel was located. To compute the channel width and cross section, a determination was made as to whether a bank was present on either side of the channel. This determination was done based on hydrographic surveys and navigation charts, and the presence or absence of a bank was defined by channel stations for both sides of the channel. The width and area were then determined based on the following criteria for determining the edge of the channel:

- If the edge of the channel was defined as a bank, then the channel was extended by a 45-degree slope until a depth of 4 m was reached (approximately half of a normal ship draft).
- If the edge of the channel was defined as open water (i.e., not a bank), then the channel was extended using the average slope of the end 5 m of the existing cross section. If the slope determined by this method was negative, then a slope of zero was used. The end of the extension was either 80 m from the channel centreline or 4 m, whichever occurred first.

The cross-sectional area was computed using the trapezoidal method with measured depths projected to the cross-section line. The width was computed as the distance between the two edges of the cross section. This determined the base area, also called the Area Key in the worksheets. This area was based on the water level at the time of the survey. This area was adjusted based on the water levels during the transit by adding an area equivalent to the width multiplied by the difference in water levels.

The water currents were determined from the EC survey data and obtained by locating the nearest survey point to the ship location. These currents were the average current measured at the cross section. The direction of the currents was not accounted for in this study and was found to be generally along the direction of the channel heading.

Because the file size and computation times were becoming very large for the ship workbooks, a separate set of workbooks for each ship was developed to perform the squat model and UKC analysis. In addition, since there were different analyses required for the lake and canal portions of the transits because of the use of models that accounted for restricted channels or open, shallow water conditions, a separate workbook was developed for each. These workbooks were identified by the abbreviated ship name and Julian date appended with “cnl” or “lk” to identify the canal or lake segments.

These squat analysis workbooks began with the extraction of the basic computed data from the DGPS worksheet from the initial ship workbook. The ship particulars and basic transit parameters required for the squat model calculations were added to the worksheet and the ship particulars and benchmark worksheets were inserted in the workbook. The ship’s acceleration was calculated as a time derivative of the ship speed. The water surface elevation was computed from the measured water level at either Lock 2 or 3, depending on the direction of travel and the pool in which the ship was located, and the water level adjustment for the position of the ship along the channel as calculated in the main worksheet. The trim and the dynamic trim in terms of elevation change were computed from the bow and stern keel elevations and change from the static trim. The maximum squat was determined as the lowest of the bow or stern squat (i.e., the lowest point along the ship’s centerline). To consider the effects of rudder and shaft speed rpm on squat and UKC, dimensionless ratios of the instantaneous rudder angle to the maximum rudder angle, the shaft rpm to rpm at “Full Ahead” ship speed, and the instantaneous velocity to the ship “Full Ahead” speed were computed.

The UKC and channel descriptive parameters were computed at each time step. The UKC was computed by adjusting the minimum keel elevation to account for the instantaneous ship heel over half the ship beam. This elevation was then reduced by the maximum bottom elevation found at the ship midpoint cross section. This maximum bottom elevation was from the SLSMC survey data if available, otherwise it was from the EC survey data.

The average depth for the channel was taken as the average of the five locations at the ship amidpoint cross section for the SLSMC survey data, if available, or from the EC survey if SLSMC data were not available. In the canal the channel width and area were taken from the SLSMC survey data if the ship was in the canal reach above Lock 2. If the ship was in the reach between Locks 1 and 2, then the width was assumed to be 100 m and the area was a trapezoidal area computed based on the average depth, the 100 m width and 45 degree bank slopes. The 100 m width and the bank conditions were determined from an analysis of a series of typical cross sections in that reach. The ship speed through water was determined by adding the water speed to the ship speed if the ship was upbound and subtracting the water speed if the ship was downbound. In the upper portion of Lake St. Louis, there were no water current data available; therefore, the last current speed recorded was used as an approximation of the current speed in that portion of the lake. In all cases the current speed was only 0.45 m/s.

The last part of these worksheets included the computation of the various squat model estimates of squat and trim being evaluated. The UKC, squat, trim, computed squat and key parameters of interest were then plotted in chart sheets throughout the remainder of the workbooks. The primary plots were the UKC and ship speed plot, the squat/trim plot along with the speed and rpm ratios and area and h/t plots, and squat versus predicted squat along the channel against each other.

If there were ship meetings that occurred in the transit, then the ship squat, trim, and operational parameters were plotted for the time period of the meeting to demonstrate the impact of ships meeting in the channel.

To avoid including effects from special manoeuvres, low speed operations, and physical forces from the guidewalls or lines near the locks, only data recorded outside the approach guidewalls were used in the squat and UKC analyses. The reaches used included the following reaches:

	Station	to	Station
Lock 1 to Lock 2	3041		15152
Lock 2 to Lock 3	16473		47035
Lake St. Francis to Snell Lock (Lock 5)			121460
Eisenhower Lock (Lock 6) to Richards Point	136730		

3. RESULTS

Data were collected on 26 different ships during the trial period. Because several of the ships were instrumented more than once, there were 17 upbound transits (three extended) and 16 downbound transits (one extended). The ships were categorized into five specific vessel types representing most of the ships using the St. Lawrence Seaway. Because of several stringent requirements concerning data quality and completeness, squat analysis was actually performed on a reduced data set from these transits. Below are listed the criteria on which data were rejected for squat analysis.

Missing base station data or static zero
Data yielding divergent solution in post-processing algorithm
Unexplained shifts in elevation data along transit
Significant changes in distances between GPS antennae
Less than three operating gauges (requires port, starboard, and bow or stern)
Missing channel bottom/area data
Data collected while ship was near locks (inside lock guide walls)

Table 3.1 shows the ships instrumented during the study. The shaded transits are the ones in which at least some of the data were not rejected by the criteria list above. Mean drafts are indicated in parentheses. The table also indicates the five ship categories investigated during the study and the general dimensions associated with them.

Table 3.1: Ship Transits Meeting Data Acceptance Criteria (shown in m)

Ship Type	**New Laker**	**Traditional Laker**	**Chemical Tanker**	**"Salty" Bulker**	**"Salty" Laker**
	(225.6 x 23.8)	**(222.6 x 22.8)**	**(123.2 x 19.8)**	**(180.2 x 22.9)**	**(200 x 23.5)**
Up					
1	*PAUL MARTIN* (7.97)	*CANADIAN VOYAGER* (7.90)	*CLIPPER EAGLE* (6.29)	*MARIUPOL* (7.86)	*FEDERAL FUJI* (7.77)
2	*NIAGARA* (7.97)	*ALGOSOUND* (7.90)	*TURID KNUTSEN* (7.50)	*SPAR GARNET* (7.96)	*FEDERAL SAGUENAY* (6.41)
3		*SS HALIFAX* (7.89)	*JADE STAR* (7.86)	*ZOITSA S* (7.21)	*ATLANTIC ERIE* (7.95))
4				*FOSSNES* (7.99)	*JOHN B. AIRD* (7.94)
5				*LAKE CARLING* (7.94)	
Down					
1	*ALGOVILLE* (7.77)	*CANADIAN VOYAGER* (7.84)	*ALGO SAR* (7.75)	*IRYDA* (7.78)	*ZIEMIA GNIEZNIENSKA* (7.82)
2	*PAUL MARTIN* (7.84)	*MANITOULIN* (7.42)	*ALGO SAR* (7.50)	*BLADE RUNNER* (8.02)	*JOHN B.AIRD* (7.72)
3	*NIAGARA* (7.90)	*SS HALIFAX* (7.90)		*MILLENIUM RAPTOR* (7.73)	*FEDERAL SCHELDE* (7.81)
4	*ALGOVILLE* (7.77)			*TECAM SEA* (7.75)	
Extended Runs					
Up					
1		*SS HALIFAX* (7.89)		*LAKE CARLING* (7.94)	*ATLANTIC ERIE* (7.95)
Down					
1	*PAUL MARTIN* (7.84)				

After the data were collected, a significant amount of organization and manipulation was required to establish a standardized method for analysis and presentation. Normally, squat is considered as a combination of sinkage and trim. Sinkage is the vertical displacement at the ship's midship point on the centreline and trim is the angular rotation of the ship about the transverse axis. Since the GPS antenna placements during the ship transits were not along the ship's centreline, the actual measured sinkage had to be translated to the required positions.

The vertical positions of the GPS antennae relative to the particular vessel's keel was critical in determining the elevation of the lowest point on the ship. To establish the lowest point (elevation) of the ship position, the midship sinkage required adjustment for trim and roll. The lowest elevation of the ship was used in conjunction with channel bottom elevation to obtain the estimated UKC for the ship transits.

3.1 Ship Tracklines

Differential GPS elevation measurements were degraded because of limited satellite availability and antenna blockage; however, the horizontal coordinates were less sensitive to these factors. The northing and easting coordinates were used during the study to produce footprints of the instrumented ships (tracklines) overlaid on plan views of the channel alignment. Figures 3.1 and 3.2 show examples of tracklines recorded during the study that shows the general accuracy of the horizontal coordinates.

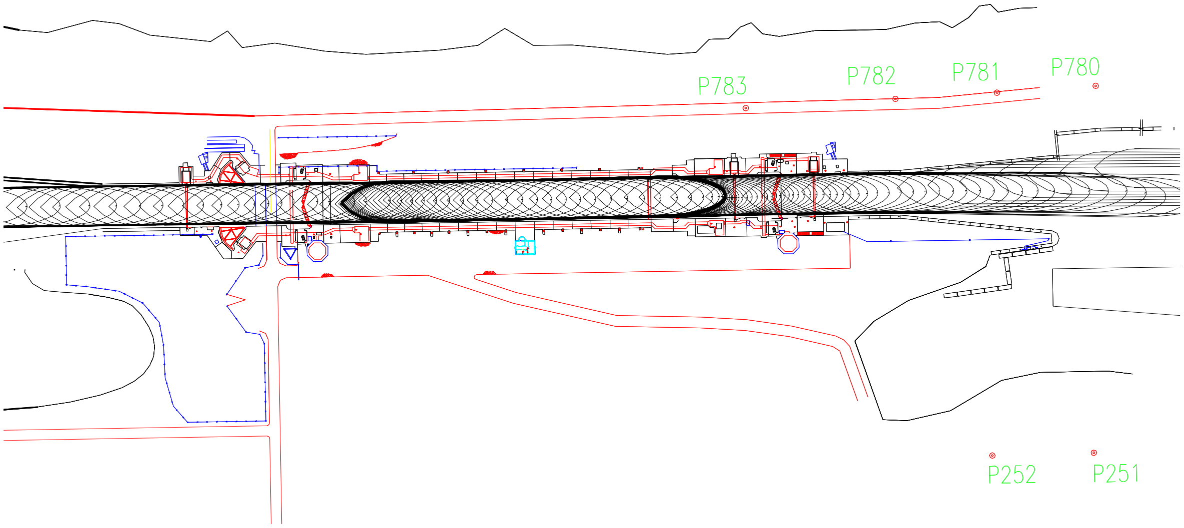


Figure 3.1: *Canadian Voyager,* Cote St. Catherine Upbound, 31 October 2000

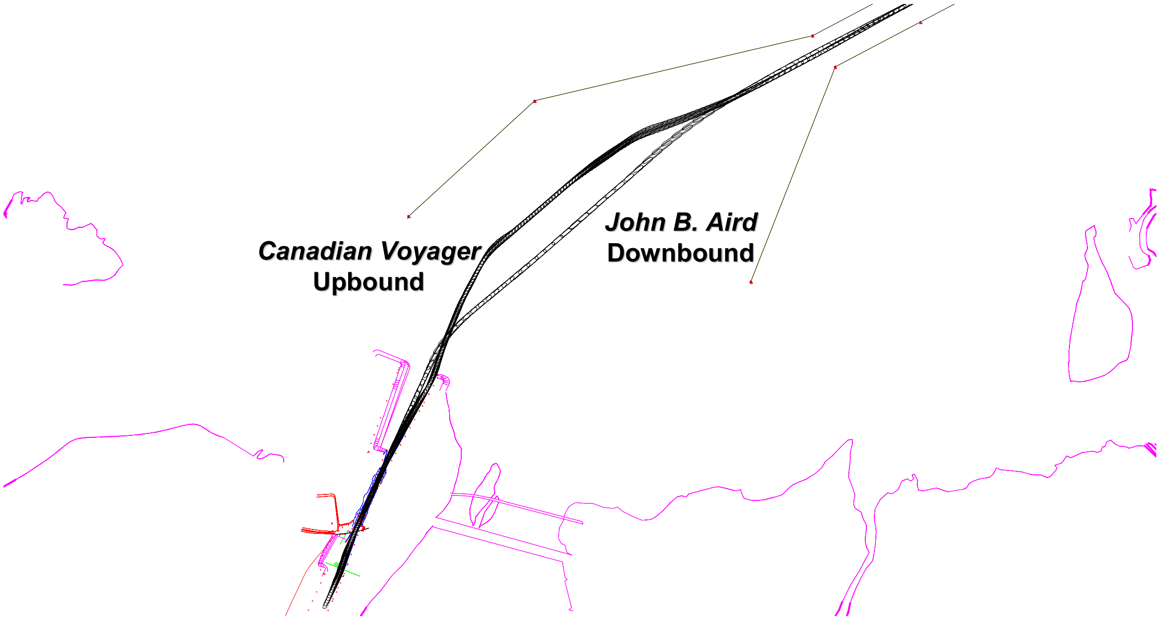


Figure 3.2: Ship Tracklines, Downstream of Beauharnois

3.2 DGPS Squat Measurements

The criteria for data acceptance were detailed in section 3 and the ship transits that met the restrictions are shown in Table 3.1. For each of these transits, the “zero” measurements were identified, the water surface slope and currents were entered, and the midpoint sinkage and trim of the vessel were calculated. Other calculations in the analysis included descriptive statistics of the distances between each pair of GPS antennae, and the elevation of the lowest point on the keel. The vertical flexure of the ship structure was estimated based on the data from the midship GPS station.

The analysis was carried out in two stages. The first stage concentrated on synchronizing the DGPS data from the four gauges, identifying times for and calculating the static “zero” elevations for the antennae, and determining the position of each antenna along the channel relative to a customized channel centreline stationing system. The raw elevation change (sinkage) of each of the four gauges was also calculated and a water surface slope correction made. Calculations were made to determine the coordinates and squat (sinkage and trim) at the midpoint of the ship in addition to deriving the ship’s roll.

The second stage of analysis began with the extraction of only the data calculated in the first stage for the centreline and midpoint of the ship. A statistical comparison between the squat and trim data and the predicted values from the 12 published formulas was carried out. Sections 3.3 to 3.5 describe important steps in the analysis process. In the interest of space, these discussions only show a few examples of results obtained during the study.

3.3 GPS/Total Station Comparison

Géolocation, Inc. conducted data verification surveys during several of the ship transits with the use of land-based total station equipment. The objective of the surveys was to compare antenna elevations recorded simultaneously by the total station equipment on land and the GPS receivers onboard the ships. The total stations were set up at points along the channel where the ships were visible from shore for a long distance. The survey instruments required a clear line-of-sight to the prism target that was installed on one of the GPS antenna poles aboard the vessels. One land-based site for the total station survey was at the upper end of Cote St. Catherine Lock and the other was close to the western end of the northern jetty leading out of the South Shore Canal. For upbound ships the prism target onboard was installed on the antenna pole on the starboard bridge wing and on the port bridge wing for downbound ships. This procedure assured optimal visibility for the longest possible target tracking from shore. Figures 3.3 and 3.4 show examples of one of the total station surveys conducted during the study. The data show general agreement between the DGPS data and the total station record both in magnitude and variation in time.

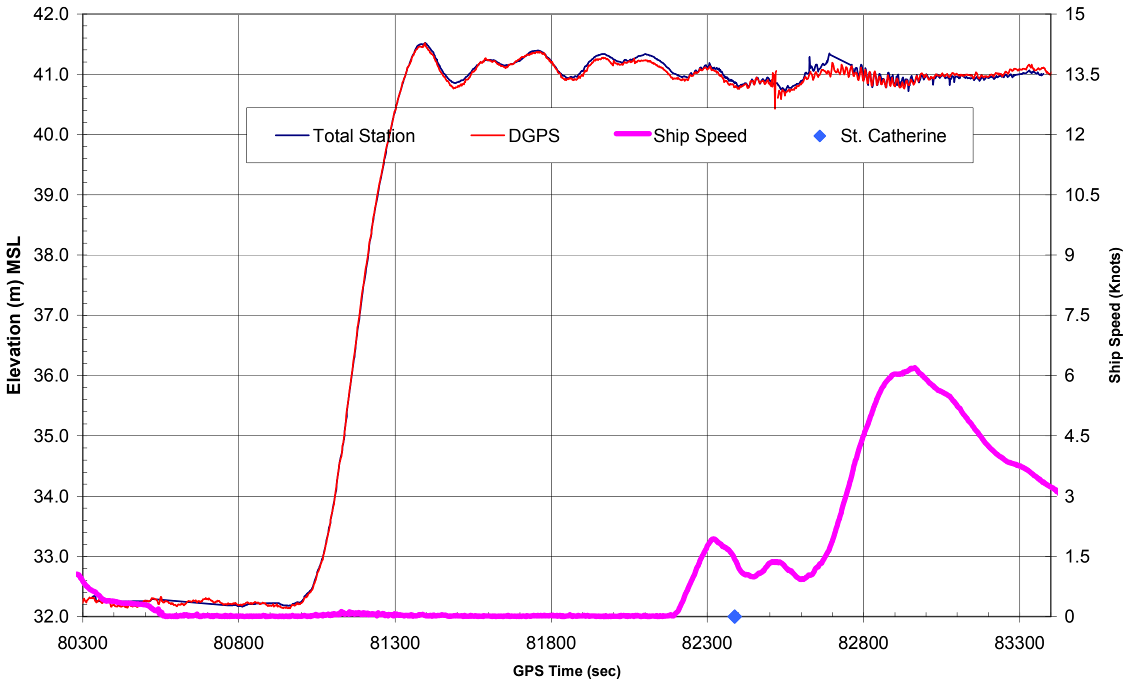


Figure 3.3: Total Station Survey Elevation Comparison
***Turid Knutsen*, Upbound at Cote St. Catherine**

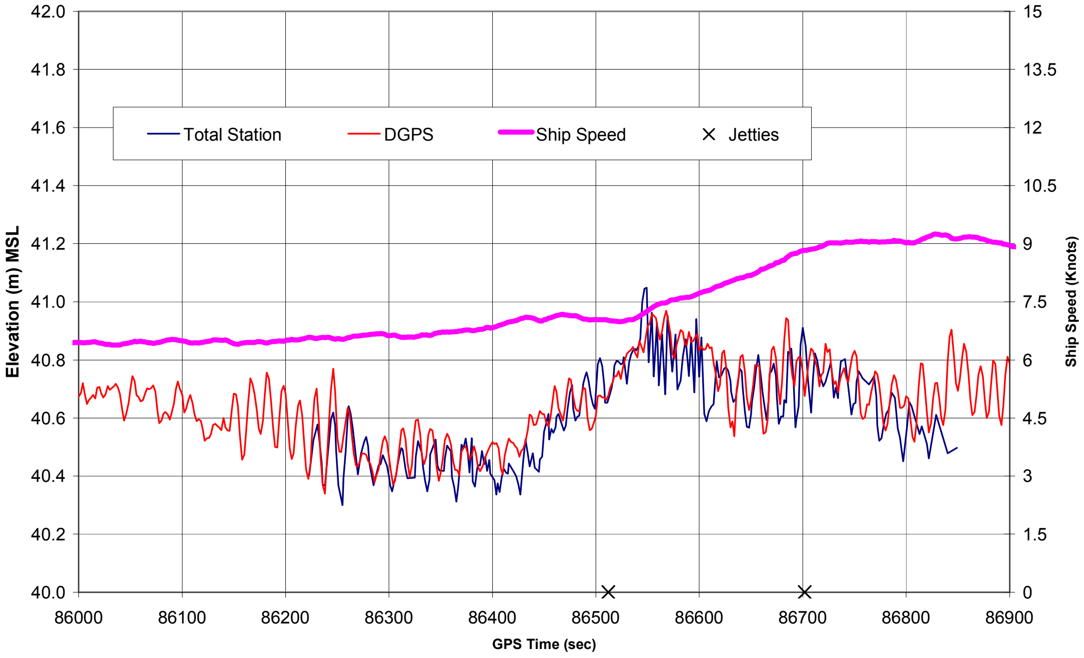


Figure 3.4: Total Station Survey Elevation Comparison
***Turid Knutsen*, Upbound at End of Jetties**

3.4 Four-Gauge Plots

The initial analysis involved plotting and analyzing the elevation change (sinkage) of each of the four DGPS antennae during the ship transits. The sinkage was relative to a static "zero" antenna elevation at one end of the transit reaches. For the lower pool of the South Shore Canal, between St. Lambert and Cote St. Catherine Locks, the static reading for the ship was made in the upper level of St. Lambert Lock. In the upper pool of the canal and the seaway section through Lake St. Louis, the static readings at either the upper level of Cote St. Catherine Lock or the lower level of Lower Beauharnois Lock were used as the reference elevation. For the extended reaches above the Beauharnois Locks, the ten-minute static readings were taken in the lower level of Snell Lock and the upper level of Eisenhower Lock. After subtracting the static elevation from the DGPS elevations recorded during the transits, an elevation adjustment for water surface slope along the channel between Chateauguay River and Lower Beauharnois Lock was made as discussed in section 2. In each channel segment for which this adjustment was made, the slope was approximated as a straight line along the channel centreline.

3.4.1 Midpoint Squat Plots

After the four-gauge plots were generated, calculations were made to geometrically transfer the recorded sinkage data to the ship's midpoint. This process was significant because squat is normally defined as the sinkage at the midpoint combined with the ship's trim. Figures 3.5 and 3.6 show examples of plots of midpoint squat and trim recorded during the study in the South Shore Canal and Lake St. Louis. Figure 3.7 shows similar data for the extended reaches above Beauharnois in Lake St. Francis and the Wiley Dondero Canal. On the horizontal axis in the plots are symbols that indicate when the instrumented ship passed notable features (benchmarks) along the channel.

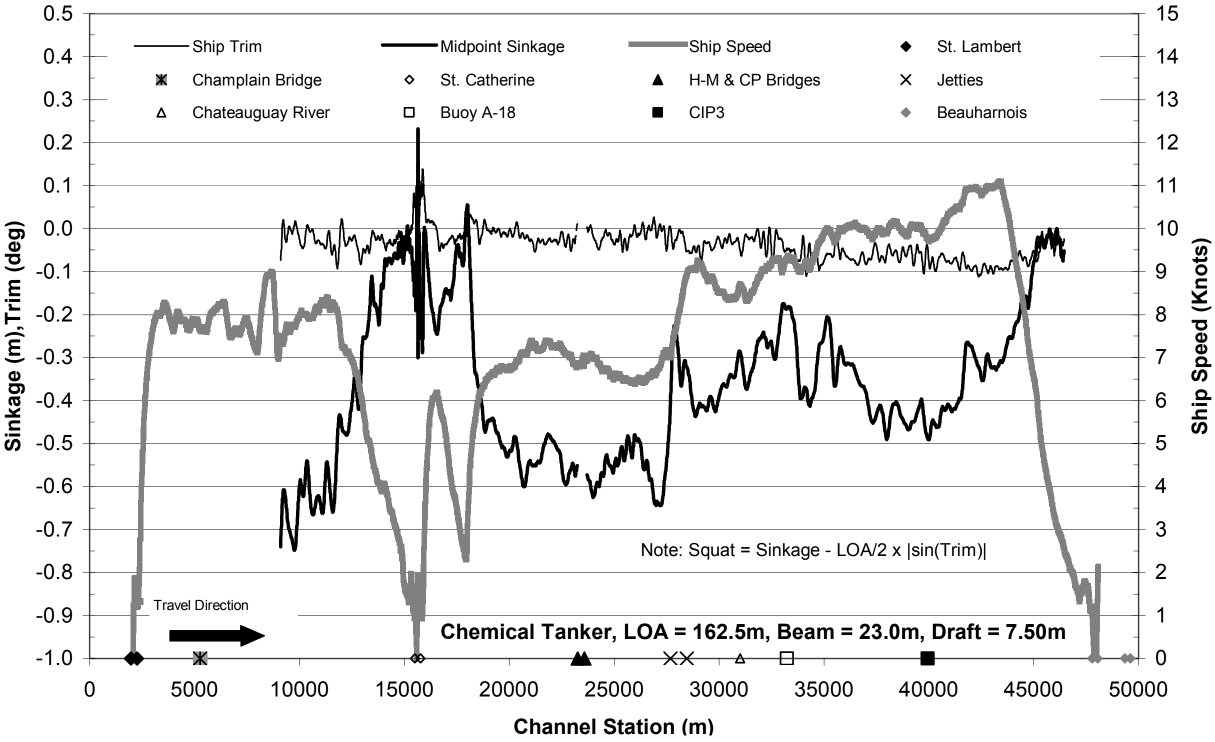


Figure 3.5: Midpoint Sinkage and Trim vs. Channel Station
***Turid Knutsen*, 12 November 2000**

It should be noted that the general magnitude of sinkage is in the range of 0.5 to 0.6 m in the canal in speeds in the range of 7 to 8 kn. After exiting the jetties, even though the ship speeds up to 11 kn the sinkage reduces significantly to about 0.3 m. This general trend was observed in the majority of ship transits analyzed. This was an indication of the change between a canal-type channel and open water conditions (trench-type channel) and required different formulas to be used for the segment analysis.

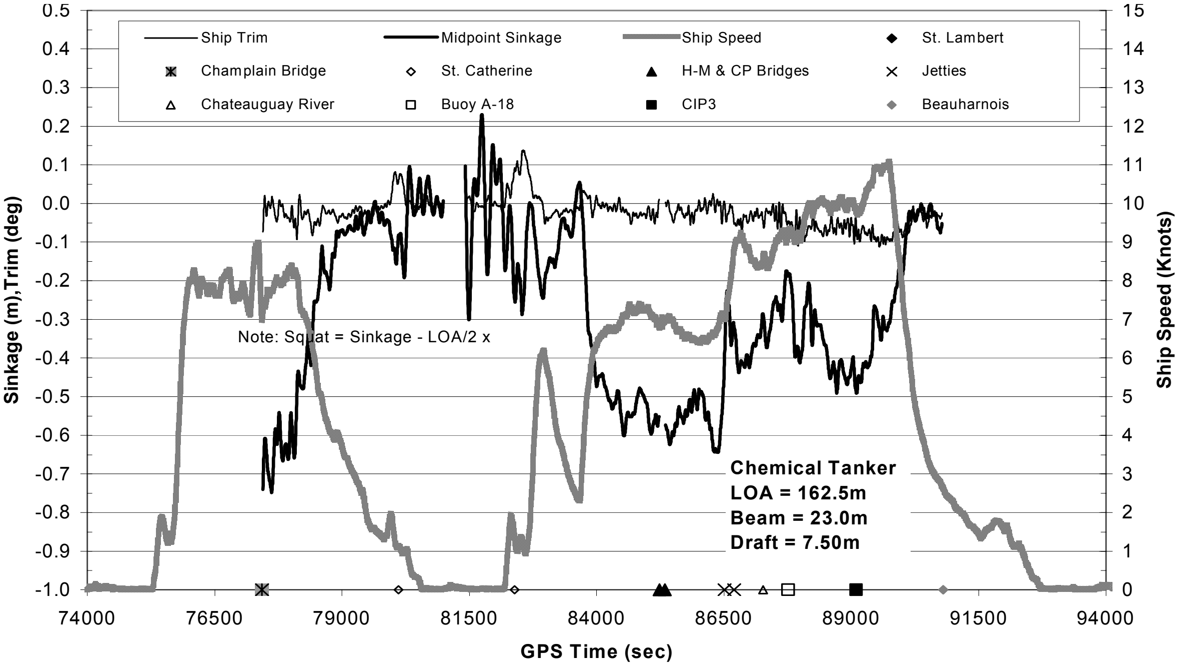


Figure 3.6: Midpoint Sinkage and Trim vs. GPS Time
***Turid Knutsen*, 12 November 2000**

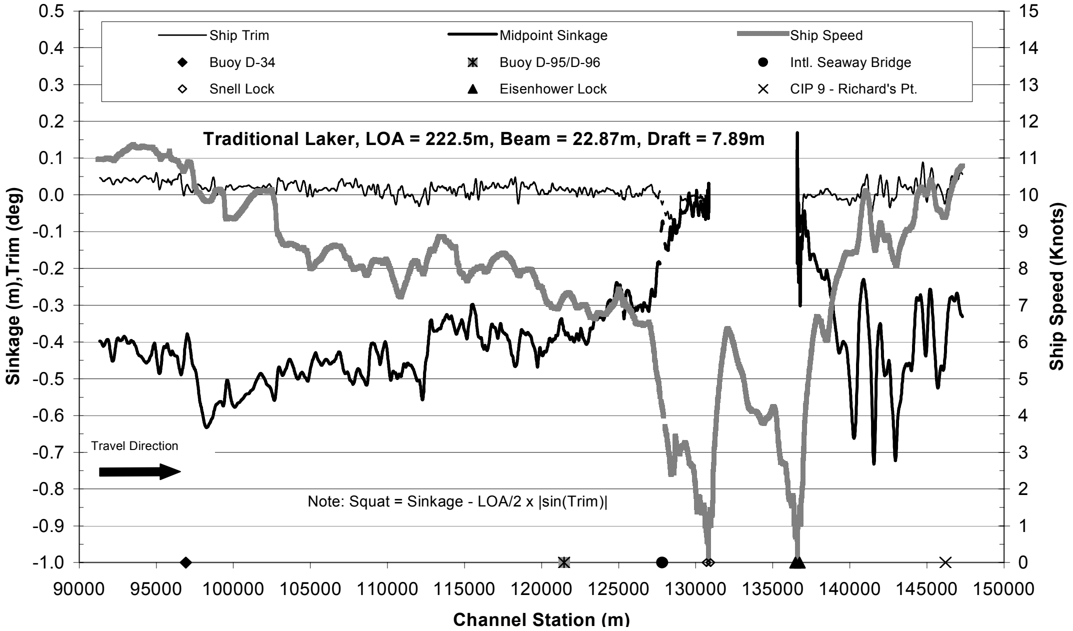


Figure 3.7: Midpoint Sinkage and Trim vs. Channel Station *Halifax* in Lake St. Francis and Wiley Dondero Canal, 3 November 2000

3.4.2 Channel Cross-sectional Area

Several of the squat prediction formulas also have parameters related to cross sectional (wetted) channel area. Hydrographic survey data from St. Lawrence Seaway Management Corporation and St. Lawrence Seaway Development Corporation were used to calculate the channel area in the test reaches according to the following procedure:

- Determine existence of banks from charts.
- Compute area of channel between slope toes using water depth derived form measured water surface and bottom elevations.
- If both sides have banks: extend banks on 1:1 slope to a depth of 4 m.
- If both sides are open: extend sides using average slope of the last 5 m (0 if negative slope) to either 4 m depth or to a point 80 m from channel centreline.
- If one side has a bank and the other is open: extend bank or side according to the appropriate method above.

When the cross sectional area as defined above was used in several of the squat prediction formulas between St. Lambert and Cote St. Catherine Locks, it became apparent that the method yielded sharp changes in area magnitude, causing the formulas to behave badly and produce unrealistic results. Further analysis of the available channel data resulted in the following revised procedure for calculation of channel area.

- Between St. Lambert and Cote St. Catherine Locks
  - Set width to 100 m
  - Compute area with constant width, water depth, and ½ bank slopes
- Above Cote St. Catherine Lock
  - Use initial method

3.5 Under-Keel Clearance and Channel Bottom Highpoints

One of the objectives of the study was to determine the UKC experienced by the instrumented ships. The keel elevation was obtained by reducing the elevation of the GPS antennae by an amount equal to the perpendicular vertical distance to the ship's keel. The vertical keel distances were obtained predominantly from ship general arrangement drawings collected while onboard. The process of determining keel elevations at different locations on the ships was aided by using the keel elevations at three of the GPS gauges (bow, port and starboard bridge wings) to generate a general equation for the keel plane in three dimensions. With the derived plane equation, the elevation of the keel was calculated by determining the horizontal coordinates at any specific point on the ship (e.g., the midpoint). Because of the difficulty of obtaining detailed mathematical descriptions of the ship hulls, the keel plane was assumed to extend to the extreme outside limits of the hull on the side and at the bow and stern. The minimum keel plane elevation for the ships was established at each time step by applying the trim to the midpoint sinkage and then accounting for the roll (rotation about the longitudinal axis). This process yielded a conservative estimate of the minimum ship hull elevation because of the assumption of the keel as a plane extending to the four corners of the ship's length and beam.

Once the minimum keel plane elevation was established, the clearance to the bottom of the channel was determined as the difference between this value and the maximum channel bottom elevation data at the ship location. The channel bottom elevation was primarily based on SLSMC hydrographic survey data. For areas with missing survey data, the elevations were obtained from the EC hydrographic survey conducted as part of this study. The bottom elevations were obtained by identifying the elevation of the nearest survey point under the ship at the midpoint cross section at five points across the ship beam – the edges of the beam, centre and quarter points.

After plotting UKC against channel station, negative UKCs appeared in the data. The opportunity was taken to use these conditions as a general method to verify the overall analysis process. For one transit, the location of negative UKCs was used to search for "high spots" in the channel bottom elevation data. Figures 3.8 to 3.10 graphically show the process used for this investigation.

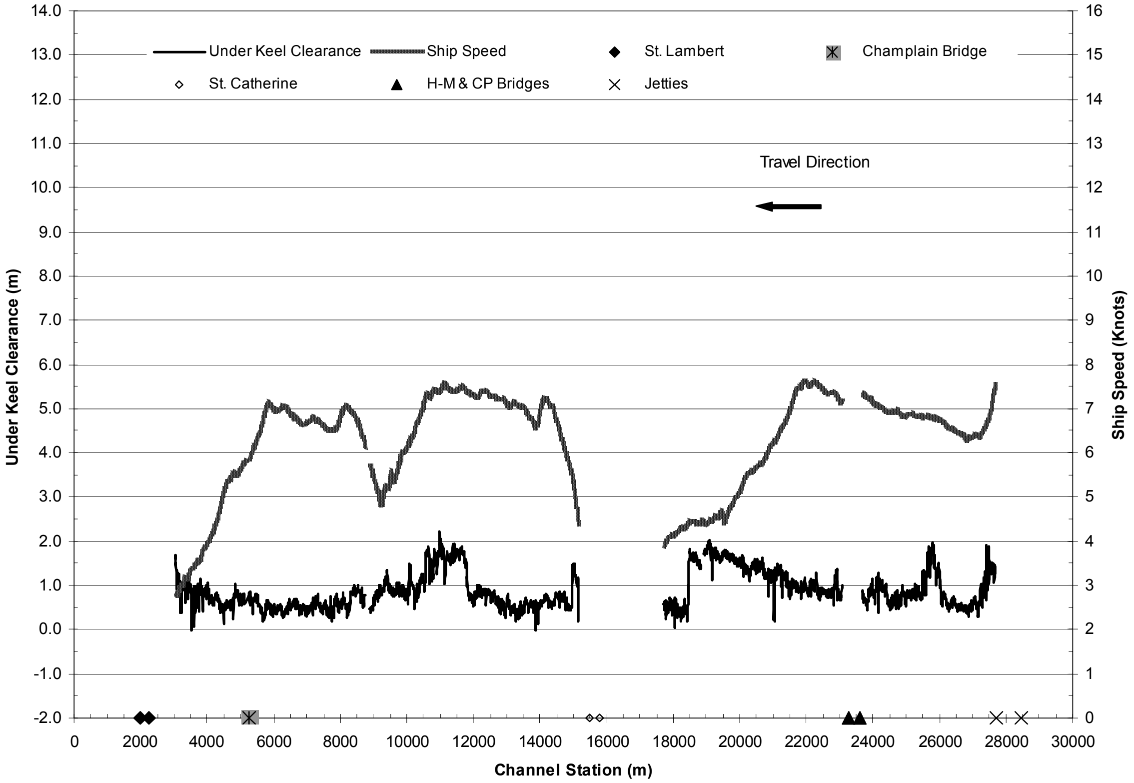


Figure 3.8: UKC During Transit of *Blade Runner*, 30 October 2000, South Shore Canal

Two of the negative UKC events occurred at station 3535 and 13870, respectively, in the South Shore Canal. In Figures 3.9 and 3.10, actual plotted cross-section elevation data from SLSMC show that there were high spots in the bottom at both of these channel locations. To assist in identifying whether all negative UKC values were associated with high bottom elevations, a list of all UKC values less than 5 cm was developed with the locations, speed, squat, UKC, minimum keel elevation and bottom elevations identified and is presented in Table 3.2.

Locations of high points in the SLSMC hydrographic survey data are presented in both the coordinate system used for this study and the coordinate system used for the surveys to assist in locating these high spots.

Where a series of low UKC values were identified over a short distance, the range is identified and the average speed, maximum squat, minimum UKC, minimum keel elevation, and maximum bottom elevation are included in the table. Specific high points in the hydrographic survey were not located for these reaches.

The physical cause of the high spots is unknown and could be the result of erroneous soundings or unusual bottom conditions; however, this analysis indicates that the process used during the study for determination of UKC was reliable since all negative UKC values were the result of unusually high bottom elevations. It should be noted that the magnitude of the UKC calculated during the study erred, necessarily, on the conservative side. This assertion is made on the basis that, as far as is known, no groundings (negative UKC) occurred during the recorded transits; therefore, the calculation of negative values must be conservative.

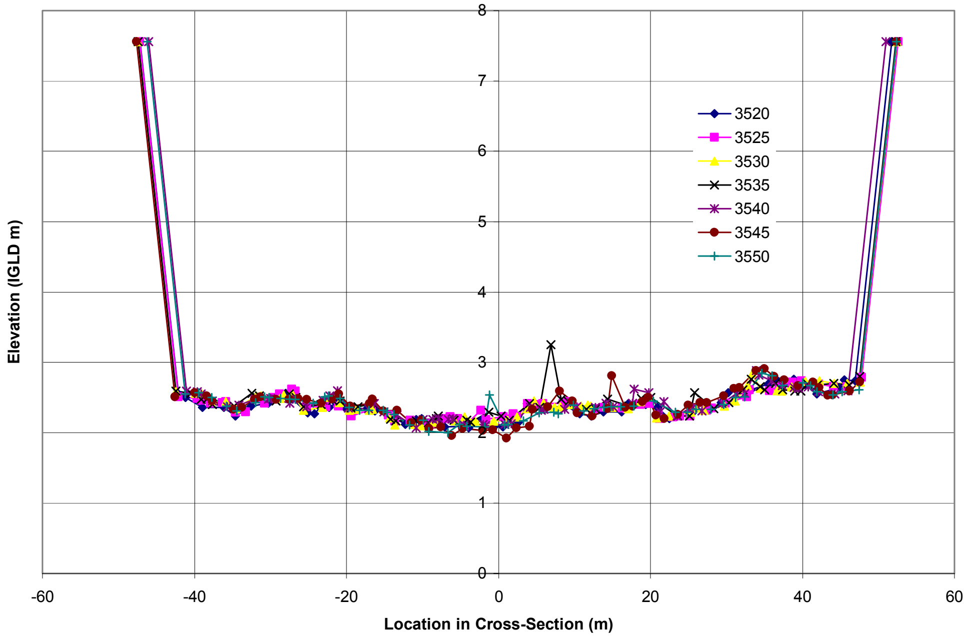


Figure 3.9: SLSMC Bottom Elevation X-Section @ Station 3535

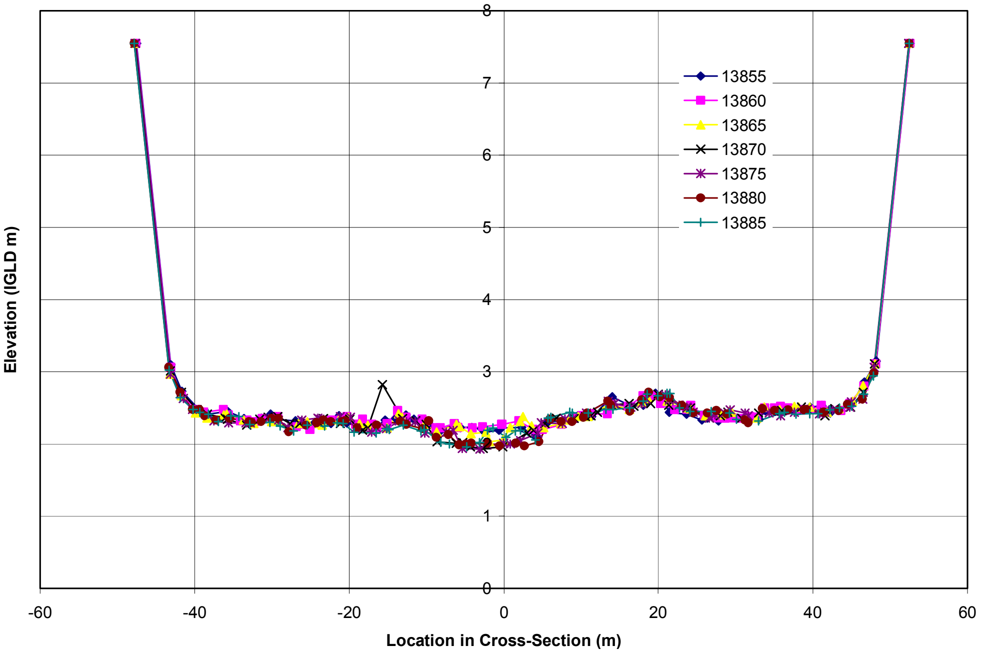


Figure 3.10: SLSMC Bottom Elevation X-Section @ Station 13870

3.6 Squat Analysis

The analysis of squat was based on graphical and statistical comparisons of measured and calculated values of sinkage and trim. The lower test reaches were separated into two analysis sections because of fundamental differences in channel characteristics. This was done because the canal geometry dictated that restricted water models be used and because early analysis of the measurements indicated that there was a very different ship behaviour at the transition between the canal and the lake at the end of the jetties; i.e., the squat was much less even at higher speeds when the ship was in the unrestricted part of the waterway. The canal portion of the analysis covers the South Shore Canal between St. Lambert Lock and the end of the jetties leading into Lake St. Louis. The lake portion covered the channel from the end of the south jetty to Beauharnois Lock. The canal portion was considered confined water and the appropriate form of the 12 squat prediction equations was used for the transit through this reach. Only a few of the equations had versions appropriate for use in unconfined water such as that in the section through Lake St. Louis. Figures 3.11 and 3.12 show examples of the comparison plots generated for the squat formula analysis. Scatter plots and descriptive statistics were used primarily for choosing the best-fit formulas for the five ship types instrumented during the study. Figures 3.13 and 3.14 show the statistical pattern of the Tuck model predicted and the measured squat for New Laker ships. These were then combined into a single plot for all ships of the same type to develop the overall statistics of the best models for a specific ship type. The UKC for the *CSL Niagara* in the canal and lake is shown in Figures 3.15 and 3.16. A sudden low UKC value is noted around station 1900 in the canal above Lock 2.

Table 3.2: Low Under-Keel Clearance Points in South Shore Canal

									SLSMC Hydrographic Survey							
		UTM NAD83 (meters)			UTM NAD83 (meters)								UTM NAD83 (meters)		MTM 3 deg (using SYREQ)	
Ship	Beg Sta.	North	East	End Sta.	North	East	Min UKC (m)	Min Keel Elev (m)	Block	Water Surface Elev.	Elevation	Depth or Contour	North	East	North	East
ALS316	24185	5029836	604156	24275	5029882	604079	-0.35	12.54	e16		12.80	-7.9				
ATE313	18784	5028958	609160				-0.54	12.33	d14	20.70	12.87	7.83	5028959	609160	5029305	296539
BLR304	18049	5029155	609868				0.05	12.32	d13	20.69	12.27	8.42	5029153	609867	5029485	297250
	13870	5029304	614041				-0.01	2.81	d09	11.57	2.82	8.75	5029294	614041	5029549	301426
	3535	5037544	616272				-0.01	3.24	d05	11.57	3.25	8.32	5037544	616272	5037757	303811
CAV305	4412	5036747	616640				-0.12	3.04	d05	11.57	3.16	8.41	5036747	616638	5036953	304162
	18047	5029153	609870	18051	5029152	609866	0.02	12.29	d13		11.94	-9.0				
CNI315	18782	5028954	609162				-0.47	12.37	d14	20.70	12.84	7.86	5028960	609163	5029306	296542
CNI320	24870	5030076	603520				-0.18	12.51	e16a	20.85	12.69	8.16	5030086	603521	5030537	290921
FEF298	17791	5029198	610124	18394	5029056	609539	-0.32	11.89	d12b		11.63	-9.1				
	18785	5028954	609161				-0.79	12.08	d14	20.70	12.87	7.83	5028959	609160	5029305	296539
	24872	5030077	603520				-0.74	11.95	e16a	20.85	12.69	8.16	5030086	603521	5030537	290921
FOS304	3855	5037257	616414				-0.12	3.26	d05	11.57	3.38	8.19	5037253	616404	5037463	303937
	4494	5036677	616683				0.03	3.05	d05	11.57	3.02	8.55	5036672	616674	5036877	304197
	17727	5029213	610185				-0.13	12.06	d13	20.69	12.19	8.50	5029221	610184	5029548	297568
	17953	5029169	609963	17960	5029168	609956	-0.13	12.13	d13		12.19	-8.5				
	18048	5029150	609870				-0.04	12.23	d13	20.69	12.27	8.42	5029153	609867	5029485	297250
HAL308	9658	5031592	617165	9699	5031552	617155	-0.22	3.13	E07		3.39	-8.2				
JBA314	17725	5029213	610187				-0.18	12.01	d13	20.69	12.19	8.50	5029221	610184	5029548	297568
	17789	5029202	610124	17802	5029200	610112	0.05	12.01	d12b		11.63	-9.1				
	17922	5029174	609994	18430	5029048	609502	-0.22	11.89	d13		12.19&11.69	-8.5&-9.0				
LAC315	7815	5033426	617209				-0.06	2.72	e06a	11.57	2.78	8.79	5033426	617208	5033621	304670
	8907	5032336	617263	9058	5032184	617258	-0.24	2.72	e07		3.19	-8.4				
	9461	5031783	617212	9548	5031698	617196	-0.24	2.72	e07		2.59	-9.0				
	9627	5031621	617179	9683	5031566	617166	-0.05	2.79	e07		2.59	-9.0				
	18450	5029053	609480				-0.16	12.16	d13	20.69	12.32	8.37	5029062	609479	5029402	296860
	21027	5028516	606975				-0.05	11.75	e15	20.74	11.80	8.94	5028512	606973	5028899	294344
	21058	5028517	606944				-0.09	11.76	e15	20.74	11.85	8.89	5028505	606940	5028892	294311
MAN301	24201	5029848	604146				-0.02	12.66	e16a	20.85	12.68	8.17	5029836	604140	5030275	291536
MAR297	3536	5037547	616282				-0.16	3.09	d05	11.57	3.25	8.32	5037543	616273	5037756	303812
	4412	5036747	616638				-0.33	2.83	d05	11.57	3.16	8.41	5036747	616639	5036953	304163
	17954	5029170	609963				-0.06	12.21	d13	20.69	12.27	8.42	5029158	609967	5029489	297350
	18051	5029146	609868				-0.13	12.14	d13	20.69	12.27	8.42	5029153	609867	5029485	297250
PMA299	17798	5029197	610116				-0.04	11.99	d13	20.69	12.03	8.66	5029190	610117	5029518	297500
	17838	5029190	610077	17844	5029189	610071	-0.04	11.98	d13		12.19	-8.5				
	17897	5029178	610019	18426	5029047	609507	-0.33	11.84	d13		12.19&11.69	-8.5&9				
	18783	5028955	609162				-0.97	11.90	d14	20.70	12.87	7.83	5028959	609160	5029305	296539
	19378	5028799	608587				-0.23	11.85	d14	20.70	12.08	8.62	5028791	608590	5029147	295966
TUK317	18781	5028955	609163				-0.03	12.81	d14	20.70	12.84	7.86	5028960	609163	5029306	296542

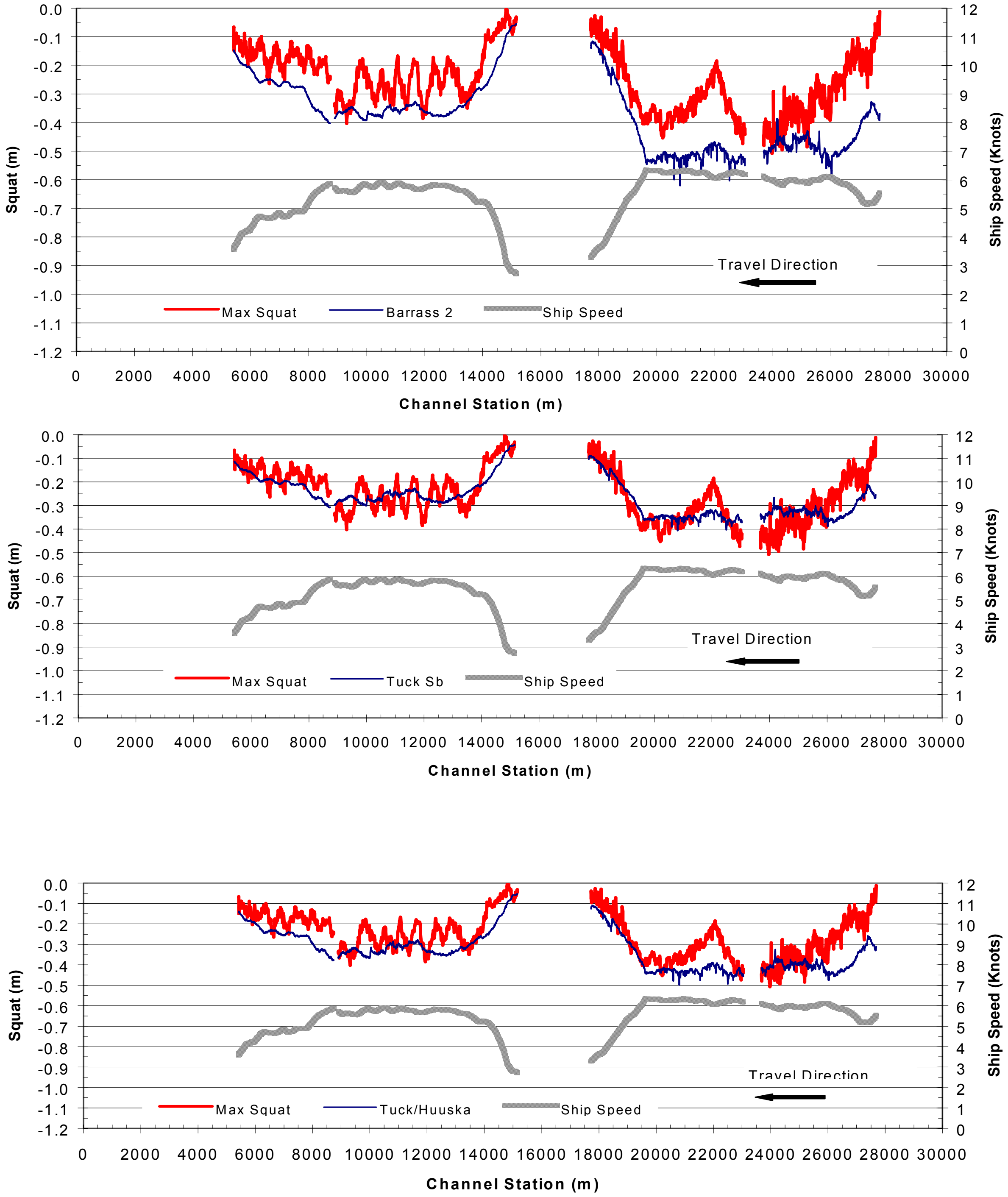


Figure 3.11: ***CSL Niagara*** **in South Shore Canal Comparison of Squat Prediction Methods**

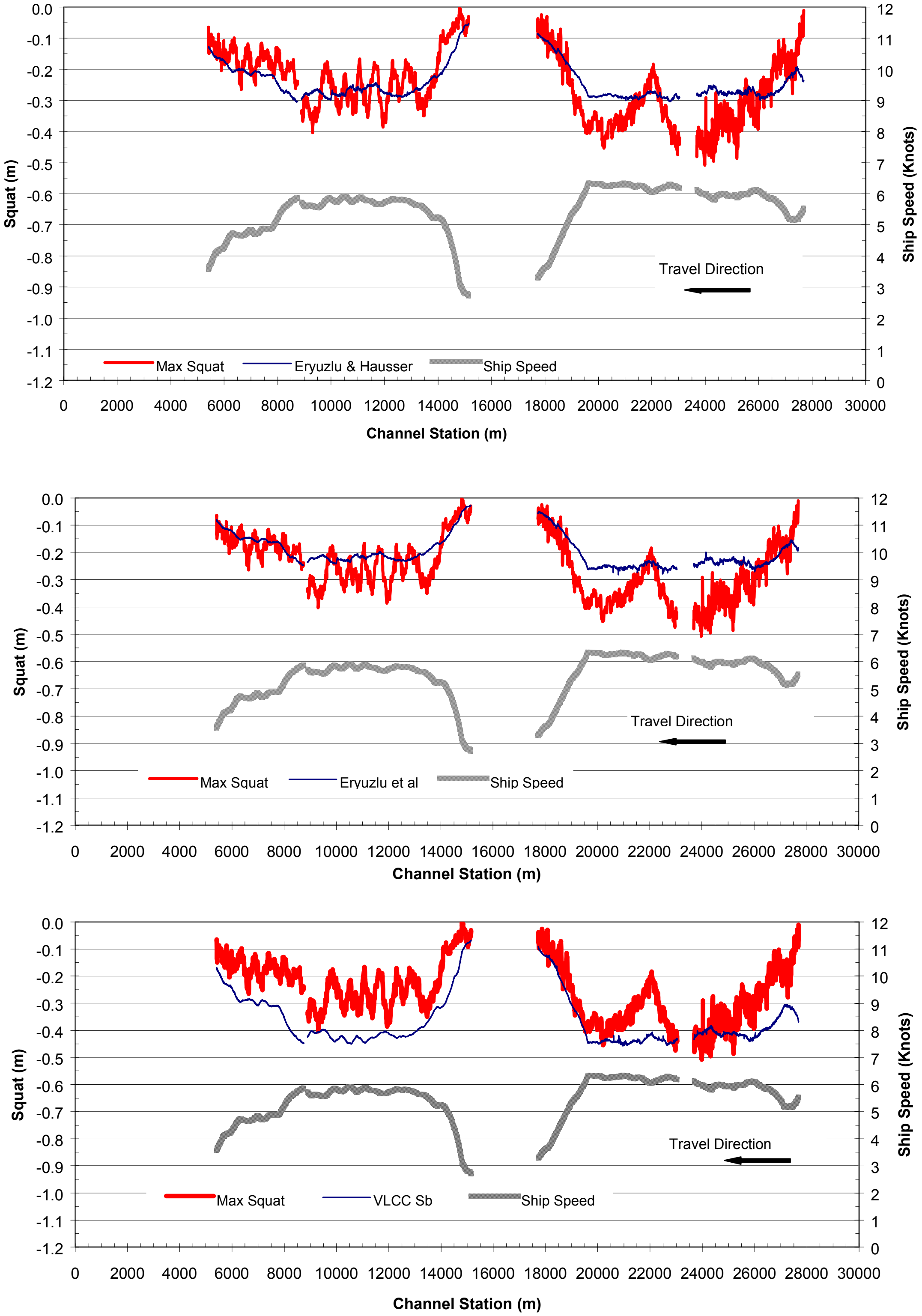
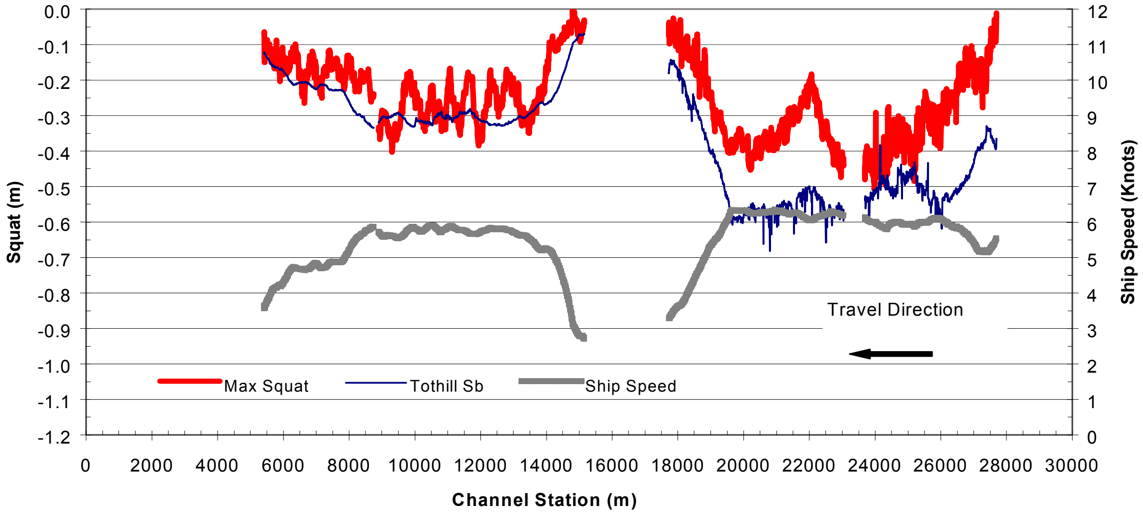
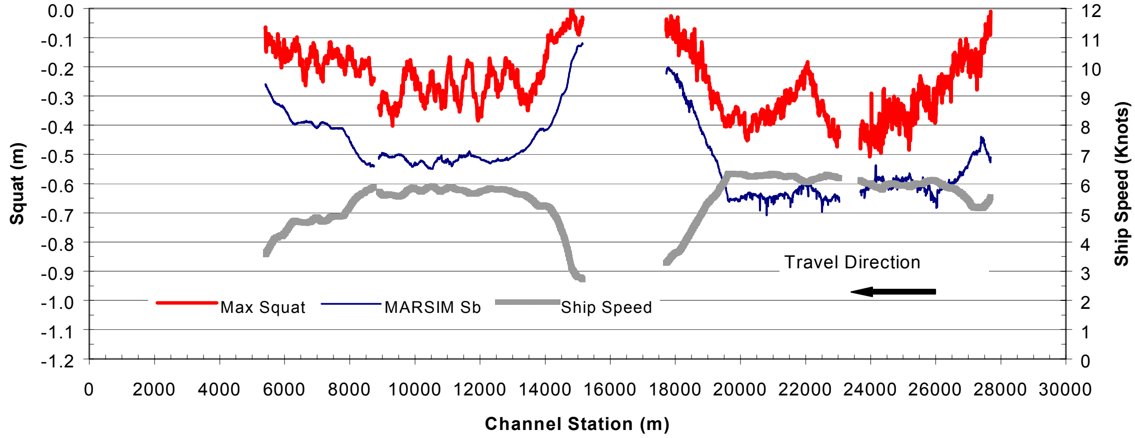


Figure 3.11: Continued





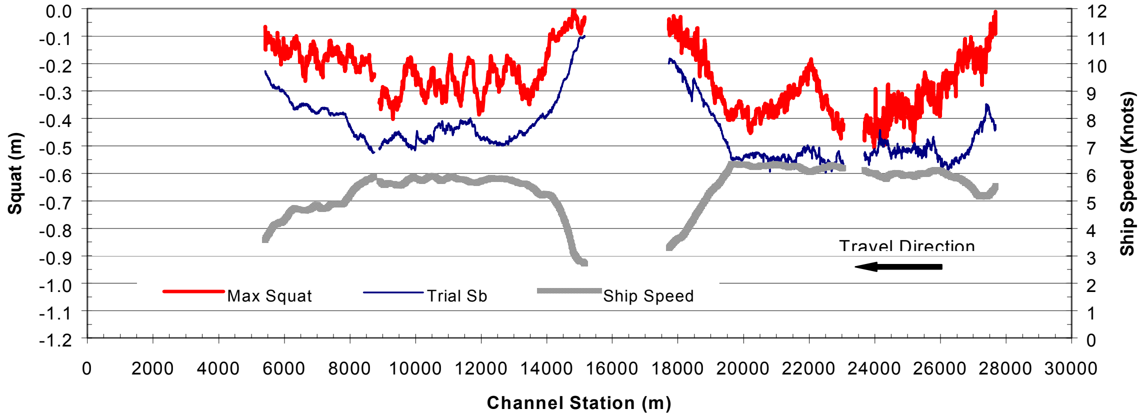


Figure 3.11: Continued

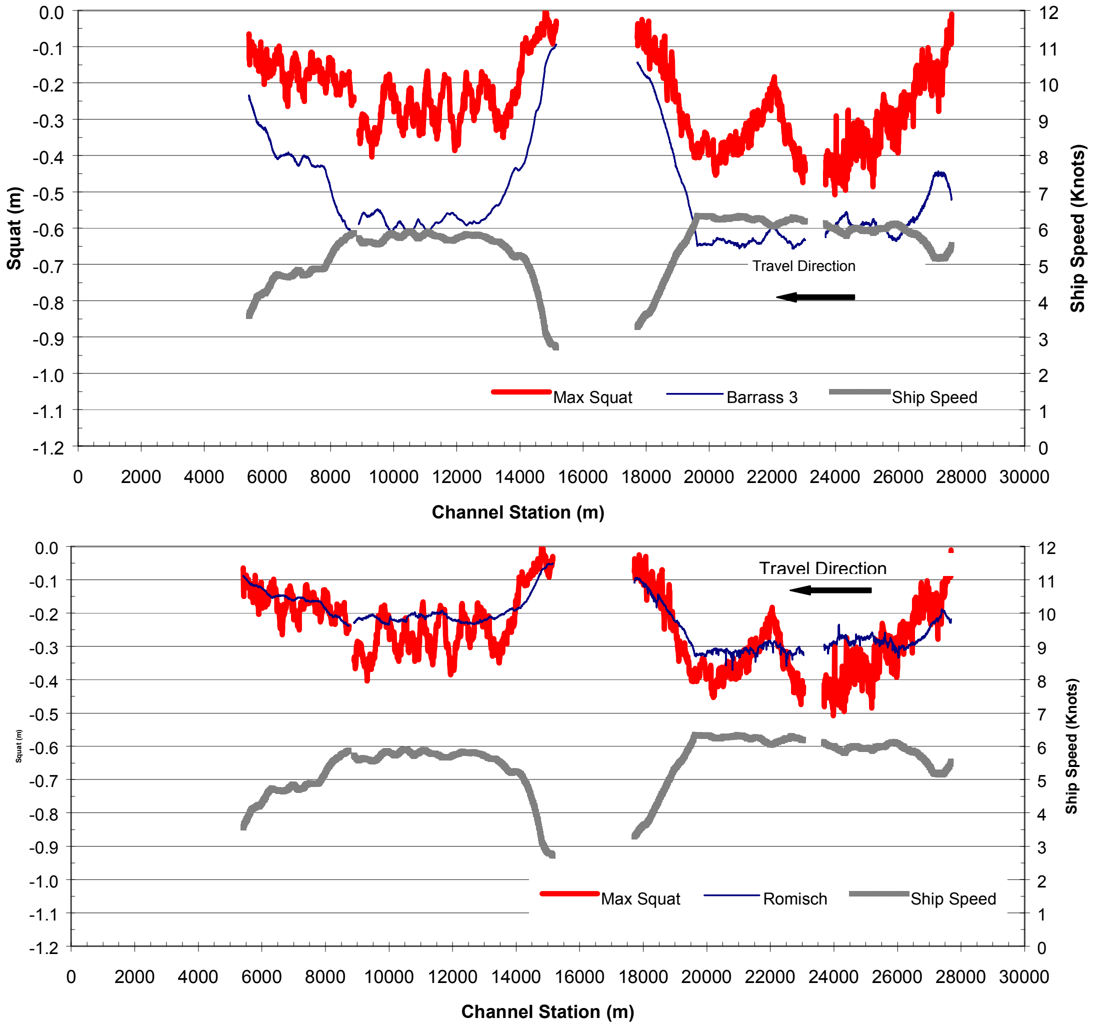


Figure 3.11: Continued

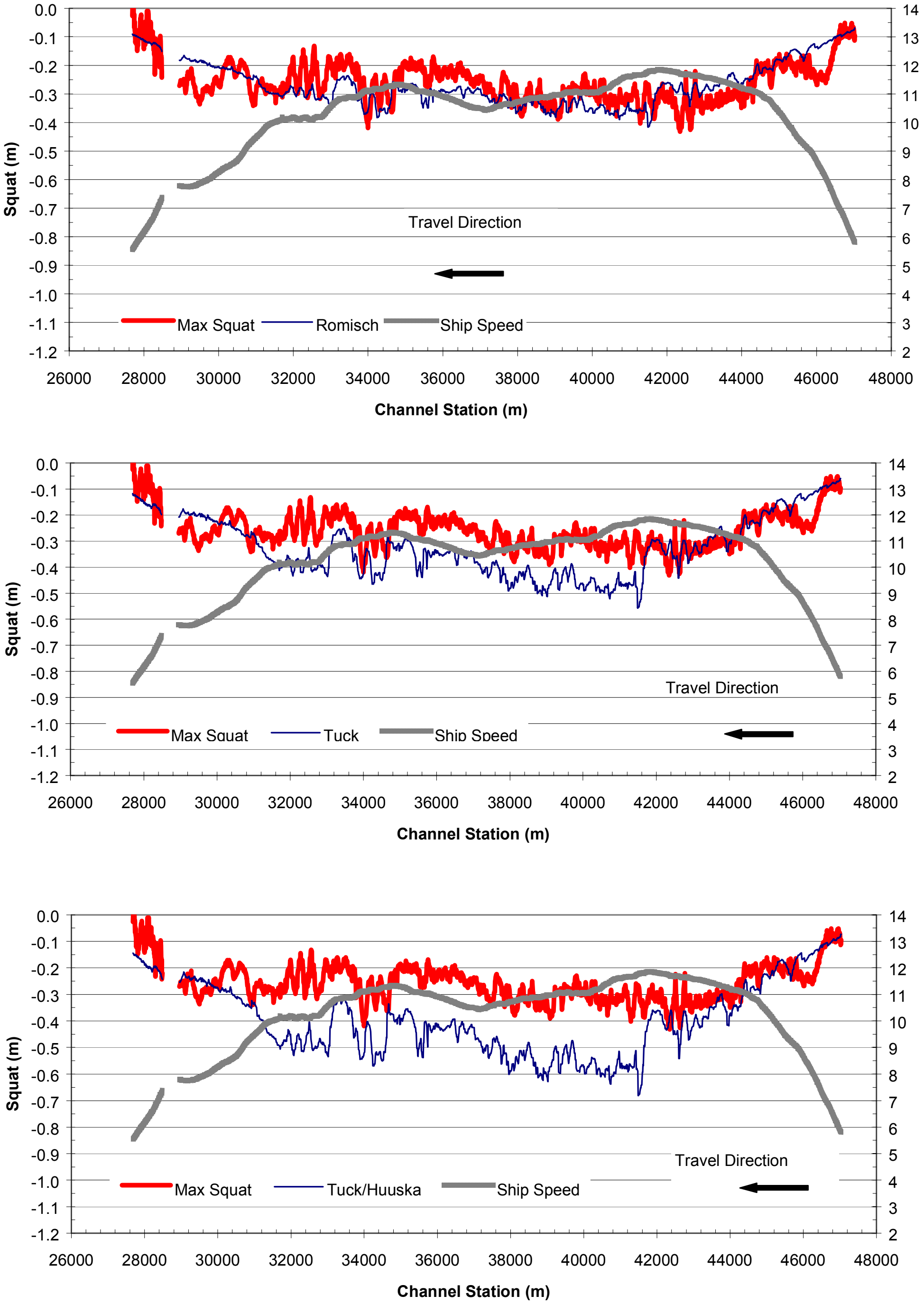


Figure 3.12: ***CSL Niagara* in Lake St. Louis Comparison of Squat Prediction Methods**

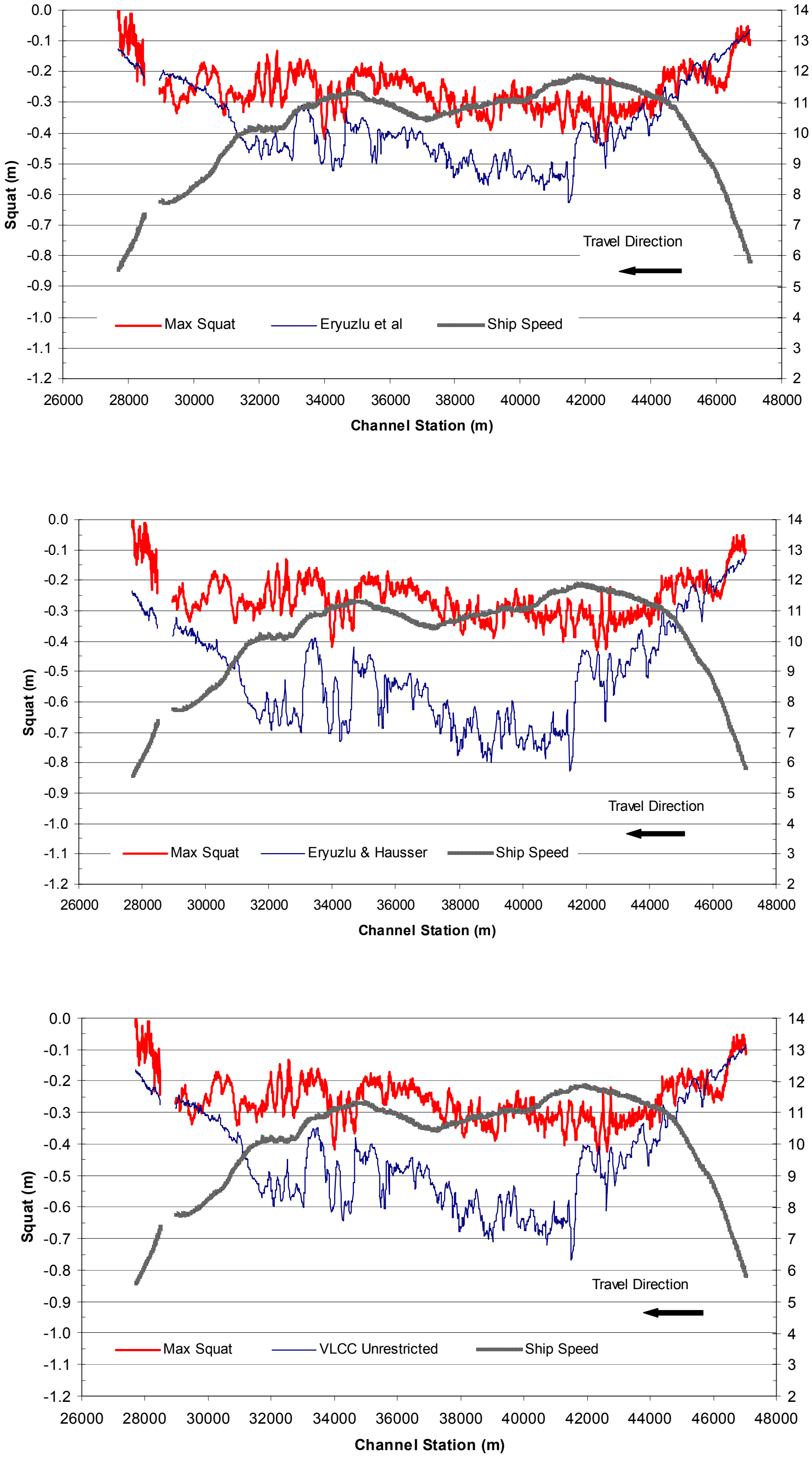


Figure 3.12: Continued

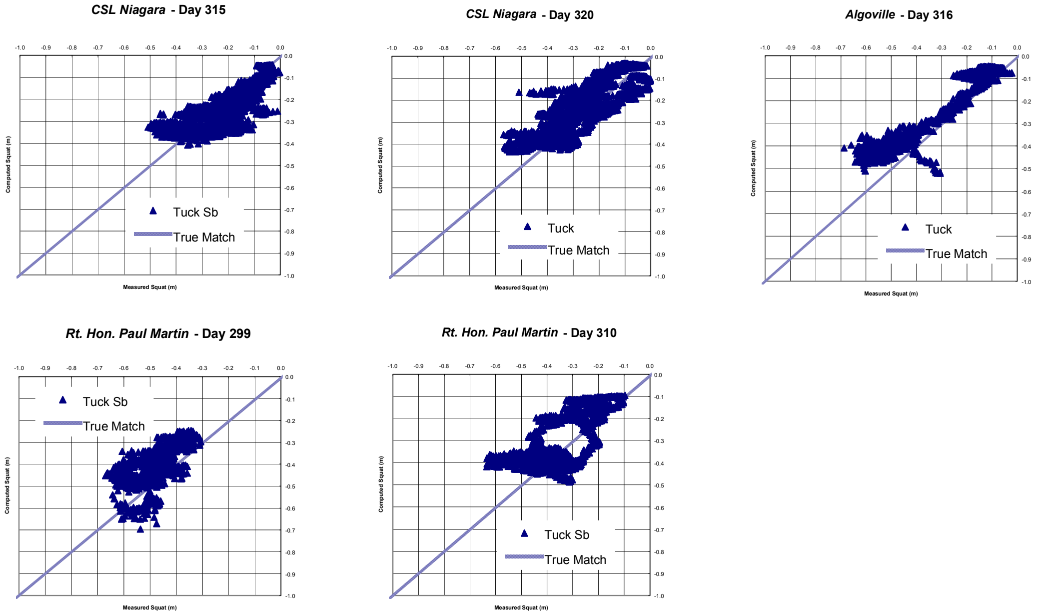


Figure 3.13: Tuck Applied to New Lakers in the South Shore Canal

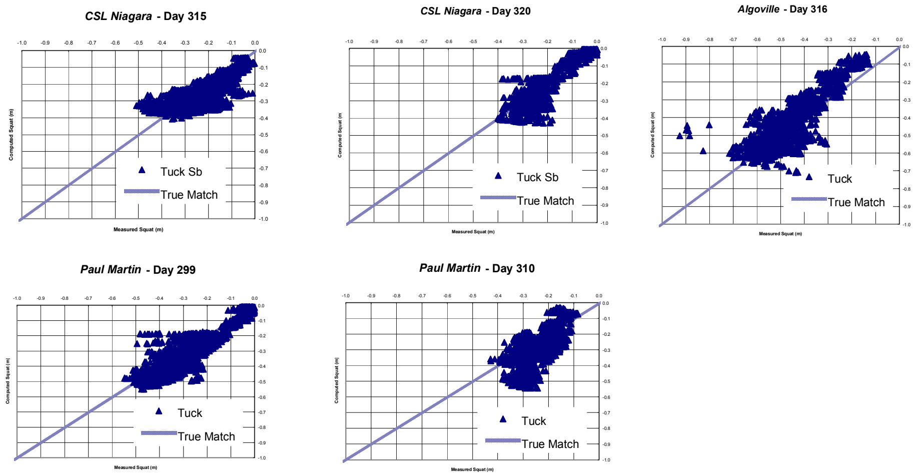


Figure 3.14: Tuck Applied to New Lakers in the Lake

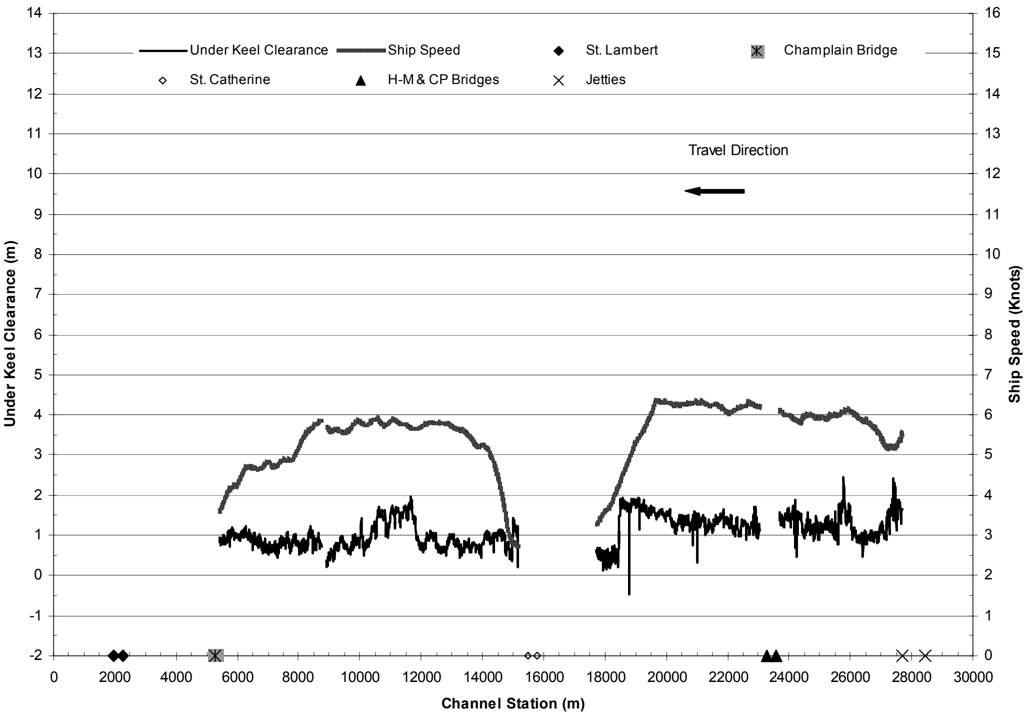


Figure 3.15: Under-Keel Clearance of *CSL Niagara* in South Shore Canal

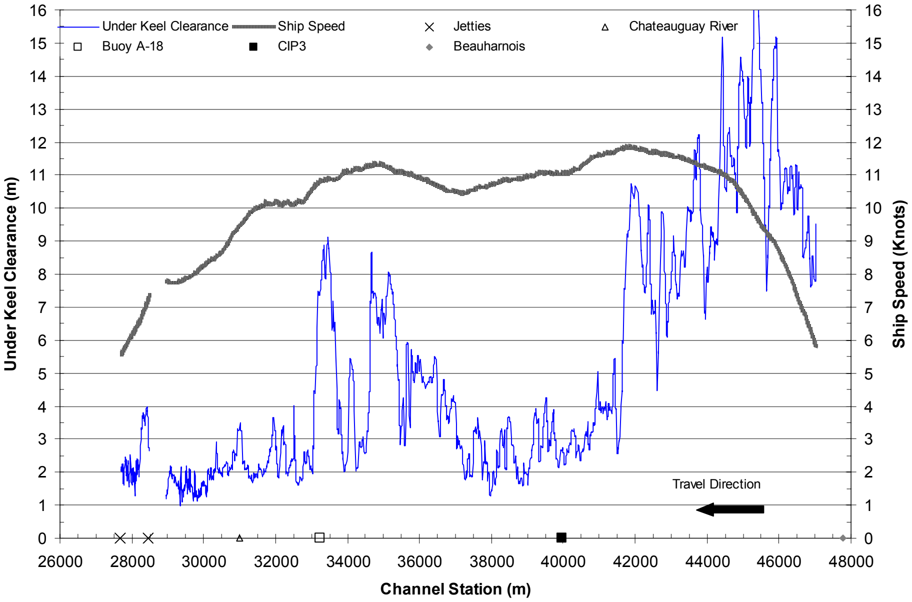


Figure 3.16: Under-Keel Clearance *CSL Niagara* in Lake St. Francis

3.6.1 Extended Reaches

A similar analysis was performed for the extended reach ship transits as for the lower test reach transits. An example of the UKC is shown in Figures 3.17 and 3.18 for Lake St. Francis and the Wiley-Dondero Canal, respectively. Significant depth changes can be observed along the channel. The channel depths were primarily obtained from the EC survey boat measurements. Similar dramatic changes in depths and hence, UKC, can be observed for the Wiley-Dondero Canal.

It should be noted that the channel data and water level data for the extended reaches were not as complete as for the lower test reaches. There were little hydrographic survey data available for the Lake St. Francis portion of the channel. The water level data were for water level gauges that were widely separated and not located along the navigation channel. As a result, the computations for the vessel squat predictions in these reaches cannot be considered as accurate as for those in the lower reaches. The channel depths were derived from the EC survey boat data and, because there were no data defining the channel beyond the navigation channel toe-line, the area was computed in a similar manner to that used in the canal section between St. Lambert and Cote St. Catherine Locks (i.e., the bottom width was assumed to be a constant 135 m and the side slopes were assumed to be 1:2 with no overbank water depths). This was done for both Lake St. Francis and the Wiley-Dondero Canal. The water depths and the channel cross sectional areas varied considerably more in these reaches than in the lower reaches.

Comparative plots of the measured squat at the mid-ship point and the predictive models were analyzed in a similar manner as in the lower test reaches. The same models were used for the Lake St. Francis analysis as were used in the Lake St. Louis analysis. Similarly, the same models were compared in the Wiley-Dondero Canal as were analyzed in the South Shore Canal. Figure 3.19 shows the comparison of some of the predictive squat models to the measured squat. It should be noted that the models generally underpredicted the squat for the New Laker and the Traditional Laker ship types in the Wiley-Dondero Canal. It is unclear what the cause for this underprediction is at this time. Scatter plots of the measured and predicted squat were generated for analysis of the accuracy of the predictions (see Figure 3.20).

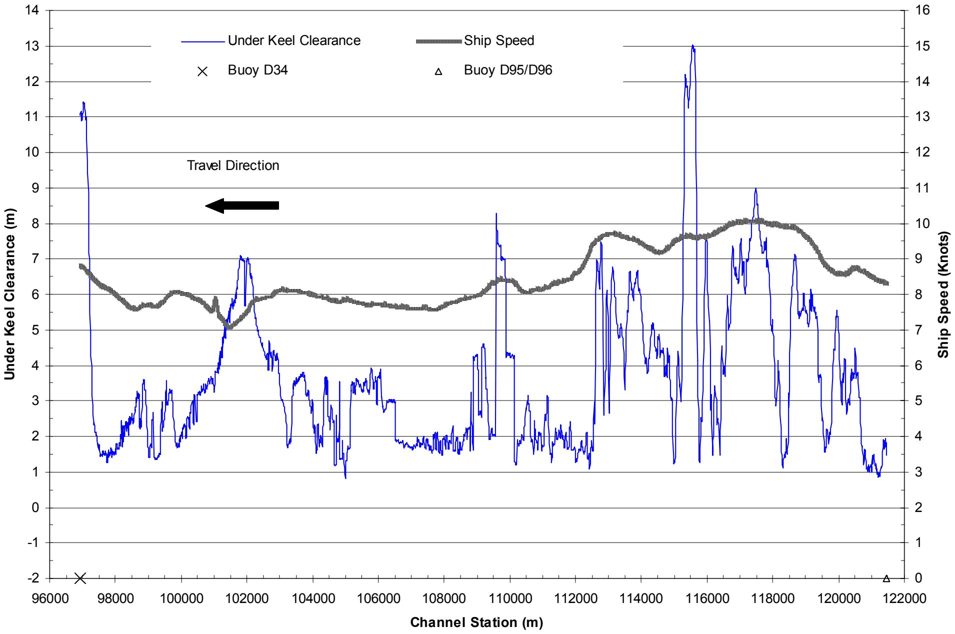


Figure 3.17: Under-Keel Clearance of *Rt. Hon. Paul Martin* in Lake St. Francis

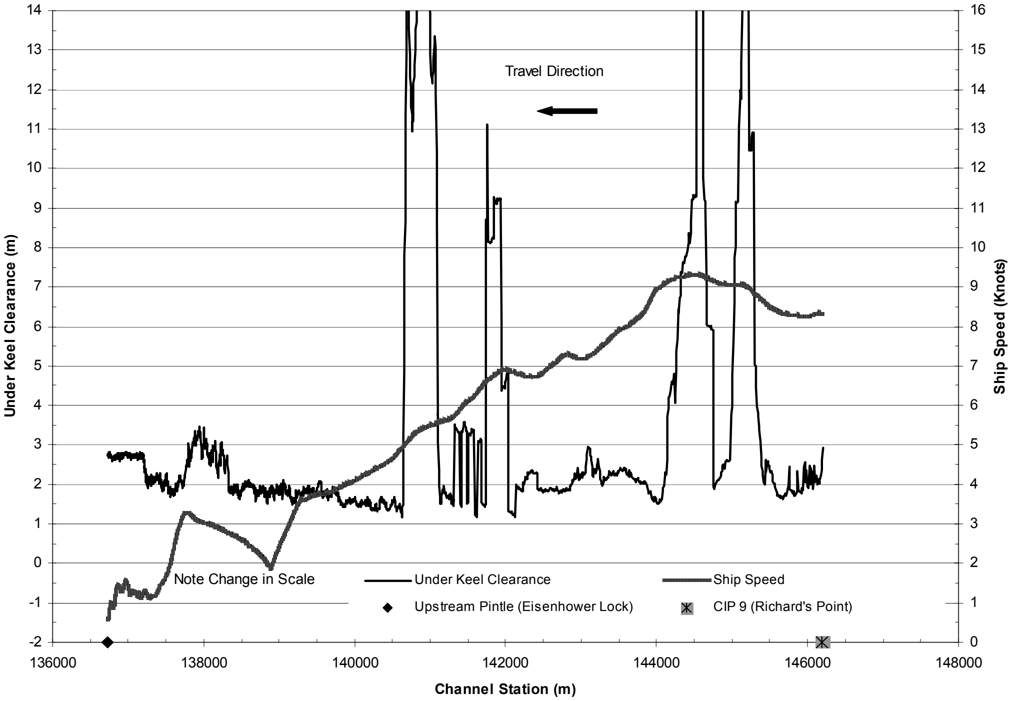


Figure 3.18: Under-Keel Clearance of *Rt. Hon. Paul Martin* in the Wiley-Dondero Canal

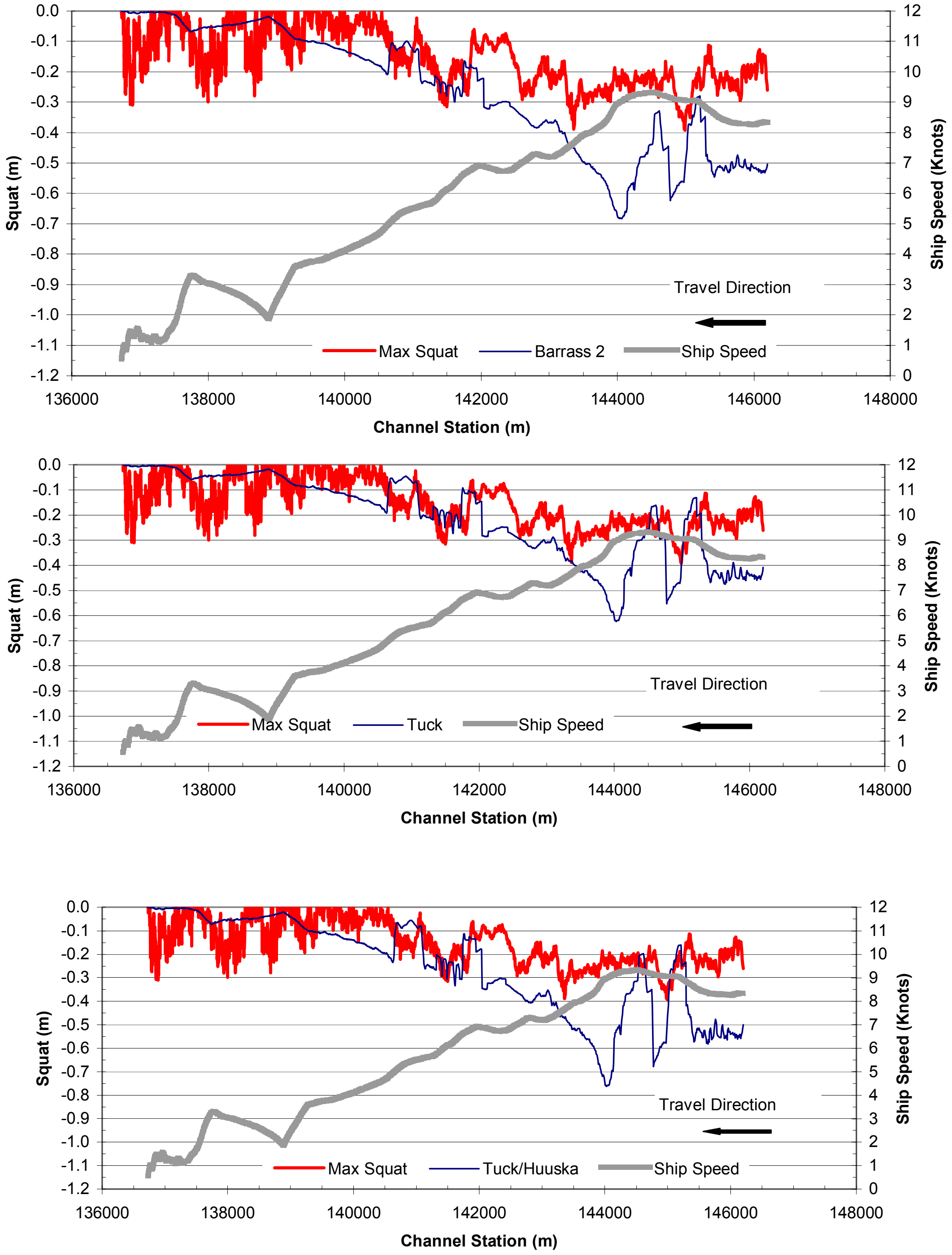
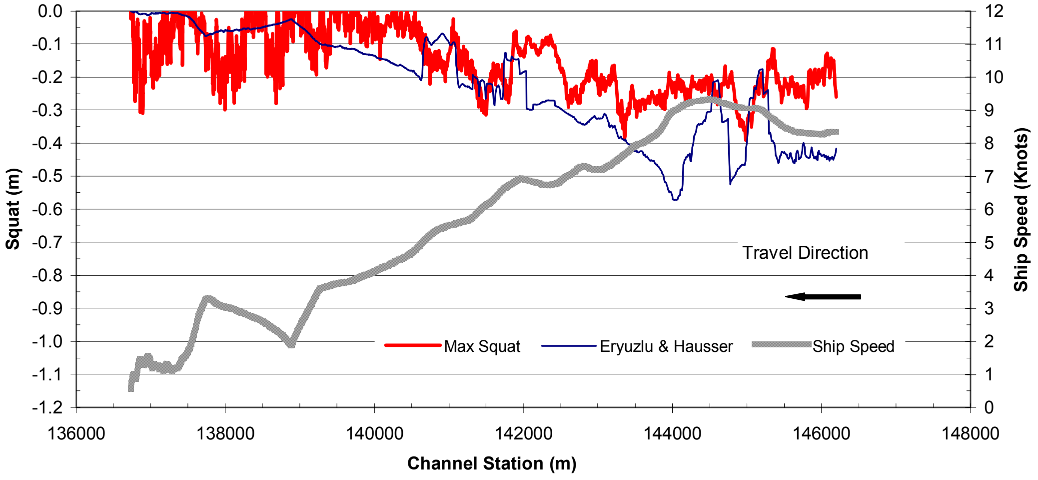
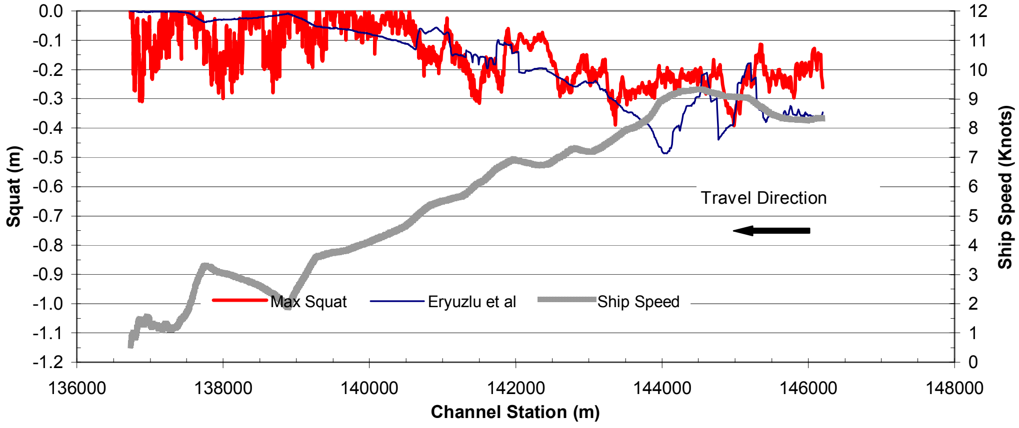


Figure 3.19: *Rt. Hon. Paul Martin* in Wiley-Dondero Canal





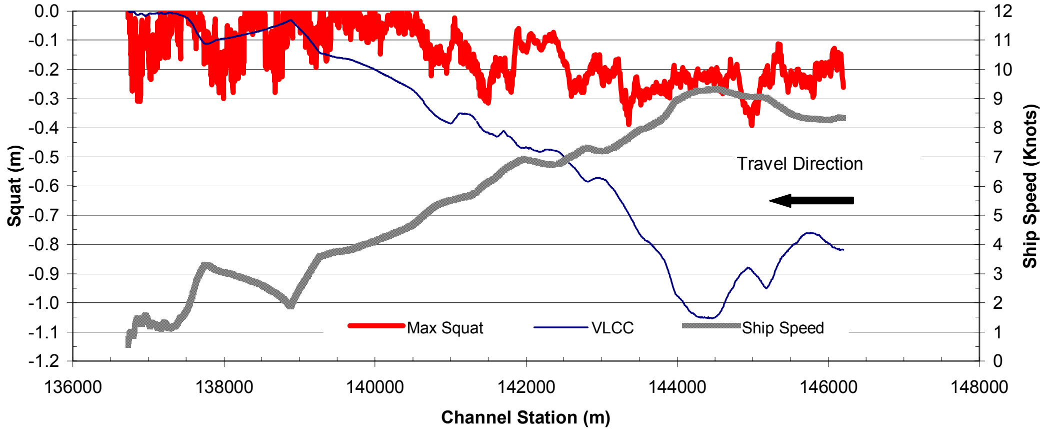


Figure 3.19: Continued

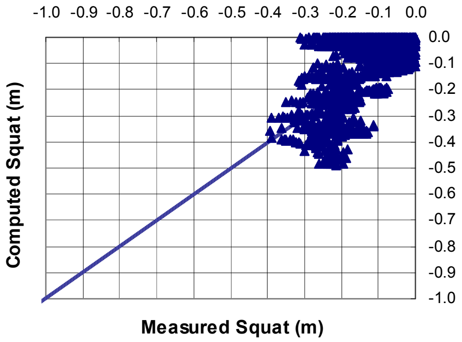


Figure 3.20: Eryuzlu et al. Model for *Rt. Hon. Paul Martin* in Wiley-Dondero Canal

3.7 Factors Affecting Squat and UKC values

The factors affecting the accuracy of the computed squat values include the DGPS measurements, the water level measurements, and the static zero measurements. In addition to these factors, the hydrographic survey of the bottom, the measurement of the ship's draft, and the determination of the distance from the GPS measurement point on the deck or bridge of the ship to the ship's keel or bottom also affect the accuracy of the UKC values. Each of these was evaluated in an attempt to demonstrate the accuracy of these measurements.

3.7.1 DGPS Measurements

An indication of DGPS accuracy can be obtained from three possible sources: the survey accuracy of the base stations and key survey network points; the intergauge distances measured onboard the ships; and the comparison of the total station measurements.

The accuracy of the base station network was analyzed using the GeoLab program. The results of this survey are shown in Table 3.3 and show that the standard deviation of the three-dimensional coordinate measurements was less than 1 cm for each of the locations and coordinates.

Comparing all three coordinate data processed against different base stations can also indicate accuracy of the DGPS data. While these data were not retained, most of the data was processed against multiple base stations, particularly where the data were within an overlap area of the base station influences. This provided an indication of whether the data were accurate enough to be useful and, in most cases, the data agreed within about 5 cm or less. The processed data from the base station that provided the best results for the largest percentage of the data were retained for further processing over the principal reach of influence of that base station.

Table 3.3: GPS Survey of Stationary Points

			NORTHING	EASTING	O-HEIGHT	MAP
CODE	**FFF**	**STATION**	**STD DEV**	**STD DEV**	**STD DEV**	**PROJECTION**
----	---	------------	-------------	------------	----------	-------
NEO	0	8205	5008226.630	552393.409	57.315	UTM 18
			0.005	0.004	0.009	
NEO	0	1	5022194.759	600072.633	38.685	UTM 18
			0.003	0.002	0.008	
NEO	111	59L9000	5017060.378	584079.520	48.127	UTM 18
			0.000	0.000	0.000	
NEO	0	69L008	5029164.396	600129.928	23.727	UTM 18
			0.004	0.003	0.007	
NEO	1	69L162	5029259.649	612573.105	13.130	UTM 18
			0.003	0.002	0.000	
NEO	0	BEAUH003	5018702.178	584730.439	40.130	UTM 18
			0.003	0.002	0.004	
NEO	1	BMSL	5039124.330	615809.263	13.121	UTM 18
			0.007	0.006	0.000	
NEO	0	COTEST01	5029293.374	611993.169	23.699	UTM 18
			0.003	0.002	0.002	
NEO	0	INT2	5022194.988	600076.113	38.672	UTM 18
			0.003	0.002	0.007	
NEO	0	JETEE001	5029374.286	600713.845	21.777	UTM 18
			0.004	0.003	0.018	
NEO	0	JETEE002	5029389.604	600737.082	24.205	UTM 18
			0.007	0.005	0.010	
NEO	0	POLY	5024103.073	599192.394	41.228	UTM 18
			0.003	0.002	0.004	
NEO	0	STCAT002	5029254.394	612265.221	29.817	UTM 18
			0.003	0.002	0.003	
NEO	0	STLA	5039226.415	615797.544	10.740	UTM 18
			0.003	0.003	0.010	
NEO	111	8205	5008226.475	552393.370	57.370	UTM 18
			0.000	0.000	0.000	
NEO	110	15	4984375.987	516824.436	61.772	UTM 18
			0.000	0.000	0.008	
NEO	1	68U395	4982525.599	506295.151	79.673	UTM 18
			0.005	0.004	0.000	
NEO	0	68U395B	4982525.718	506296.410	80.914	UTM 18
			0.011	0.008	0.024	
NEO	0	68U395C	4982525.596	506295.161	79.675	UTM 18
			0.005	0.005	0.013	
NEO	1	BMCORN1	4984624.066	522754.840	48.742	UTM 18
			0.004	0.004	0.000	
NEO	0	MACS0001	4996564.530	539022.300	49.596	UTM 18
			0.002	0.002	0.008	

The three-dimensional intergauge distances of the GPS gauges on the ships was another indicator of the accuracy of the GPS measurements onboard the moving ships. Table 3.4 presents the average, standard deviation, maximum, and minimum of the distances between each of the four gauges mounted onboard the ships while the static zero readings were taken in the locks. These values indicate the variance that the DGPS measurements had in three locations and orientations while the ship was essentially stationary. During the static zeroing process at some locks, however, some significant ship motions (principally vertical) occurred as a result of lock filling or gate opening operations. It can be observed that the maximum standard deviation of these measurements was 5 cm. The average standard deviation of all the measurements was 2 cm. The average range between the maximum and minimum readings for any intergauge distance was 4 cm. The largest range between maximum and minimum readings during the zero process was between the mid-side gauge and the bow for the *Blade Runner* at 43 cm. The other mid-side gauge readings for this zero were also large compared to the other measurements (>20 cm). It should be noted that the mid-side gauge data were not used in the calculation of the squat and UKC; these values were only used to indicate dynamic hogging or sagging during transits.

The distances between gauges over the entire set of measurements for each ship are shown in the last columns of Table 3.4. These values reflect the consistency of DGPS positioning with all the dynamics of the ship movements throughout the two lower pools, including varying orientation, movement past other objects, and any flexure of the ship body. For these measurements, the average standard deviation between any pair of gauges was between 2 and 7 cm. The average range between the maximum and minimum distance was about 34 cm. Since the average of the maximum and minimum distances was within a few centimetres of the overall mean value, it was concluded that the variance was equally distributed about the mean value. Again, the worst values were between the mid-side gauge and the other gauges.

Table 3.4: Onboard Inter-Gauge Distance Statistics

Ship	Statistic	Lock 1						Lock 2						Lock 3						Total Run					
		PB	SB	MB	MP	MS	PS	PB	SB	MB	MP	MS	PS	PB	SB	MB	MP	MS	PS	PB	SB	MB	MP	MS	PS
ALS303	**Max**							103.35	103.36				21.67	103.35	103.38				21.67	103.57	103.45				21.76
	Min							103.33	103.34				21.63	103.30	103.32				21.60	103.16	103.26				21.57
	Avg							103.34	103.35				21.66	103.32	103.35				21.64	103.33	103.35				21.64
	SD							0.00	0.01				0.01	0.01	0.01				0.01	0.02	0.02				0.02
ALS316	**Max**							103.38	103.42	65.95	39.34	44.91	21.67	103.41	103.43				21.64	103.47	103.48	66.07	39.53	45.13	21.75
	Min							103.36	103.40	65.92	39.31	44.89	21.64	103.36	103.38				21.57	103.32	103.36	65.75	39.20	44.73	21.53
	Avg							103.37	103.41	65.94	39.32	44.90	21.65	103.39	103.41				21.60	103.38	103.41	65.93	39.34	44.90	21.64
	SD							0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01				0.01	0.01	0.01	0.02	0.02	0.02	0.02
BLR304	**Max**	146.39	146.56	88.14	59.54	63.64	22.25	146.39	146.55	88.36	59.56	63.67	22.20	146.38	146.55	88.22	59.50	63.59	22.23	146.39	146.56	88.36	59.56	63.67	22.25
	Min	146.35	146.52	88.08	59.49	63.58	22.20	146.37	146.53	87.92	59.28	63.44	22.17	146.34	146.50	88.04	59.40	63.47	22.18	146.34	146.50	87.92	59.28	63.44	22.17
	Avg	146.38	146.54	88.11	59.51	63.61	22.22	146.38	146.54	88.13	59.49	63.59	22.19	146.36	146.52	88.16	59.44	63.54	22.21	146.37	146.53	88.13	59.48	63.58	22.20
	SD	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.03	0.02	0.02	0.01	0.01	0.01	0.03	0.02	0.02	0.01	0.01	0.01	0.03	0.04	0.04	0.02
CAV305	**Max**	202.06	202.12	116.44	86.30	88.42	16.85	202.03	202.10	116.42	86.28	88.42	16.84	202.08	202.13				16.88	202.15	202.16	116.49	86.37	88.50	16.92
	Min	201.97	202.04	116.39	86.22	88.35	16.80	202.02	202.07	116.40	86.27	88.38	16.81	201.96	202.04				16.80	201.84	201.92	116.23	86.18	88.26	16.75
	Avg	202.02	202.08	116.41	86.26	88.39	16.83	202.03	202.08	116.41	86.27	88.40	16.82	202.02	202.09				16.83	202.02	202.07	116.40	86.27	88.40	16.83
	SD	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.02	0.02				0.02	0.03	0.03	0.03	0.01	0.01	0.02
FEF298	**Max**	144.37	144.45	90.70	55.11	59.40	21.59							144.33	144.41				21.57	144.37	144.46	90.76	55.14	59.52	21.60
	Min	144.27	144.37	90.55	55.00	59.29	21.54							144.27	144.36				21.53	144.10	144.21	90.43	54.90	59.20	21.49
	Avg	144.31	144.41	90.64	55.05	59.35	21.57							144.30	144.38				21.56	144.31	144.40	90.62	55.07	59.36	21.56
	SD	0.02	0.02	0.04	0.02	0.03	0.01							0.01	0.01				0.01	0.02	0.02	0.02	0.02	0.02	0.01
HAL308	**Max**	204.21	204.22	109.84	94.98	97.00	17.24	204.17	204.17	109.82	94.93	96.96	17.25	204.18	204.20	109.94	94.98	96.97	17.26	204.25	204.25	109.94	95.04	97.02	17.42
	Min	204.11	204.12	109.76	94.88	96.92	17.19	204.15	204.14	109.80	94.91	96.95	17.20	204.13	204.10	109.75	94.80	96.83	17.17	204.02	204.02	109.68	94.80	96.83	17.01
	Avg	204.17	204.17	109.81	94.93	96.97	17.21	204.16	204.15	109.81	94.92	96.95	17.22	204.15	204.14	109.84	94.88	96.91	17.22	204.15	204.15	109.80	94.92	96.95	17.22
	SD	0.03	0.02	0.02	0.02	0.02	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.02	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
MAN301	**Max**	210.84	210.83				11.91	210.84	210.80	113.08	98.94	100.19	11.90							210.96	210.93	113.20	99.08	100.36	12.01
	Min	210.75	210.72				11.87	210.81	210.77	113.06	98.92	100.17	11.88							210.71	210.67	112.91	98.78	100.06	11.76
	Avg	210.80	210.77				11.89	210.82	210.79	113.07	98.93	100.18	11.89							210.81	210.78	113.07	98.92	100.18	11.88
	SD	0.02	0.02				0.01	0.00	0.01	0.00	0.00	0.01	0.01							0.02	0.02	0.02	0.02	0.02	0.03
MAR297	**Max**	141.79	141.72				18.38							141.78	141.72				18.39	141.93	141.82				18.45
	Min	141.70	141.63				18.34							141.74	141.66				18.31	141.64	141.61				18.26
	Avg	141.75	141.68				18.36							141.76	141.68				18.35	141.76	141.68				18.36
	SD	0.02	0.02				0.01							0.01	0.01				0.02	0.02	0.02				0.02
PMA299	**Max**							200.36	200.52	111.51	90.48	91.98	11.37	200.40	200.53	111.55	90.69	92.16	11.42	200.47	200.59	111.61	90.69	92.16	11.44
	Min							200.35	200.50	111.49	90.47	91.97	11.35	200.31	200.45	111.29	90.43	91.91	11.32	200.29	200.44	111.29	90.34	91.80	11.29
	Avg							200.35	200.51	111.50	90.47	91.97	11.36	200.35	200.49	111.47	90.52	91.99	11.36	200.36	200.50	111.50	90.47	91.97	11.36
	SD							0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02
PMA310	**Max**							217.33	217.41	111.23	107.50	108.31	7.41	217.32	217.39				7.39	217.40	217.46	111.26	107.58	108.40	7.42
	Min							217.29	217.37	111.18	107.45	108.28	7.37	217.22	217.31				7.34	217.21	217.29	111.06	107.38	108.16	7.14
	Avg							217.31	217.39	111.20	107.48	108.30	7.39	217.27	217.36				7.36	217.31	217.38	111.20	107.48	108.29	7.37
	SD							0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02				0.01	0.02	0.02	0.02	0.02	0.02	0.02
ZOS302	**Max**	137.85	138.22	84.28	55.02	58.94	19.57	137.78	138.10	84.22	55.04	58.88	19.66	137.76	138.10	82.79	56.46	60.21	19.71	137.85	138.27	84.31	56.60	60.35	19.75
	Min	137.74	138.15	84.15	54.94	58.84	19.40	137.71	138.05	84.08	54.93	58.79	19.54	137.72	138.05	82.57	56.25	60.04	19.64	137.63	138.02	82.44	54.80	58.71	19.40
	Avg	137.77	138.18	84.20	54.97	58.90	19.53	137.74	138.08	84.20	54.96	58.82	19.60	137.74	138.08	82.68	56.38	60.15	19.67	137.75	138.09	83.17	55.93	59.76	19.64
	SD	0.02	0.01	0.02	0.02	0.02	0.03	0.02	0.01	0.02	0.01	0.01	0.03	0.01	0.01	0.05	0.04	0.03	0.01	0.02	0.04	0.69	0.68	0.61	0.05
FSA301	**Max**							168.06						168.07	168.19				21.98	168.11	168.19				22.03
	Min							167.98						167.93	168.01				21.83	167.90	167.99				21.66
	Avg							168.03						168.00	168.08				21.89	168.02	168.06				21.87
	SD							0.02						0.03	0.04				0.03	0.02	0.02				0.03

Note: Distances between gauges XY where X & Y are: P= Port, S= Starboard, M= Mid-side , and B= Bow

Table 3.4: Continued

Ship	Statistic	Lock 1						Lock 2						Lock 3						Total Run					
		PB	SB	MB	MP			PB	SB	MB	MP			PB	SB	MB	MP			PB	SB	MB	MP		
ALV316	**Max**							194.41	194.54	100.94	94.53	96.23	15.17	194.39	194.52				15.16	195.15	194.62	101.28	95.32	96.35	15.38
	Min							194.36	194.48	100.88	94.48	96.18	15.11	194.33	194.47				15.13	194.22	194.42	100.44	94.31	96.03	14.21
	Avg							194.38	194.51	100.91	94.51	96.21	15.15	194.36	194.49				15.15	194.39	194.50	100.91	94.51	96.21	15.15
	SD							0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01				0.01	0.02	0.01	0.03	0.03	0.03	0.02
ATE313	**Max**	208.02	208.41				10.18	207.98	208.36				10.16	207.98	208.36				10.18	208.26	208.54	105.01	104.59	105.64	10.26
	Min	207.93	208.32				10.15	207.94	208.34				10.14	207.92	208.31				10.14	207.74	208.05	103.83	104.10	105.41	9.94
	Avg	207.97	208.37				10.17	207.96	208.35				10.16	207.96	208.34				10.16	207.97	208.35	104.84	104.29	105.50	10.16
	SD	0.02	0.02				0.00	0.01	0.01				0.00	0.01	0.01				0.01	0.02	0.02	0.11	0.03	0.02	0.01
CLE307	**Max**	125.91	126.11	73.23	54.49	58.73	21.60	125.93	126.11	73.26	54.44	58.71	21.58	125.94	126.12				21.60	126.04	126.22	73.47	54.49	58.76	21.69
	Min	125.86	126.05	73.15	54.36	58.64	21.55	125.91	126.10	73.19	54.39	58.66	21.56	125.89	126.07				21.54	125.84	126.02	73.13	54.28	58.55	21.46
	Avg	125.89	126.08	73.20	54.42	58.68	21.58	125.92	126.10	73.22	54.42	58.69	21.57	125.91	126.09				21.57	125.92	126.10	73.25	54.40	58.67	21.58
	SD	0.01	0.01	0.02	0.03	0.02	0.01	0.00	0.00	0.02	0.01	0.01	0.00	0.01	0.01				0.01	0.01	0.01	0.03	0.04	0.03	0.01
CNI315	**Max**							202.25	202.42	111.17	92.67	93.97	9.59	202.27	202.46				9.63	202.34	202.77	111.65	92.81	94.35	9.71
	Min							202.22	202.40	111.16	92.65	93.93	9.52	202.14	202.33				9.52	201.91	201.87	110.85	92.30	93.63	9.48
	Avg							202.24	202.41	111.16	92.66	93.95	9.56	202.21	202.39				9.57	202.23	202.40	111.17	92.66	93.96	9.57
	SD							0.01	0.01	0.00	0.00	0.01	0.01	0.03	0.03				0.02	0.03	0.08	0.07	0.02	0.06	0.03
CNI320	**Max**	202.30	202.49	111.19	92.73	94.01	9.64	202.28	202.45	111.18	92.71	93.97	9.60	202.24	202.43				9.60	202.35	202.52	111.30	92.77	94.04	9.69
	Min	202.24	202.41	111.14	92.65	93.91	9.54	202.22	202.39	111.14	92.65	93.90	9.51	202.20	202.39				9.56	202.08	202.32	111.05	92.52	93.85	9.50
	Avg	202.27	202.44	111.16	92.69	93.95	9.60	202.25	202.42	111.16	92.68	93.94	9.55	202.22	202.41				9.58	202.24	202.43	111.16	92.68	93.95	9.58
	SD	0.01	0.02	0.01	0.02	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01				0.01	0.02	0.02	0.02	0.02	0.02	0.02
FOS304	**Max**	126.32	126.57	74.47	53.75	57.73	19.60	126.31	126.56	74.47	53.70	57.68	19.56	126.34	126.58				19.61	126.45	126.65	74.61	54.06	57.97	19.65
	Min	126.28	126.50	74.41	53.67	57.65	19.52	126.30	126.53	74.43	53.66	57.65	19.54	126.26	126.52				19.46	126.21	126.34	74.14	53.49	57.49	19.42
	Avg	126.30	126.54	74.44	53.70	57.68	19.56	126.31	126.55	74.45	53.69	57.66	19.55	126.30	126.55				19.55	126.30	126.54	74.41	53.72	57.68	19.56
	SD	0.01	0.01	0.01	0.01	0.02	0.02	0.00	0.00	0.00	0.01	0.01	0.00	0.02	0.01				0.03	0.02	0.03	0.09	0.08	0.05	0.02
JBA306	**Max**	212.61	212.60	110.66	103.38	104.51	10.27	212.57	212.57	110.65	103.37	104.48	10.26	212.59	212.58	110.70	103.44	104.55	10.28	212.71	212.67	110.77	103.49	104.61	10.31
	Min	212.51	212.51	110.60	103.31	104.44	10.21	212.54	212.55	110.63	103.32	104.45	10.23	212.54	212.52	110.56	103.28	104.35	10.22	212.45	212.47	110.52	103.20	104.35	10.16
	Avg	212.56	212.56	110.63	103.34	104.46	10.24	212.56	212.56	110.64	103.35	104.46	10.24	212.57	212.55	110.65	103.34	104.44	10.25	212.56	212.56	110.64	103.35	104.47	10.24
	SD	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.03	0.03	0.03	0.01	0.01	0.01	0.02	0.01	0.02	0.01
JBA314	**Max**	212.72	212.26				11.26	211.95	211.92				10.28	211.93	211.90				10.26	212.72	212.30				11.28
	Min	212.60	212.15				11.18	211.92	211.88				10.23	211.89	211.86				10.23	211.62	211.58				10.09
	Avg	212.66	212.21				11.21	211.94	211.90				10.25	211.91	211.88				10.25	211.97	211.92				10.31
	SD	0.02	0.02				0.02	0.01	0.01				0.01	0.01	0.01				0.01	0.18	0.08				0.24
LAC315	**Max**							152.04	152.23	90.31	63.40	67.09	20.81	152.03	152.22				20.79	152.07	152.26	90.33	63.43	67.12	20.91
	Min							152.00	152.19	90.27	63.33	67.02	20.75	151.98	152.17				20.73	151.94	152.14	90.23	63.31	66.98	20.65
	Avg							152.02	152.21	90.29	63.37	67.05	20.78	152.01	152.20				20.76	152.02	152.20	90.29	63.37	67.04	20.77
	SD							0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01				0.01	0.01	0.01	0.01	0.02	0.02	0.02
MIR311	**Max**	160.23	160.06	92.96	68.84	71.92	19.34	160.21	160.04	92.97	68.83	71.91	19.35							160.55	160.13	93.17	69.18	72.02	19.38
	Min	160.16	160.02	92.86	68.79	71.90	19.32	160.18	160.00	92.84	68.78	71.81	19.29							160.10	159.94	92.82	68.40	71.78	19.04
	Avg	160.19	160.04	92.92	68.82	71.91	19.33	160.19	160.02	92.95	68.80	71.89	19.32							160.20	160.03	92.95	68.80	71.90	19.32
	SD	0.01	0.01	0.02	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.02	0.01							0.02	0.02	0.02	0.02	0.02	0.01
TUK317	**Max**	136.09						136.07	136.06	80.65	56.72	61.00	22.56	136.07						136.83	136.19	80.73	56.76	61.17	22.69
	Min	136.04						136.03	135.97	80.61	56.66	60.87	22.46	135.99						135.84	135.88	80.53	56.58	60.78	22.40
	Avg	136.07						136.05	136.02	80.63	56.70	60.95	22.50	136.03						136.05	136.01	80.62	56.69	60.95	22.53
	SD	0.01						0.01	0.02	0.01	0.01	0.03	0.02	0.02						0.02	0.02	0.02	0.02	0.03	0.03
Average SD		0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.03	0.03	0.01	0.03	0.02	0.07	0.06	0.06	0.03

Note: Distances between gauges XY where X & Y are: P= Port, S= Starboard, M= Mid-side , and B= Bow

A comparison of three-dimensional dynamic positions from the DGPS and total station tracking results also provides an indication of the accuracy of the ship position and orientation measurements. Comparisons were made for six sets of measurements at two different locations: four at the upper approach to Lock 2 and two near the end of the western jetty (Figures 3.21 through 3.26). The total station tracking equipment is only rated for a distance of 600 m; therefore, the comparison was limited to a range of +/- 300 m horizontally. If the total station measurements are considered correct and the differences taken to be a measure of the error of the GPS measurements, then it is noted that there is a average error of 1 to 7 cm with a standard deviation of 3 to 12 cm. The total station and GPS elevation plots show that the GPS measurements are generally much smoother and more consistent than the total station data. Comparing the port and starboard gauge elevations to the total station elevations for *Algosar* and for *Turid Knutson* at the jetties demonstrates these inconsistencies even more. This suggests that the GPS measurements are more accurate than the total station measurements.

Table 3.5: Total Station Measurements Compared to GPS Measurements

	Elevation Difference					
Ship	**Location**	**Avg**	**Std Dev**	**Max**	**Min**	**Range**
		(m)	**(m)**	**(m)**	**(m)**	**(m)**
JBA314	Lock 2	-0.07	0.03	0.04	-0.16	0.20
CNI315	Jetty	0.01	0.05	0.11	-0.09	0.20
CNI315	Lock 2	-0.05	0.03	0.03	-0.19	0.21
ALS316	Lock 2	-0.06	0.04	0.08	-0.21	0.29
TUK317	Lock 2	-0.04	0.03	0.07	-0.10	0.17
TUK317	Jetty	0.02	0.12	0.28	-0.22	0.50
	Distance Difference					
Ship	**Location**	**Avg**	**Std Dev**	**Max**	**Min**	**Range**
		(m)	**(m)**	**(m)**	**(m)**	**(m)**
JBA314	Lock 2	0.42	0.48	3.67	0.01	3.66
CNI315	Jetty	2.64	1.56	6.53	0.27	6.26
CNI315	Lock 2	1.20	0.55	2.74	0.15	2.59
ALS316	Lock 2	0.80	0.61	2.73	0.01	2.72
TUK317	Lock 2	1.11	1.25	7.16	0.03	7.13
TUK317	Jetty	3.24	1.91	7.57	0.25	7.32

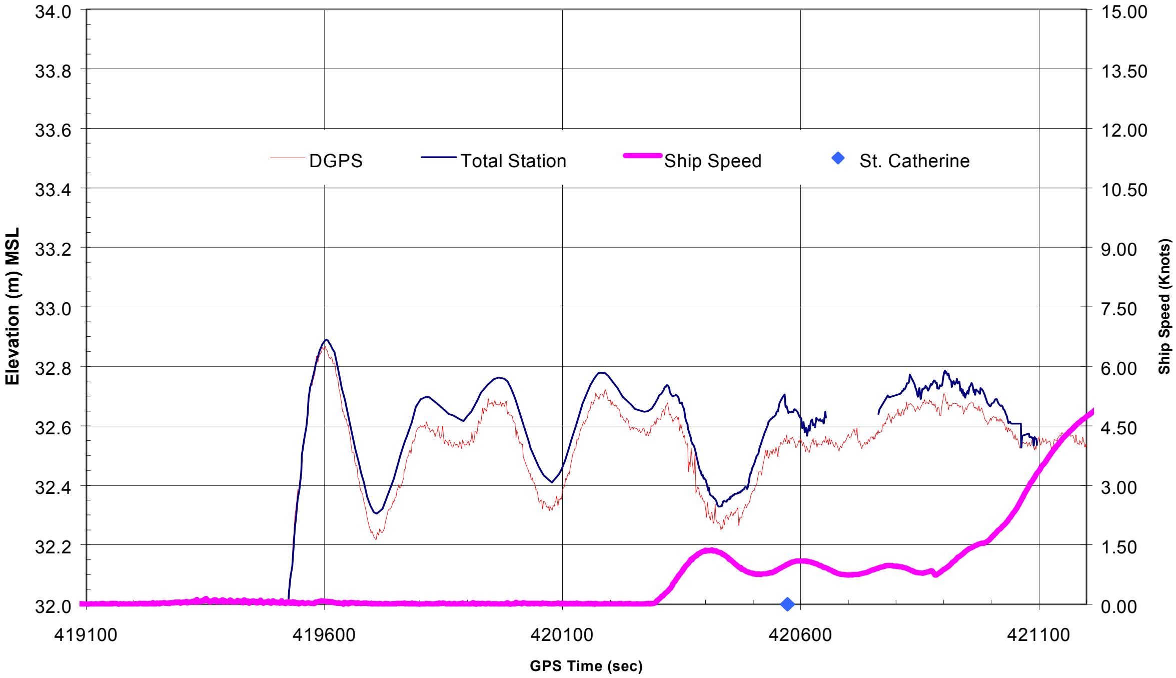


Figure 3.21: *John B. Aird* Departing Cote St. Catherine Lock

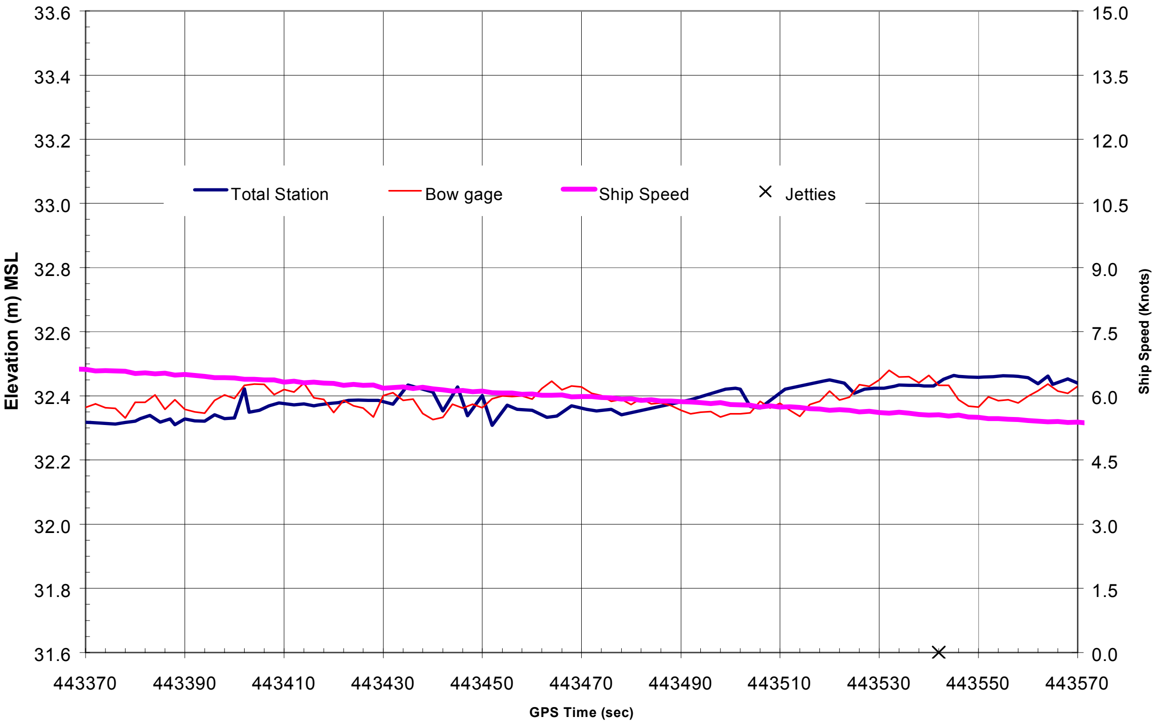


Figure 3.22: *CSL Niagara* Entering the Canal at the Jetties

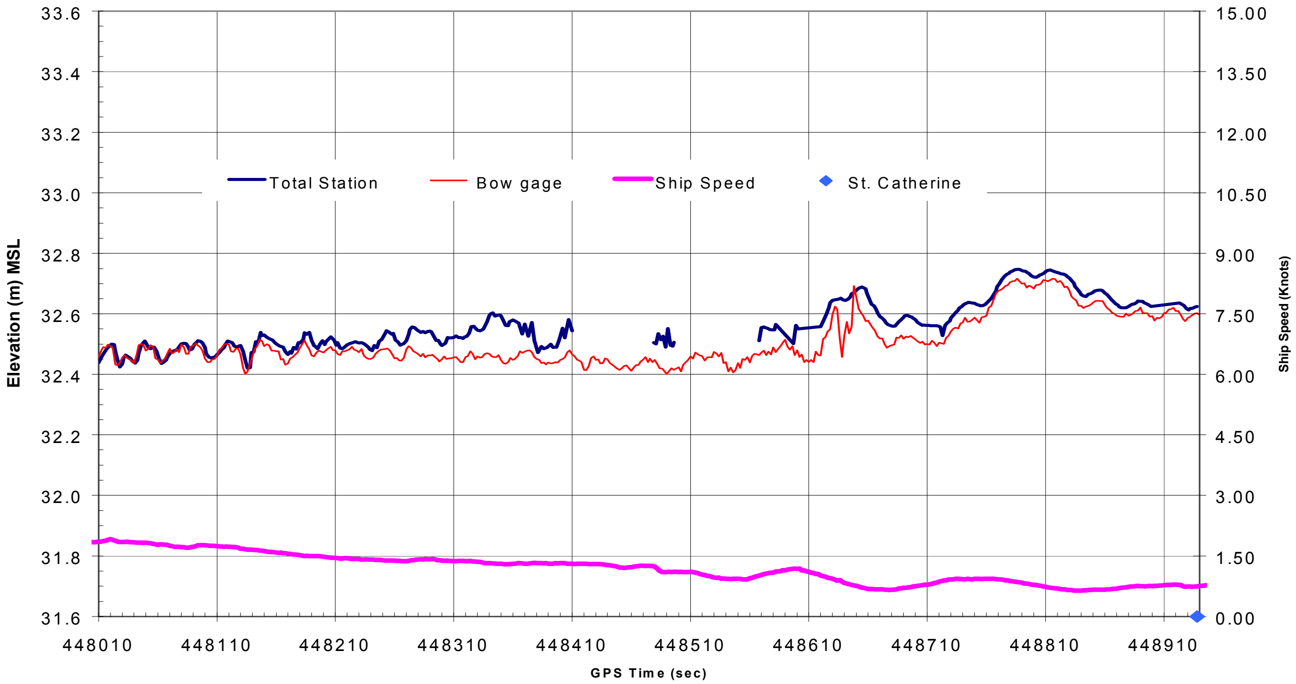


Figure 3.23: *CSL Niagara* Approaching Cote St. Catherine Lock

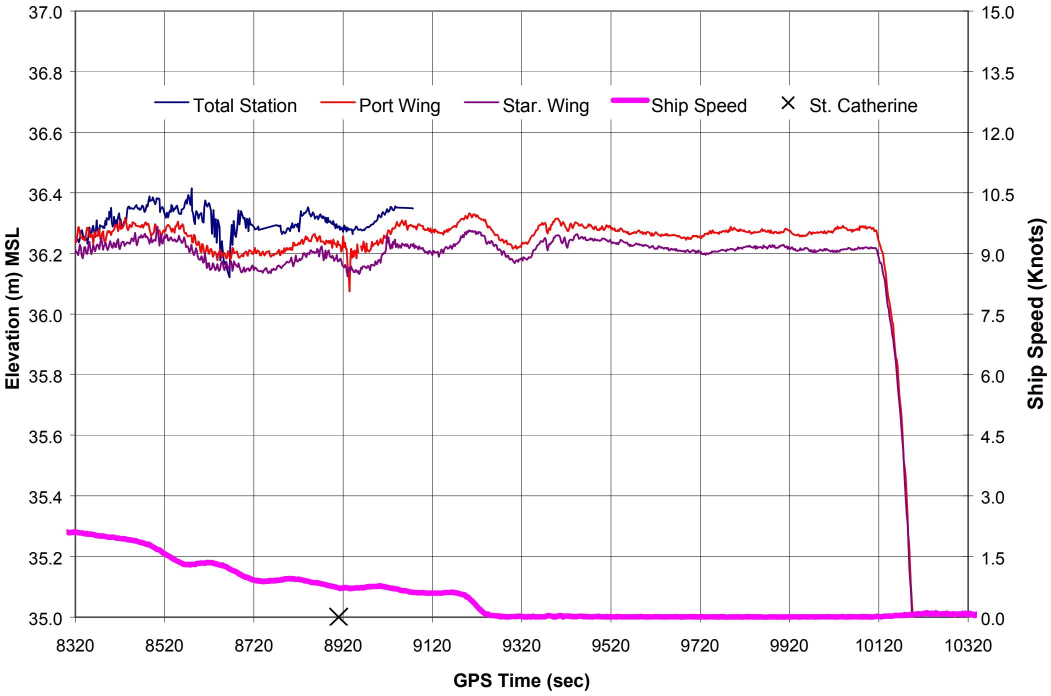


Figure 3.24: *Algosar* Approaching Cote St. Catherine Lock

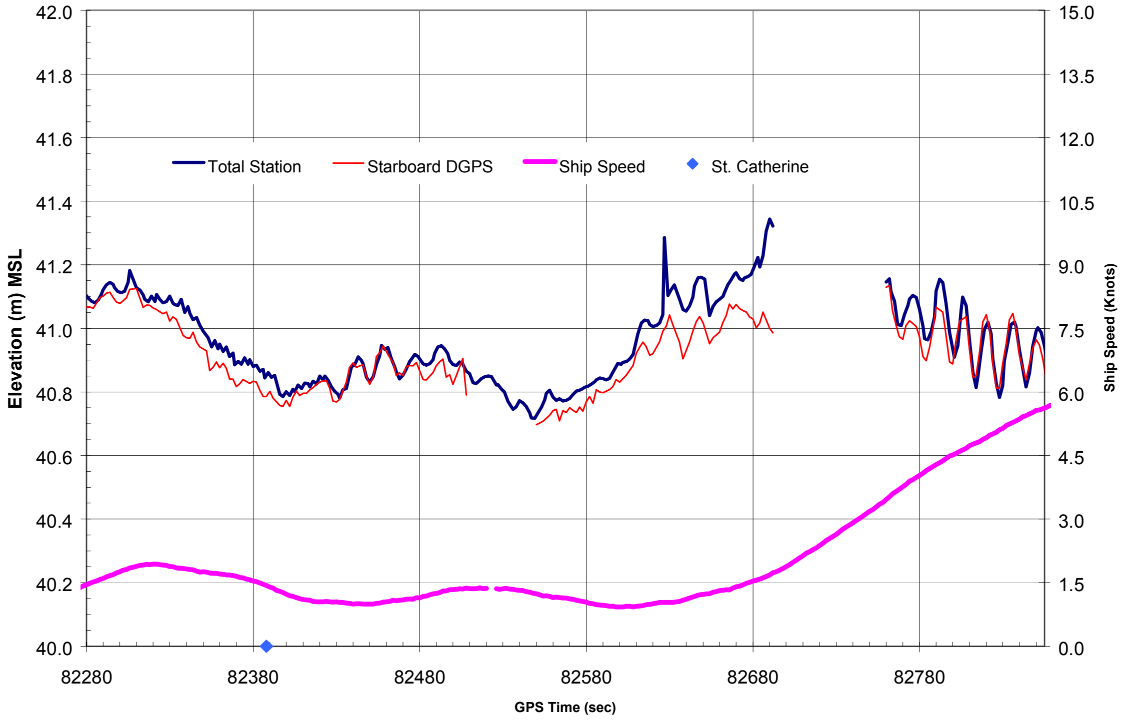


Figure 3.25: ***Turid Knutson*** **Departing Cote St. Catherine Lock**

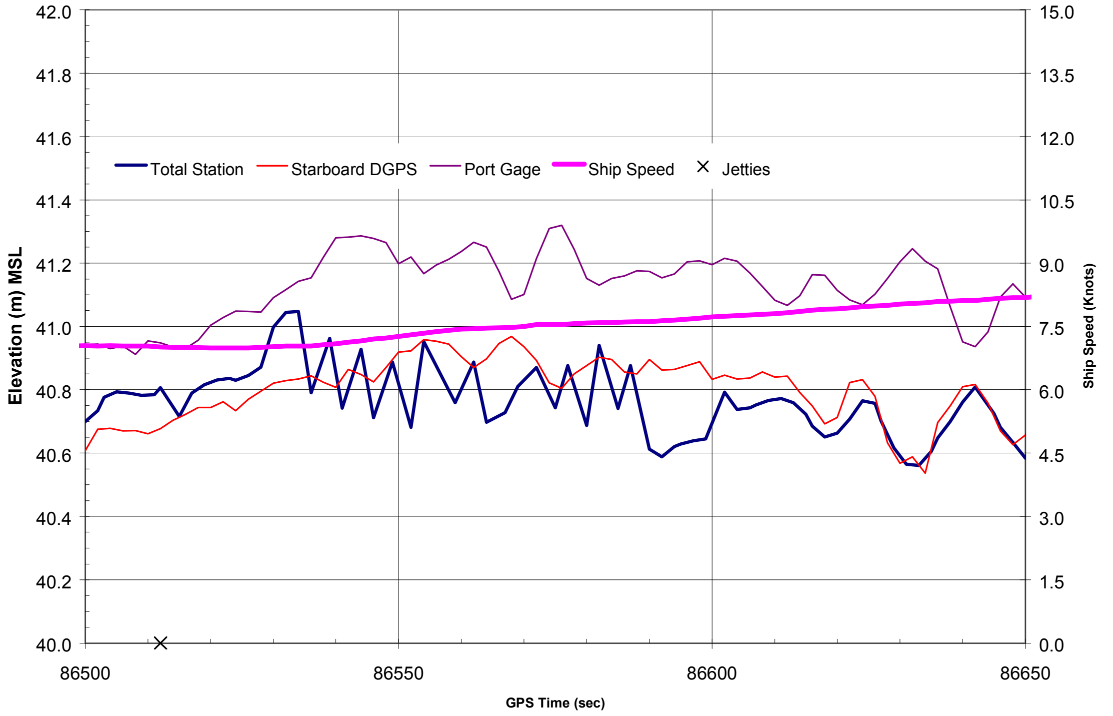


Figure 3.26: ***Turid Knutson*** **Departing South Shore Canal at Jetties**

3.7.2 Water Level Measurements

Variations in the water level during ship transits directly affected squat. The basic procedure for calculating squat was to subtract the elevation of a gauge while the ship was underway from the static reference elevation recorded while the ship was stationary in the appropriate lock. This assumed a water surface that was level. Using a straight line to correct for the sloping water surface, as required in the lakes with flowing water did not account for short-term variations such as surges due to lock filling and emptying and/or changes in the hydropower discharge. These changes in water level can directly change the squat and UKC values and, depending on the wavelength, could change the trim of the ship. Since the water level is only recorded at a few locations, the temporal and spatial movement of surges in the canal was not directly measured. The water surfaces for the lower and upper pools during the transit of the *CSL Niagara* on day 320 are shown in Figures 3.27 and 3.28. It can be seen that the water level changed nearly 10 cm during this period with variations of 4 to 7 cm from the average water level. During the transit of the upper pool on the same day, the water level dropped about 6 cm with surges of +7 cm and – 6 cm in the canal above Lock 2.

The average pool elevations, standard deviation, maximum elevation, minimum elevation, and differences of the maximum and minimum elevations from the average are documented in Table 3.6 for all ship transits included in the squat and UKC analysis. The maximum standard deviations for all gauges except Lock 3 Lower were 5 to 6 cm, while the maximum water level differences above and below the transit average were 5 to 17 cm.

It is not easy to correct the elevation measurements of the gauges and the squat and UKC values of the ships since the time record of water levels at the water gauges must be translated into a time history along the canal and correlated with the position of the ship at any point in time. More information about the timing and attenuation of the wave movements in the canal will be required to accurately make these adjustments. In any case, the keel elevation measurements are real and should not be adjusted because they physically include the effect of the instantaneous water level at the ship location.

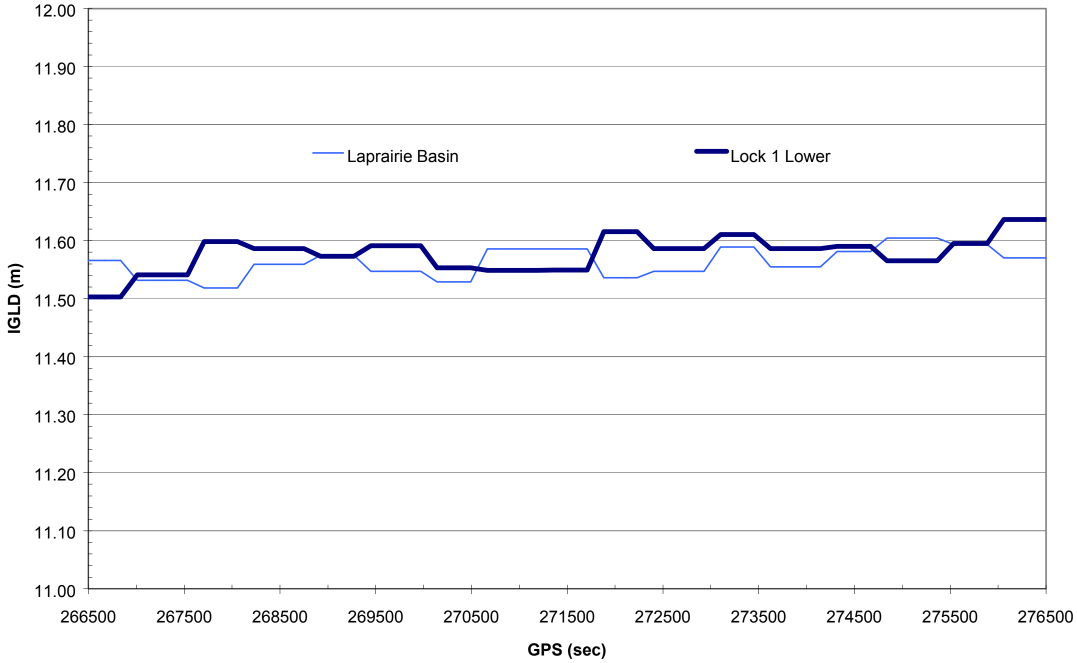


Figure 3.27: Water Levels During *CSL Niagara*'s Lower Pool Transit – Day 320

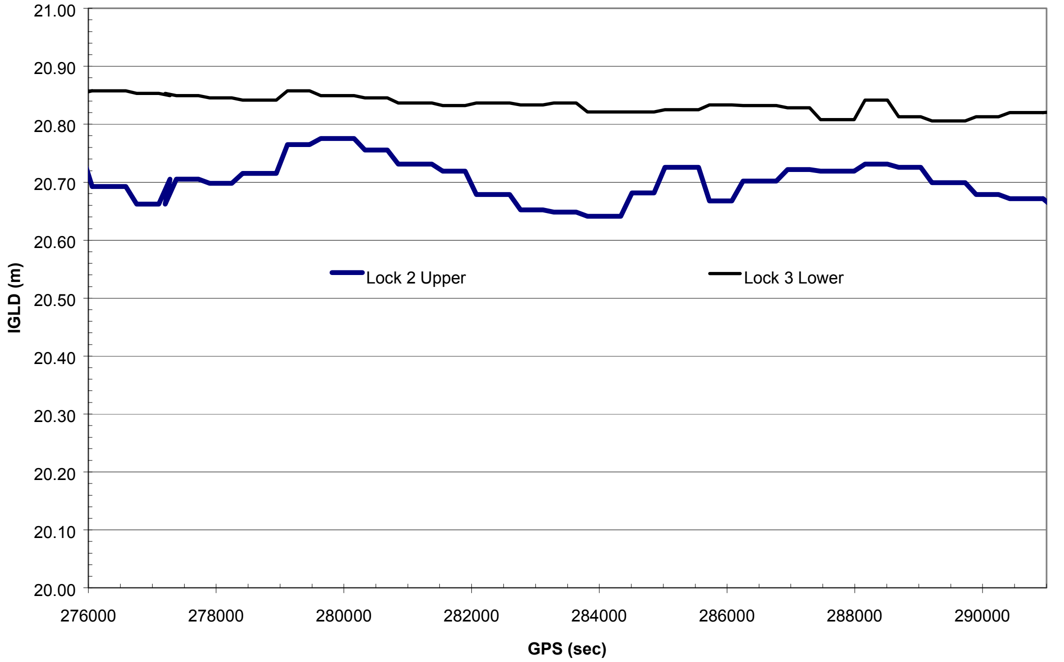


Figure 3.28: Water Levels During *CSL Niagara*'s Upper Pool Transit – Day 320

Table 3.6: Water Level Conditions During Ship Transits

Ship	Statistic	Lower Pool Transit			Upper Pool Transit			Ship	Statistic	Lower Pool Transit			Upper Pool Transit		
		Lock 1 Upper (m)	Laprairie Basin (m)	LB - Lk1 (m)	Lock 2 Upper (m)	Lock 3 Lower (m)	Lk3 - Lk2 (m)			Lock 1 Upper (m)	Laprairie Basin (m)	LB - Lk1 (m)	Lock 2 Upper (m)	Lock 3 Lower (m)	Lk3 - Lk2 (m)
MAR297	**Avg.**	11.55	11.54	-0.01	20.72	20.90	0.18	**HAL308**	**Avg.**	11.56	11.54	-0.02	20.61	20.79	0.18
	Std. Dev.	0.02	0.02	0.03	0.02	0.01	0.02		**Std. Dev.**	0.02	0.02	0.03	0.04	0.01	0.04
	Max.	11.57	11.56	0.03	20.77	20.91	0.23		**Max.**	11.58	11.59	0.05	20.69	20.82	0.24
	Diff with Avg.	0.01	0.02	0.05	0.05	0.01	0.04		**Diff with Avg.**	0.02	0.05	0.07	0.08	0.03	0.05
	Min.	11.52	11.53	-0.03	20.67	20.88	0.13		**Min.**	11.53	11.50	-0.06	20.55	20.77	0.10
	Diff with Avg.	-0.04	-0.01	-0.02	-0.05	-0.02	-0.05		**Diff with Avg.**	-0.03	-0.04	-0.04	-0.06	-0.02	-0.09
FEF298	**Avg.**	11.62	11.60	-0.02	20.70	20.87	0.17	**PMA310**	**Avg.**	11.52	11.51	-0.01	20.66	20.81	0.15
	Std. Dev.	0.02	0.02	0.03	0.03	0.01	0.03		**Std. Dev.**	0.02	0.02	0.02	0.05	0.02	0.05
	Max.	11.66	11.66	0.01	20.75	20.88	0.21		**Max.**	11.55	11.53	0.01	20.74	20.85	0.25
	Diff with Avg.	0.04	0.06	0.03	0.05	0.01	0.04		**Diff with Avg.**	0.03	0.02	0.03	0.08	0.03	0.09
	Min.	11.58	11.56	-0.07	20.65	20.85	0.12		**Min.**	11.49	11.48	-0.05	20.58	20.77	0.03
	Diff with Avg.	-0.04	-0.04	-0.04	-0.05	-0.02	-0.05		**Diff with Avg.**	-0.03	-0.02	-0.03	-0.08	-0.05	-0.13
PMA299	**Avg.**				20.71	20.87	0.16	**MIR311**	**Avg.**	11.55	11.55	0.00	20.57	20.69	0.13
	Std. Dev.				0.04	0.02	0.04		**Std. Dev.**	0.02	0.02	0.03	0.01	0.01	0.02
	Max.				20.78	20.94	0.22		**Max.**	11.58	11.61	0.04	20.59	20.71	0.16
	Diff with Avg.				0.07	0.06	0.07		**Diff with Avg.**	0.03	0.06	0.04	0.03	0.01	0.04
	Min.				20.65	20.84	0.10		**Min.**	11.53	11.51	-0.04	20.54	20.66	0.08
	Diff with Avg.				-0.06	-0.03	-0.05		**Diff with Avg.**	-0.02	-0.04	-0.04	-0.03	-0.04	-0.05
FSA 301	**Avg.**	11.54	11.53	-0.01	20.71	20.89	0.18	**ATE313**	**Avg.**	11.59	11.58	-0.01	20.53	20.69	0.16
	Std. Dev.	0.02	0.02	0.03	0.03	0.00	0.03		**Std. Dev.**	0.02	0.02	0.02	0.05	0.01	0.05
	Max.	11.57	11.58	0.07	20.76	20.90	0.25		**Max.**	11.62	11.60	0.03	20.63	20.71	0.28
	Diff with Avg.	0.04	0.05	0.08	0.05	0.00	0.08		**Diff with Avg.**	0.03	0.03	0.04	0.09	0.02	0.13
	Min.	11.50	11.46	-0.06	20.64	20.89	0.13		**Min.**	11.56	11.53	-0.05	20.42	20.65	0.07
	Diff with Avg.	-0.04	-0.06	-0.05	-0.07	0.00	-0.05		**Diff with Avg.**	-0.03	-0.05	-0.04	-0.11	-0.04	-0.09
MAN301	**Avg.**	11.54	11.54	0.00	20.71	20.87	0.16	**JBA314**	**Avg.**	11.53	11.51	-0.02	20.68	20.89	0.21
	Std. Dev.	0.02	0.01	0.02	0.05	0.02	0.05		**Std. Dev.**	0.01	0.02	0.02	0.04	0.01	0.04
	Max.	11.57	11.57	0.03	20.82	20.93	0.27		**Max.**	11.55	11.54	0.02	20.75	20.91	0.30
	Diff with Avg.	0.04	0.03	0.03	0.12	0.06	0.10		**Diff with Avg.**	0.02	0.03	0.04	0.06	0.02	0.09
	Min.	11.51	11.52	-0.04	20.61	20.84	0.06		**Min.**	11.51	11.46	-0.06	20.59	20.87	0.13
	Diff with Avg.	-0.02	-0.02	-0.05	-0.10	-0.03	-0.10		**Diff with Avg.**	-0.02	-0.04	-0.04	-0.09	-0.02	-0.08
ZOS302	**Avg.**	11.55	11.54	-0.01	20.71	20.91	0.20	**CNI315**	**Avg.**	11.62	11.60	-0.02	20.72	20.92	0.20
	Std. Dev.	0.01	0.05	0.05	0.03	0.00	0.03		**Std. Dev.**	0.05	0.05	0.03	0.02	0.01	0.02
	Max.	11.57	11.57	0.02	20.77	20.92	0.25		**Max.**	11.68	11.69	0.03	20.75	20.95	0.26
	Diff with Avg.	0.02	0.03	0.03	0.05	0.01	0.05		**Diff with Avg.**	0.06	0.09	0.05	0.03	0.03	0.06
	Min.	11.53	11.36	-0.18	20.67	20.90	0.14		**Min.**	11.54	11.46	-0.08	20.68	20.91	0.17
	Diff with Avg.	-0.02	-0.17	-0.17	-0.04	-0.01	-0.06		**Diff with Avg.**	-0.08	-0.14	-0.06	-0.04	-0.02	-0.03

Table 3.6: Continued

Ship	Statistic	Lower Pool Transit			Upper Pool Transit			Ship	Statistic	Lower Pool Transit			Upper Pool Transit		
		Lock 1 Upper (m)	Laprairie Basin (m)	LB - Lk1 (m)	Lock 2 Upper (m)	Lock 3 Lower (m)	Lk3 - Lk2 (m)			Lock 1 Upper (m)	Laprairie Basin (m)	LB - Lk1 (m)	Lock 2 Upper (m)	Lock 3 Lower (m)	Lk3 - Lk2 (m)
ALS303	**Avg.**	11.55	11.53	-0.02	20.68	20.85	0.16	**LAC315**	**Avg.**	11.65	11.64	-0.01	20.72	20.88	0.16
	Std. Dev.	0.02	0.03	0.04	0.02	0.01	0.02		**Std. Dev.**	0.02	0.02	0.02	0.03	0.01	0.03
	Max.	11.58	11.59	0.06	20.72	20.88	0.21		**Max.**	11.69	11.68	0.04	20.79	20.90	0.21
	Diff with Avg.	0.03	0.06	0.07	0.04	0.04	0.05		**Diff with Avg.**	0.04	0.04	0.05	0.07	0.02	0.04
	Min.	11.52	11.49	-0.06	20.65	20.82	0.10		**Min.**	11.59	11.61	-0.03	20.67	20.83	0.09
	Diff with Avg.	-0.03	-0.04	-0.04	-0.03	-0.03	-0.06		**Diff with Avg.**	-0.06	-0.03	-0.02	-0.05	-0.05	-0.07
BLR304	**Avg.**	11.53	11.51	-0.02	20.62	20.81	0.19	**ALV316**	**Avg.**	11.55	11.54	-0.01	20.73	20.91	0.18
	Std. Dev.	0.02	0.03	0.04	0.03	0.01	0.03		**Std. Dev.**	0.02	0.02	0.03	0.06	0.02	0.06
	Max.	11.57	11.54	0.04	20.67	20.82	0.24		**Max.**	11.61	11.59	0.03	20.82	20.95	0.30
	Diff with Avg.	0.04	0.03	0.06	0.05	0.02	0.05		**Diff with Avg.**	0.05	0.05	0.04	0.09	0.04	0.12
	Min.	11.49	11.45	-0.09	20.56	20.79	0.14		**Min.**	11.52	11.49	-0.06	20.61	20.88	0.06
	Diff with Avg.	-0.04	-0.06	-0.07	-0.06	-0.02	-0.06		**Diff with Avg.**	-0.03	-0.05	-0.05	-0.12	-0.03	-0.12
CAV305	**Avg.**	11.65	11.65	0.00	20.64	20.80	0.16	**ALS316**	**Avg.**	11.58	11.56	-0.02	20.73	20.89	0.16
	Std. Dev.	0.02	0.02	0.03	0.05	0.01	0.05		**Std. Dev.**	0.01	0.03	0.04	0.02	0.01	0.02
	Max.	11.68	11.67	0.04	20.71	20.82	0.25		**Max.**	11.62	11.61	0.02	20.76	20.89	0.21
	Diff with Avg.	0.04	0.03	0.04	0.08	0.02	0.09		**Diff with Avg.**	0.04	0.05	0.04	0.03	0.01	0.05
	Min.	11.62	11.60	-0.05	20.54	20.79	0.07		**Min.**	11.56	11.48	-0.11	20.68	20.87	0.13
	Diff with Avg.	-0.03	-0.04	-0.05	-0.09	-0.01	-0.09		**Diff with Avg.**	-0.01	-0.08	-0.09	-0.05	-0.02	-0.03
FOS304	**Avg.**	11.67	11.65	-0.02	20.64	20.80	0.16	**TUR317**	**Avg.**	11.57	11.56	-0.01	20.62	20.76	0.14
	Std. Dev.	0.02	0.03	0.03	0.05	0.01	0.05		**Std. Dev.**	0.02	0.01	0.02	0.02	0.01	0.02
	Max.	11.71	11.69	0.04	20.73	20.82	0.25		**Max.**	11.60	11.59	0.03	20.66	20.77	0.19
	Diff with Avg.	0.04	0.04	0.06	0.09	0.02	0.09		**Diff with Avg.**	0.03	0.03	0.04	0.04	0.01	0.04
	Min.	11.63	11.61	-0.08	20.54	20.79	0.07		**Min.**	11.53	11.55	-0.04	20.57	20.74	0.12
	Diff with Avg.	-0.04	-0.04	-0.07	-0.10	-0.02	-0.09		**Diff with Avg.**	-0.04	-0.01	-0.03	-0.05	-0.03	-0.03
JBA306	**Avg.**	11.63	11.62	-0.01	20.75	20.90	0.15	**CNI320**	**Avg.**	11.58	11.56	-0.01	20.70	20.83	0.13
	Std. Dev.	0.02	0.03	0.03	0.03	0.01	0.04		**Std. Dev.**	0.03	0.03	0.04	0.03	0.01	0.03
	Max.	11.68	11.69	0.04	20.81	20.94	0.22		**Max.**	11.64	11.60	0.06	20.78	20.86	0.19
	Diff with Avg.	0.05	0.07	0.05	0.06	0.03	0.07		**Diff with Avg.**	0.06	0.04	0.08	0.07	0.02	0.06
	Min.	11.60	11.56	-0.08	20.70	20.87	0.09		**Min.**	11.50	11.52	-0.08	20.64	20.81	0.07
	Diff with Avg.	-0.03	-0.06	-0.07	-0.05	-0.03	-0.07		**Diff with Avg.**	-0.07	-0.04	-0.06	-0.06	-0.03	-0.06
CLE307	**Avg.**	11.62	11.60	-0.02	20.73	20.87	0.14								
	Std. Dev.	0.02	0.02	0.03	0.03	0.02	0.04								
	Max.	11.68	11.64	0.02	20.78	20.94	0.23								
	Diff with Avg.	0.06	0.04	0.04	0.06	0.07	0.09								
	Min.	11.58	11.55	-0.09	20.63	20.84	0.07								
	Diff with Avg.	-0.04	-0.05	-0.06	-0.10	-0.03	-0.07								

3.7.3 Static Zero Measurements

Yet another indication of the accuracy of the squat measurements and computation procedures, including the use of the average difference in water level gauges as a slope correction, was provided by a cross-check calculation of the squat during the static zero at the lock at the opposite end of the pool from the lock used as a reference for the water surface slope adjustment. It would be expected that the squat in that pool would be 0.00 m since the ship is not moving. The average error in this squat is less than 2 cm and the standard deviation is 4 to 5 cm. On individual ships the average error varies up to 7 cm.

Table 3.7: Accuracy of Static Zeroing and Water Slope Correction

Ship	**Static Reference**	**Transit Direction**	**Upper Pool Elevation Difference**	**Avg. Sinkage in Lock not used for Static Reference Elevation**				
				Bow	**Port**	**Starboard**	**Mid-Side**	**Average**
ALS303	Lock 2	Down	0.16	-0.01	-0.02	-0.01		**-0.01**
ALS316	Lock 2	Down	0.16	-0.01	0.02	-0.07		**-0.02**
BLR304	Lock 2	Down	0.19	0.03	-0.01	0.10	0.06	**0.05**
CAV305	Lock 3	Up	0.16	0.04	-0.02	0.01		**0.01**
FEF298	Lock 3	Up	0.17					
HAL308	Lock 3	Up	0.18	-0.04	-0.11	-0.06	-0.08	**-0.07**
MAR297	Lock 3	Up	0.18					
PMA299	Lock 3	Up	0.16	-0.03	-0.05	-0.05	0.02	**-0.03**
PMA310	Lock 2	Down	0.15	0.00	-0.05	-0.04		**-0.03**
ZOS302	Lock 3	Up	0.20	-0.06	-0.08	-0.03		**-0.06**
ALV316	Lock 2	Down	0.17	-0.07	-0.10	-0.05		**-0.07**
ATE313	Lock 3	Up	0.16	0.01	-0.03	-0.01		**-0.01**
CLE307	Lock 3	Up	0.14	0.01	-0.03	0.03	0.01	**0.01**
CNI315	Lock 2	Down	0.20	0.07	0.08	0.06		**0.07**
CNI320	Lock 3	Up	0.13	0.00	0.01	0.01	0.00	**0.01**
FOS304	Lock 3	Up	0.21	0.00	-0.03	-0.01	-0.01	**-0.01**
JBA306	Lock 2	Down	0.15	0.05	0.07	0.06	0.03	**0.05**
LAC315	Lock 3	Up	0.16	0.01	0.01	0.01	0.01	**0.01**
MIR311	Lock 2	Down	0.13					
TUK317	Lock 2	Up	0.14	0.00				**0.00**
			Average Error	**0.00**	**-0.02**	**0.00**	**0.01**	**-0.01**
			Standard Deviation	**0.04**	**0.05**	**0.05**	**0.04**	**0.04**

3.7.4 Hydrographic Survey Data

The hydrographic survey data were obtained and provided by the SLSMC. The accuracy of these data was generally stated to be +/- 5 to 7 cm. However, on a number of occasions that were described more fully in section 3.5 (Figures 3.9 and 3.10), this study found significant changes in the bottom elevations within the SLSMC hydrographic survey data, sometimes as much as 1 to 2 m. Often this was only a single point in the local area. The bottom elevations are particularly significant when considering the UKC.

3.7.5 Ship Draft Measurements

The measurements of ship drafts at six locations around the ship were based on the draft marks on the sides of the ships. Generally these marks were raised welded areas that are painted as shown in Figure 2.2. Most ships had draft marks in 0.1 m increments. To obtain readings to the nearest centimetre, the draft reading had to be interpolated between the marks. This meant that the reading error was 5 cm if a normal assumption of half the graduation mark increment was used as a measure of error; however, unless the water surface was very rough due to strong winds, the draft readings were probably accurate within a few centimetres (i.e., +/- 2 cm). It should be noted, however, that the draft readings taken by the study crew at the locks frequently differed from those posted on the ship bridge and provided by the ship's crew to the boarding team.

3.7.6 Ship's Geometry

The determination of the ship's keel plane elevations and orientation was made by computing the elevations below the GPS gauge elevation reading using the recorded heights of the mounting pole above the deck and the distance of the deck above the keel at the location of the gauge. Sometimes this information was provided by the ship's officers and sometimes it had to be derived by scaling the distances from a general arrangements diagram or similar drawing. Often these were copied and scaled after disembarking. In the case of a 1:100 drawing, the scaling could result in accuracies of 2 to 5 cm. If the drawing is a smaller scale (e.g., 1:200), then the accuracy of these keel elevations could be 4 to 10 cm. This assumed that the drawing was an accurate representation of the existing hull.

3.7.7 Ship Bottom Elevations

If the measurement of the GPS elevation and the determination of the ship's bottom elevation, using the ship's design elevation data, and the measurement of the water level, ship's draft and the determination of the ship's squat, trim, and heel values are all accurate, then the ship's bottom elevation computed using both sets of data should be in agreement. This approach should provide an indication of the accuracy of the combined information recorded during the study. The water level and draft data would normally be available to Seaway operations personnel and the squat and trim will be predicted by the squat models developed by this study. Plots of a few ship transits using both the GPS/ship depth and the ship draft, squat, and water level methods have been developed and are provided (Figures 3.29 to 3.35) to demonstrate the combined accuracy of determining the UKC values.

Figure 3.29 shows the bottom elevations of *Blade Runner* during the zero in Lock 1. During this time, the water level used to calculate the bottom elevation by subtracting the ship's maximum draft, squat, trim and heel (which should have been nearly zero since the ship was not moving) was nearly 16 cm throughout the zero period. Figure 3.30 shows the bottom elevations for *Blade Runner* during the transit through the pool between Lock 1 and Lock 2. The difference between the elevations based on the GPS/ship geometry and the water level/draft/squat varies between 10 and 20 cm. It also is different if the elevations are based on the water level readings from the Lock 1 gauge or the Laprairie Basin gauge as there is a separation of the water surface elevations between the gauges near the middle of the transit. Figure 3.31 shows similar results for the transit through the upper canal. Locations of high bottom elevations are clearly shown that cause low UKC at several points. Channel bottom elevations clearly fluctuate 20 to 30 cm much of the time. This suggests that there could be a 15 to 20 cm error in determination of the bottom elevation, meaning that more research is needed into why these differences exist.

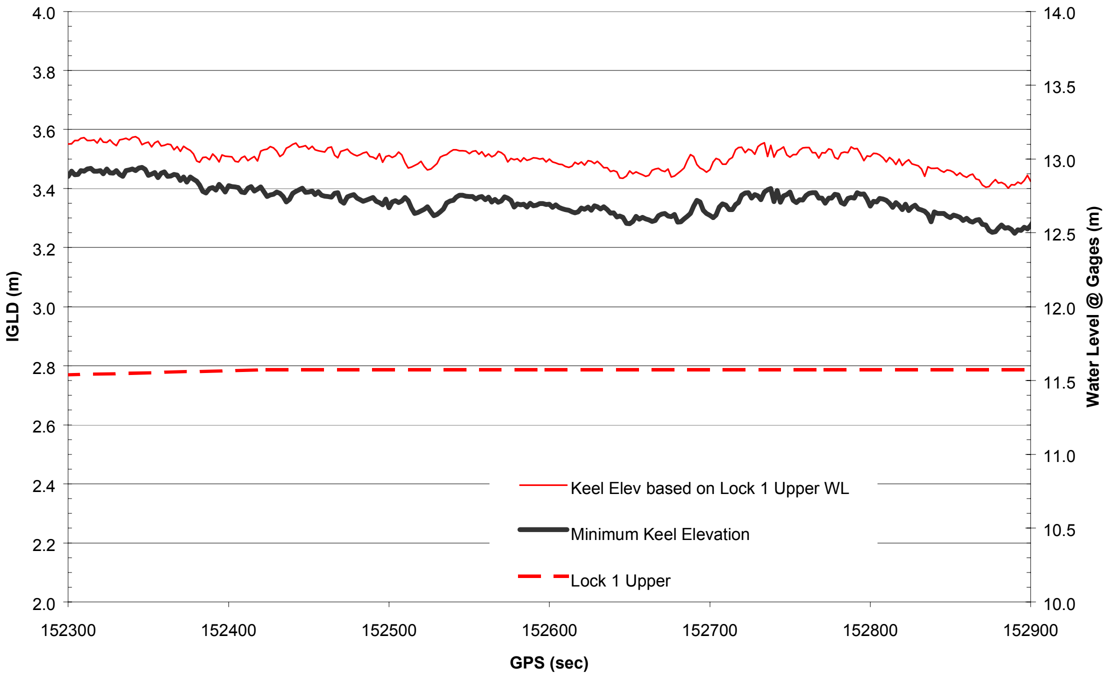


Figure 3.29: *Blade Runner* Bottom Elevations During Lock 1 Zero

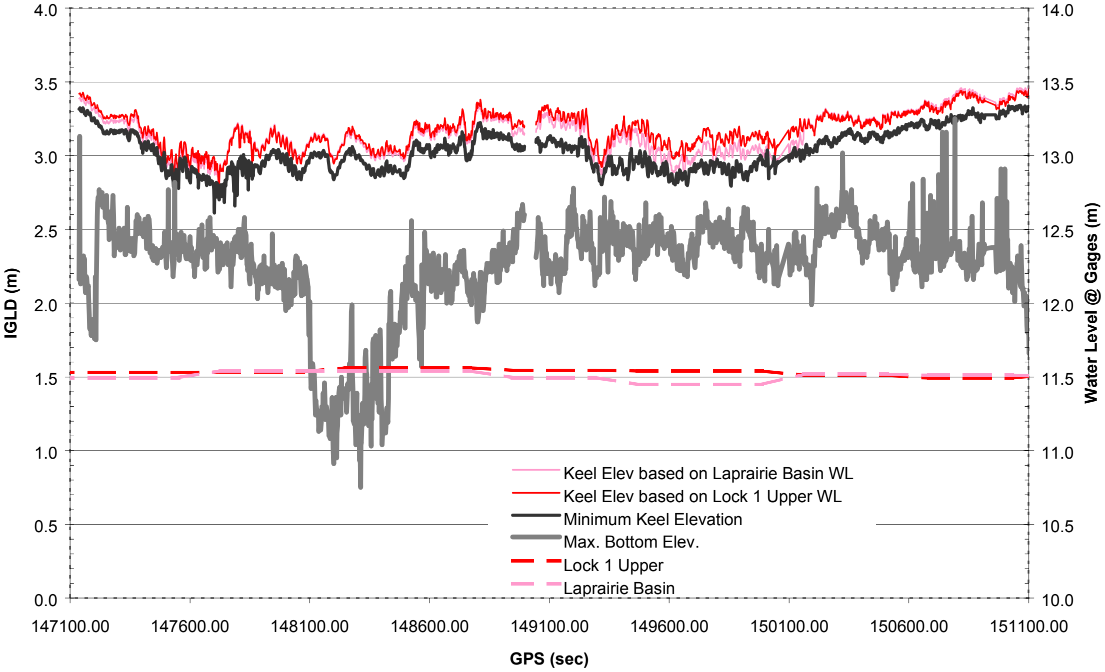


Figure 3.30: *Blade Runner* Bottom Elevations During Lower Pool Transit

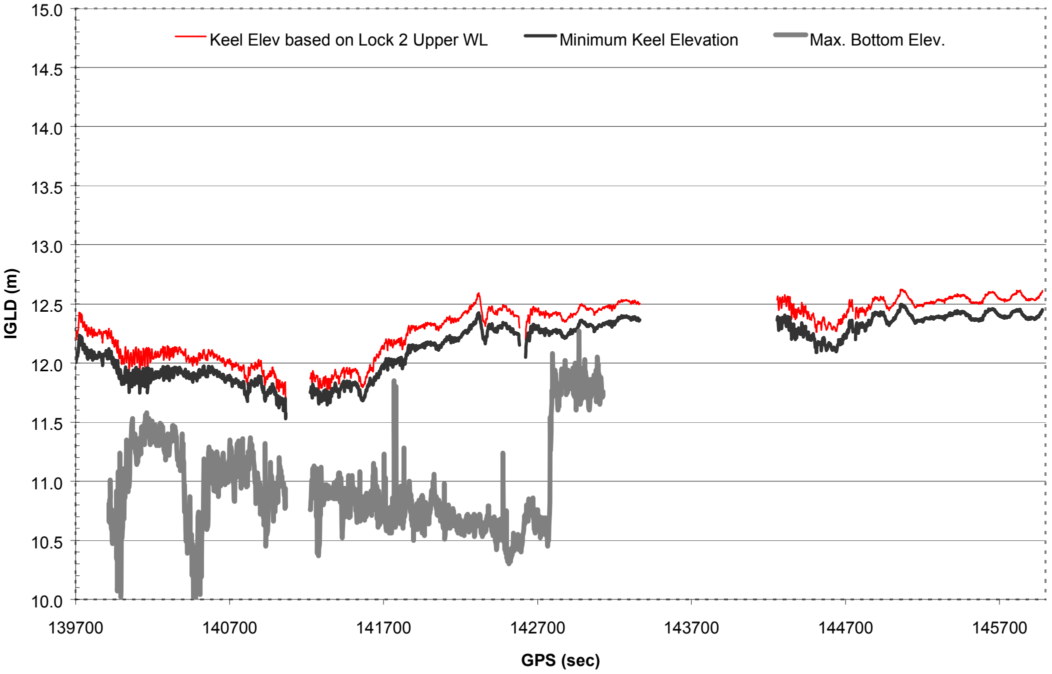


Figure 3.31: *Blade Runner* Bottom Elevations During Upper Canal Transit and Lock 2 Zero

The bottom elevations of *Lake Carling* show a similar, nearly parallel fluctuation over both the lower pool and upper canal transits with some low or negative UKC values occurring, (see Figures 3.32 and 3.33). The differences in the elevations vary between 23 and 33 cm in the lower pool and 12 and 23 cm in the upper canal with an average difference of 33/32 cm and 16 cm, respectively. The surging of nearly 0.5 m in Lock 2 due to the lock filling operations is clearly seen in Figure 3.33.

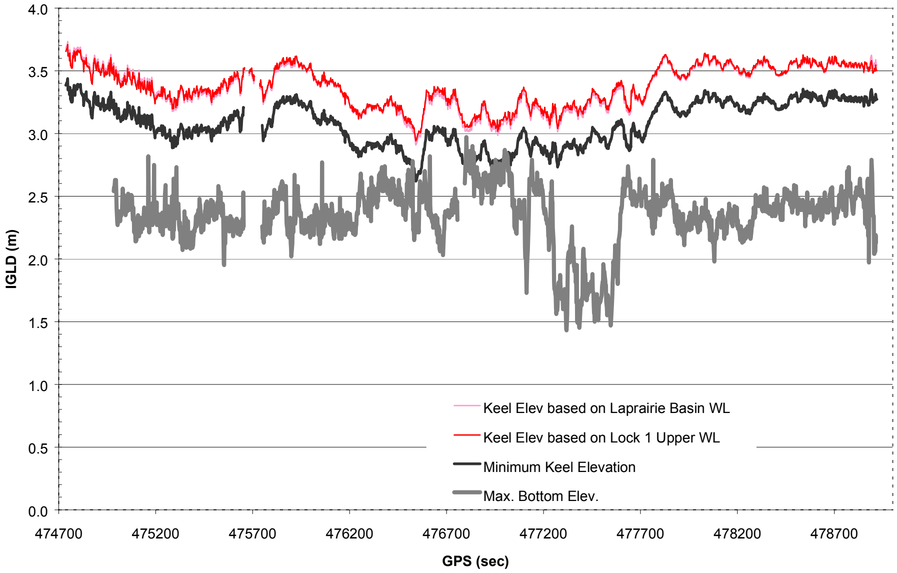


Figure 3.32: *Lake Carling* Bottom Elevations During Lower Pool Transit

Figure 3.33: *Lake Carling* Bottom Elevations During Lock 2 Zero and Upper Canal Transit

Turid Knutson's bottom elevations based on the water level/draft/squat calculations are lower than those computed with the GPS/ship geometry by about 45 cm. Even for this case (draft of only 7.5 m), there is a bottom elevation spike that causes a negative UKC value in the upper canal.

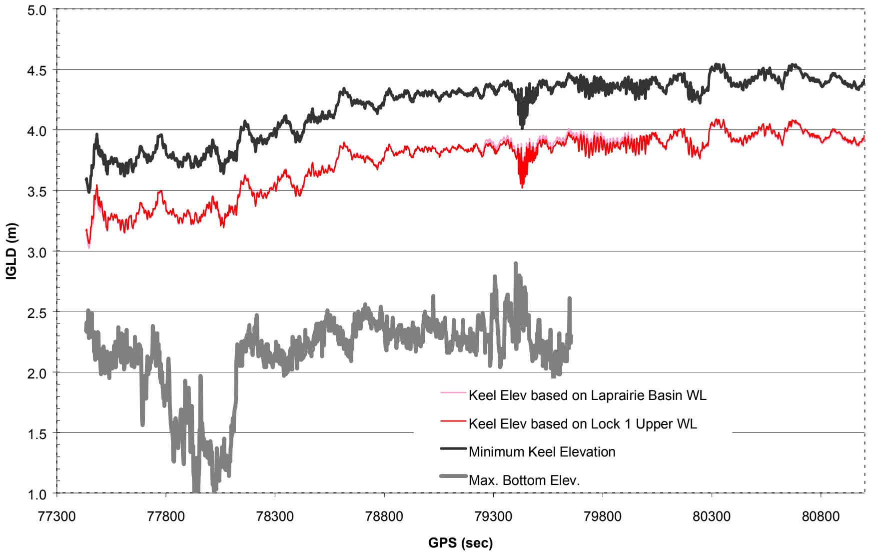


Figure 3.34: ***Turid Knutson*** **Bottom Elevations During Lower Pool Transit and Entry into Lock 2**

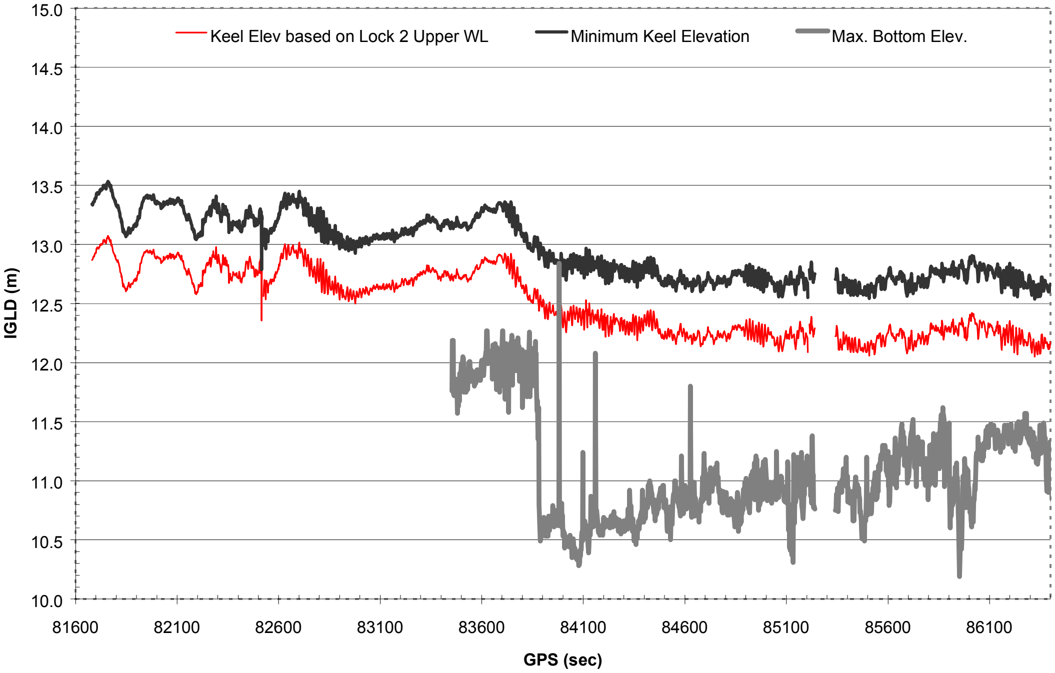


Figure 3.35: ***Turid Knutson*** **Bottom Elevations During Lock 2 Zero and Upper Canal Transit**

3.8 Panama Canal Experience

During recent years, Waterway Simulation Technology (WST) has conducted three ship squat measurement studies in the Panama Canal. The first, in December 1997, measured ship squat just prior to the start of the dry season subsequent to an abnormally dry wet season. The Panama Canal Commission predicted very low water conditions by the end of the dry season in mid-1998 with probable draft restrictions. WST travelled to Panama again in April 1998 to measure squat on ships at these low water conditions. Draft restrictions at this time had been implemented. Long-term impact on ship traffic in the Panama Canal by these draft restrictions was averted because of a return to normal rainfall patterns and a resulting water level increase. The third squat study, in June 1999, represented a shift in focus with measurement of ship behaviour during some of the first meeting/passing manoeuvres of two Panamax ships in a newly widened reach of the Gaillard Cut.

Table 3.8 shows a summary of the ships instrumented in the first Panama Canal squat study and the respective maximum squat measured during each transit through the Gaillard Cut. The Gaillard Cut is a canal-type channel, about 152 m (500 ft.) wide and 12.2 to 13.7 m (40 to 45 ft.) deep, with essentially no overbank areas. These characteristics made the Cut most similar to the South Shore Canal channel in the St. Lawrence Seaway. Table 3.9 shows similar data for the latter. Figure 3.36 shows a comparison of these two sets of data. Despite different sets of conditions and factors involved in the two data sets, it is evident that results are similar (except for one very fast ship in the Gaillard Cut). Similar comparison of the more open reaches from the two waterways is not available because of dissimilarity of channel characteristics and lack of data from the Panama Canal studies.

Table 3.8: Panama Canal Maximum Squat Measurements

SHIP	VESSEL TYPE	Length & Beam (m)	Mean Draft (m)	Speed (kn)	Max Sinkage (m)
Endeavor	Bulk Carrier	225.0 x 32.3	12.1	6.6	0.85
Trade Carrier	Bulk Carrier	200.0 x 32.3	12.0	7.6	0.98
Adventure I	Bulk Carrier	186.6 x 29.0	11.6	6.6	0.67
Chian Emerald	Cargo	174.7 x 28.0	6.1	10.1	0.76
Lucky Fortune	Bulk Carrier	186.0 x 30.5	11.3	7.3	0.82
Global Challenger	Bulk Carrier	225.0 x 32.3	11.7	9.3	1.43
Majestic Maersk	Containership	294.2 x 32.3	11.8	11.0	2.35
Aegean Bulker	Bulk Carrier	179.0 x 27.7	8.81	5.7	0.76
Ever Refine	Containership	294.2 x 32.3	9.1	9.5	0.91
Trader	Tanker	228.7 x 32.3	11.2	7.7	0.91
Sea Pearl	Bulk Carrier	184.1 x 28.4	10.9	7.8	0.76
Jo Cedar	Bulk Carrier	182.6 x 32.0	10.9	6.6	0.61
Elixir	Bulk Carrier	200.6 x 29.0	11.3	9.9	0.95
Eternal Fortune	Bulk Carrier	185.7 x 30.5	11.0	7.0	0.52
Bravewind	Bulk Carrier	225.0 x 32.3	11.6	7.3	0.52
Shi Tang Hai	Bulk Carrier	243.9 x 32.3	12.0	6.3	0.55
Shearwater	Woodchip	204.0 x 32.3	9.7	7.0	0.55
Hanjin Los Angeles	Containership	289.6 x 32.3	11.5	6.2	0.85
CSAV Rapel	Containership	163.1 x 26.5	8.1	8.9	1.01
Nedlloyd Dejima	Containership	287.2 x 32.3	12.0	8.0	1.22

Table 3.9: South Shore Canal Maximum Squat Measurements

SHIP	VESSEL TYPE	Length & Beam (m)	Mean Draft (m)	Speed (kn)	Max Sinkage (m)
Algosar	C. Tanker	132.6 x 22.6	7.75	7.1	0.64
Algosar	C. Tanker	132.6 x 22.6	7.50	6.5	0.52
Algoville	New Laker	222.6 x 23.8	7.77	6.6	0.69
Atlantic Erie	Salty Laker	224.5 x 23.1	7.95	6.6	0.62
Blade Runner	Salty Bulker	178.2 x 22.96	8.02	7.3	0.85
Canadian Voyager	Trad. Laker	222.5 x 22.9	7.90	6.6	0.63
Clipper Eagle	C. Tanker	149.4 x 23.0	6.29	8.3	0.76
CSL Niagara	New Laker	225.5 x 23.8	7.90	6.0	0.49
CSL Niagara	New Laker	225.5 x 23.8	7.97	6.0	0.56
Federal Fuji	Salty Laker	182.8 x 23.1	7.77	9.3	1.2
Fossnes	Salty Bulker	149.4 x 23.0	7.99	8.0	1.1
Federal Saguenay	Salty Laker	200.0 x 23.5	6.41	8.5	1.1
Halifax	Trad. Laker	222.5 x 22.9	7.89	6.7	0.68
John B. Aird	Salty Laker	222.5 x 23.5	7.94	6.7	0.55
Lake Carling	Salty Bulker	180.0 x 23.1	7.95	7.3	0.63
Manatoulin	Trad. Laker	222.5 x 22.7	7.42	7.1	0.45
Mariupol	Salty Bulker	178.2 x 22.9	7.86	6.9	0.88
Millenium Raptor	Salty Bulker	200.0 x 23.5	7.81	8.8	0.72
Rt. Hon. Paul Martin	New Laker	225.5 x 24.1	7.97	6.2	0.66
Rt. Hon. Paul Martin	New Laker	225.5 x 24.1	7.84	6.7	0.64
Turid Knutsen	C. Tanker	123.7 x 17.7	7.86	7.1	0.96
Zoitsa S.	Salty Bulker	172.0 x 22.9	7.21	8.0	1.0

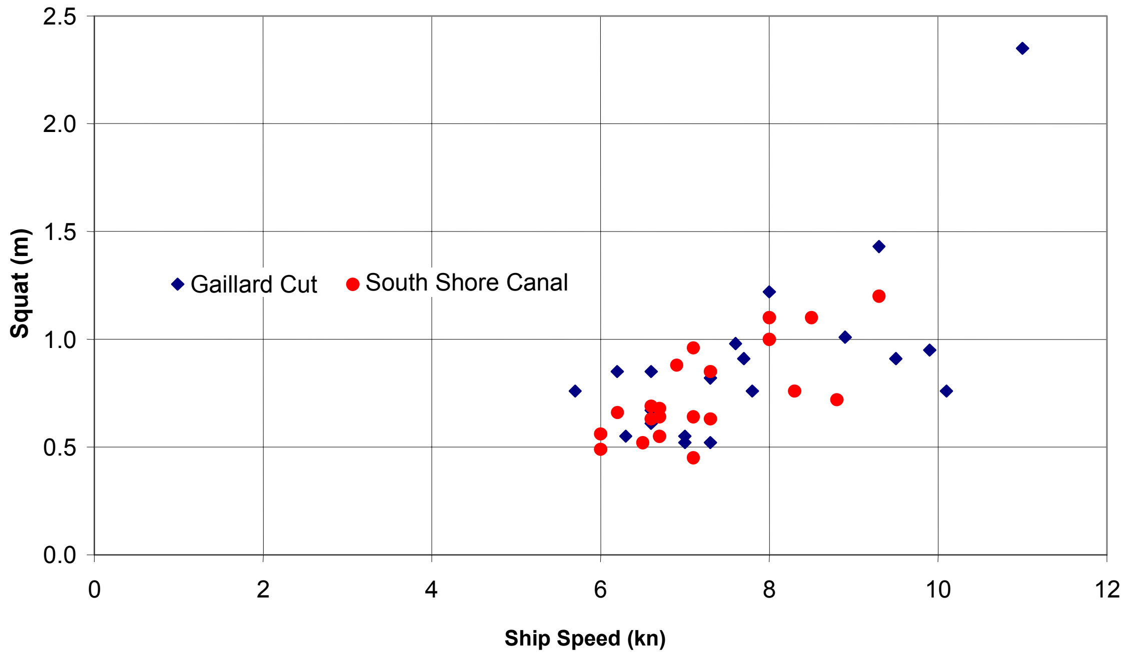


Figure 3.36: Squat Data Set Comparison

3.9 Previous St. Lawrence Seaway Measurements

The St. Lawrence Seaway authorities performed full-scale prototype squat measurements between 1964 and 1966 in the South Shore Canal. These measurements were made using calibrated photographs of ship draft lines taken from shore. This approach made measurements of many ships possible; however, the squat of each ship was only measured at one location along the channel. Figures 3.37 and 3.38 show the bow and stern squat collected during this study compared to the predicted squat from the Tothill formula presented in section 2.6. These plots show a fairly good comparison. The present study also concludes that the Tothill formula results in a good approximation for squat in portions of the channel.

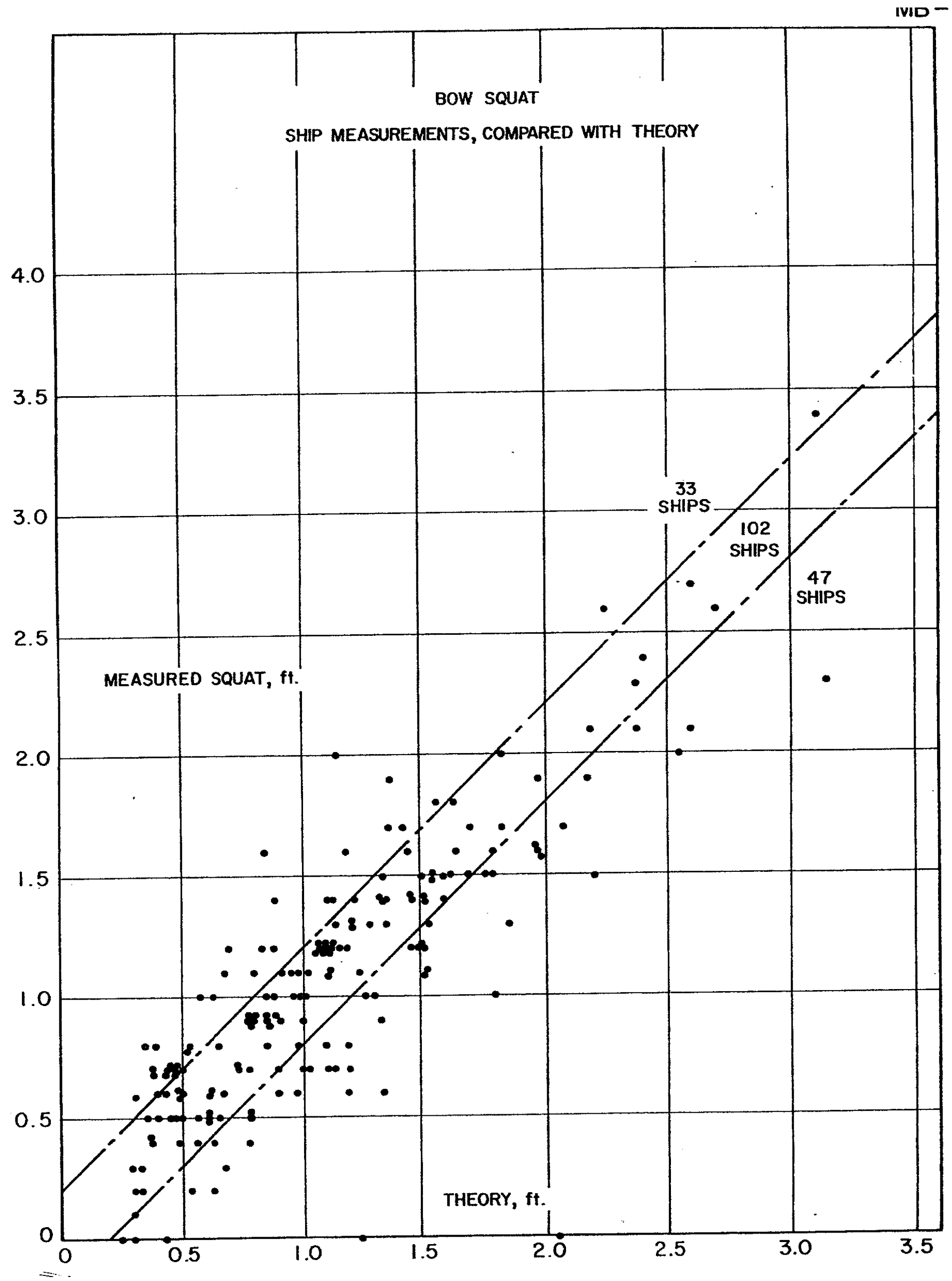


Figure 3.37: Tothill Formula Compared to Bow Squat from St. Lawrence Seaway

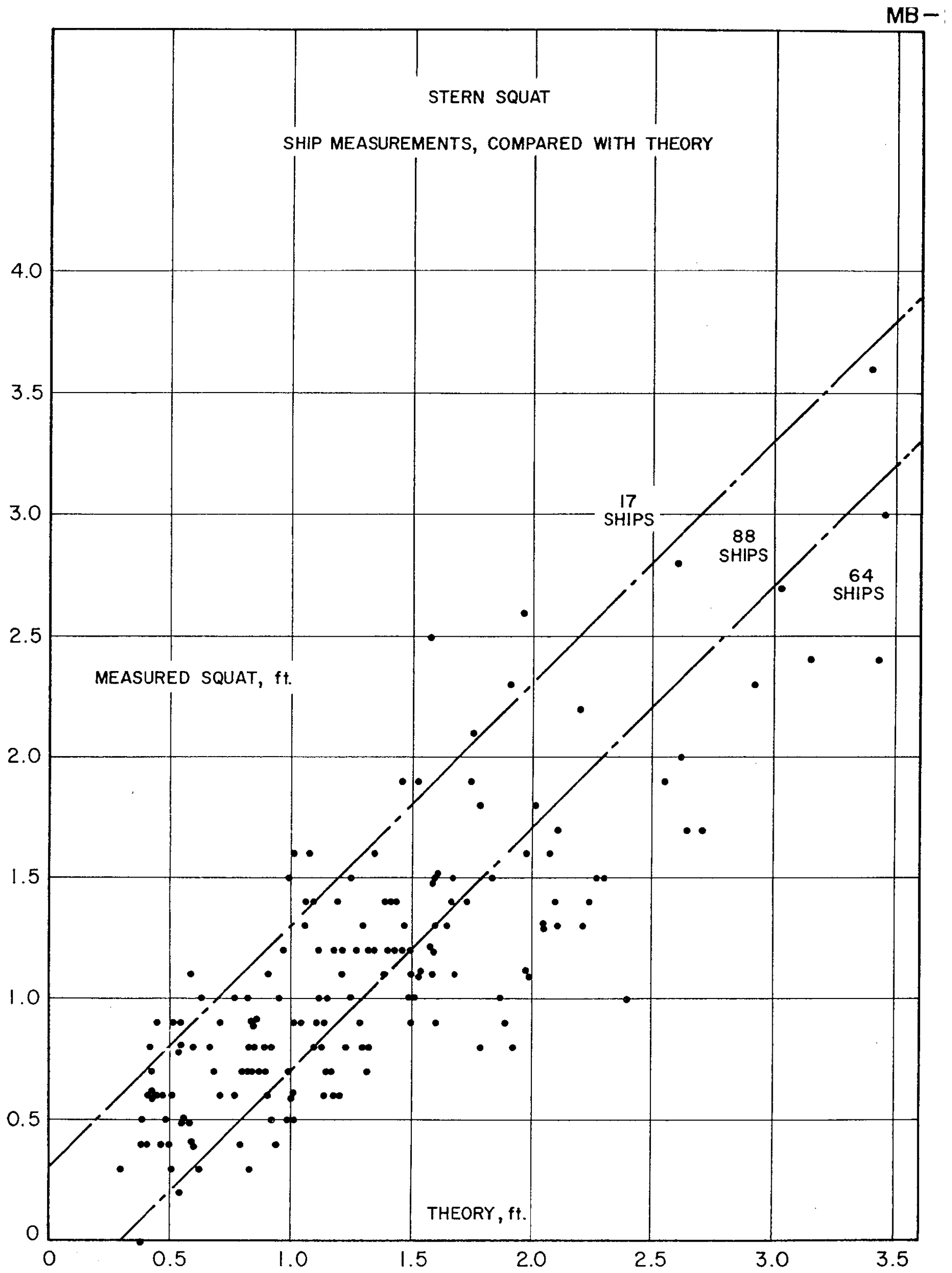


Figure 3.38: Tothill Formula Compared to Stern Squat from St. Lawrence Seaway

3.10 Ships Meeting

An attempt was made during the study to arrange meeting/passing manoeuvres between instrumented ships to measure vessel behaviour when cross sectional flow area is significantly reduced. Significant meeting/passing manoeuvres were difficult to arrange because of inherent operational complications requiring ships to transit at slow speed (e.g., during lock approaches). Figure 3.31 shows some measures and parameters recorded during one meeting/passing manoeuvre near the downstream end of Lake St. Louis. The plots in Figure 3.39 show that sinkage increased by an approximate factor of two during the meeting manoeuvre. The third Panama Canal study discussed in Section 3.8 had as its focus the measurement of ship behaviour during meeting/passing manoeuvres. Table 3.10 shows the results of this study that were recorded in the Gaillard Cut, which is a confined waterway somewhat similar to (although larger than) the South Shore Canal. The table indicates the approximate increase in sinkage during the meetings.

Table 3.10: Meeting Situations in Panama Canal, June 1999

Meeting Ships	Draft (m)	Length (m)	Beam (m)	Meeting Speed (kn)	Meeting Distance (m) Centre-to-Centre	Sinkage Increase Factor
Mette Maersk (co)	11.6	294.2	32.3	5.3	84	1.2
Neapolis (co)	10.9	228.7	32.3	5.2		1.0
Protank Orinoco (t)	8.0	228.7	32.3	6.7	89	1.4
Maren Maersk (co)	11.9	294.2	32.3	6.7		1.4
Michele Iuliano (b)	12.0	225.0	32.3	4.7	66	2.0
Ming Asia (co)	11.1	275.9	32.3	6.2		1.5
Marit Maersk (co)	11.5	294.2	32.3	6.5	72	2.0
Tokio Express (co)	11.4	287.8	32.3	6.6		1.2
Ever Excellent (b)	11.9	225.0	32.3	5.5	88	1.4
Sea Clipper (b)	12.0	225.0	32.3	5.5		1.25
Zim Israel (co)	10.7	234.0	32.3	6.6	83	1.6
Mehmet Bey (b)	12.0	225.0	32.3	5.8		1.3
Hanjin Marseilles (co)	10.6	289.6	32.3	7.6	86	1.4
Harmony (b)	12.1	225.0	32.3	6.0		1.4
Yick Zao (b)	11.4	177.7	29.0	5.5	77	2.0
Ever Dainty (co)	11.5	294.2	32.3	8.9		1.5
CCNI Atacama (b)	11.4	185.1	32.3	6.0	91	1.7
Beauty Sea (b)	11.4	225.0	32.3	5.6		2.0
Jin Qiang (b)	11.6	185.7	31.1	6.3	67	1.75
St. Joseph (b)	11.8	220.1	32.3	5.8		1.6
Ever Right (co)	10.5	293.9	32.3	6.9	64	2.0
Manzanillo (co)	9.2	242.7	32.3	6.7		2.0
Auk Arrow (b)	10.6	187.5	29.0	6.3	59	1.4
CO-OP Phoenix (b)	12.0	225.0	32.3	6.7		1.25
Aegean Bulker (b)	9.1	179.0	27.7	5.5	61	1.75
CSAV Rapel (b)	8.5	163.1	26.6	9.0		1.6
Ever Refine (co)	9.00	294.2	32.3	11.8	76	2.0
Nedlloyd Dejima (co)	11.9	287.2	32.3	11.5		2.33

** designations: co = containership; t = tanker; b = bulk carrier

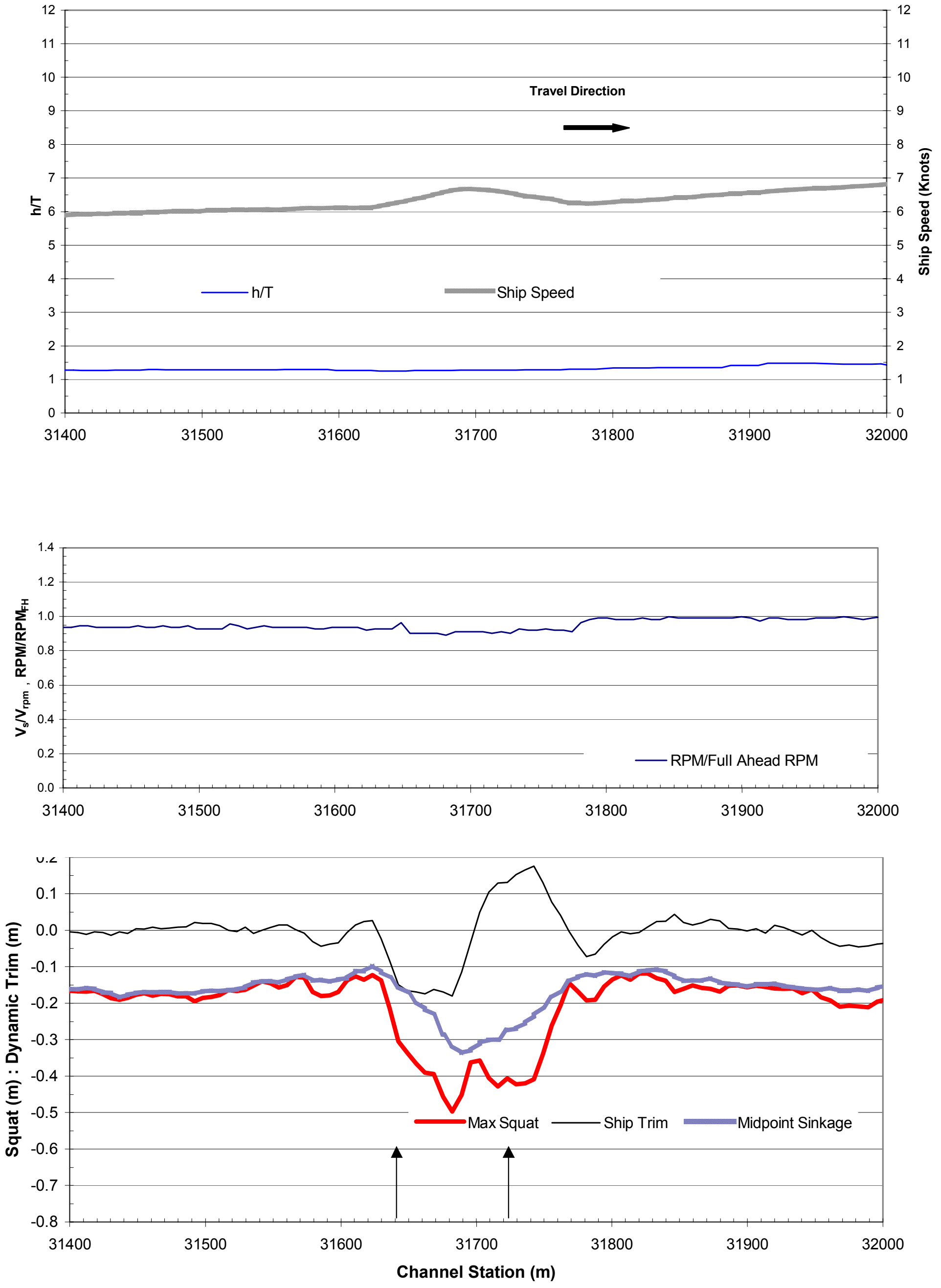


Figure 3.39: ***Rt. Hon. Paul Martin*** **Meeting** ***Algoport***

An example of how this affects the squat prediction results is shown in Figures 3.40 and 3.41. These figures show that a series of points that underpredict the squat significantly have been removed from Figure 3.40; these are the horizontal "tails" in Figures 3.41 about midway down the graph. These data were not removed during the squat and UKC analysis and, therefore, account for some of the underprediction results.

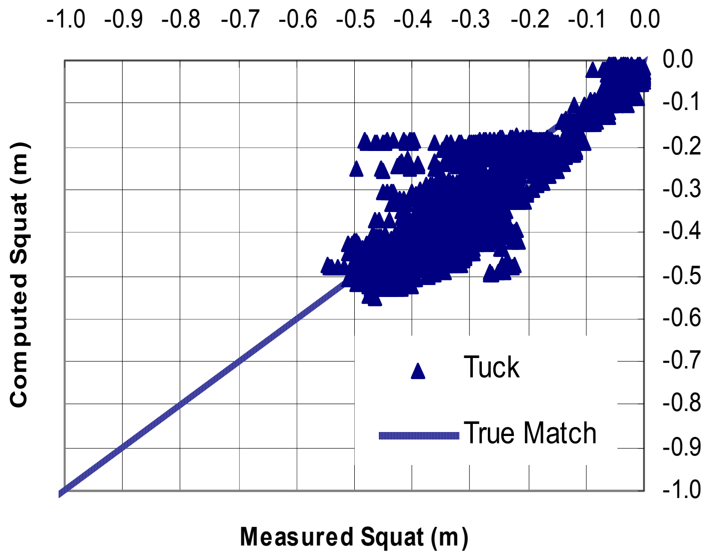


Figure 3.40: Predicted and Measured Squat Using Tuck for *Rt. Hon. Paul Martin* – Day 299 Without Data During Meeting Removed

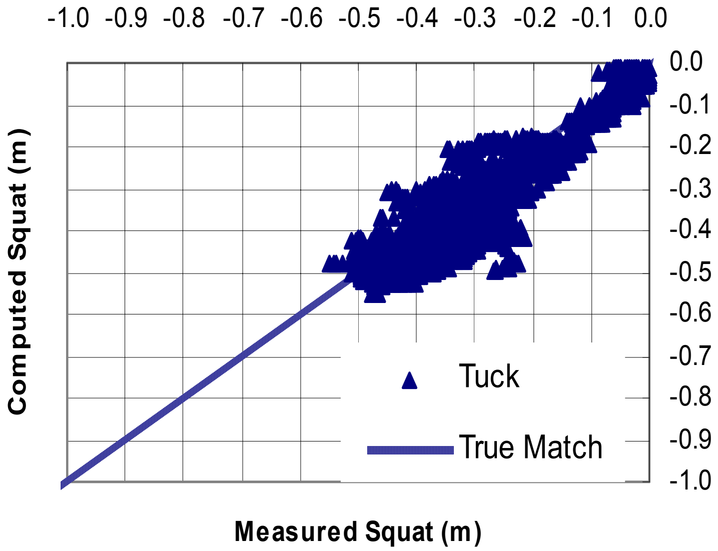


Figure 3.41: Predicted vs. Measured Squat Using Tuck for *Rt. Hon. Paul Martin* – Day 299 with Meeting Data Removed

4. RECOMMENDATIONS

Squat model recommendations resulting from this study vary according to channel segment and ship type. The analysis was based on comparative statistics obtained from scatter plots of predicted versus measured squat. Table 4.1 summarizes the sample mean error and standard deviations for the best-fit methods. The specific recommended methods are indicated by summary statistics in bold. A negative mean error indicates that squat is underestimated in comparison to measured squat. Conservative estimation was desired; therefore, all recommended methods are those with small positive mean error and relatively small variance. For Traditional Lakers in South Shore Canal, both Tothill and Tuck are good candidates; Tothill was selected to maintain consistency with the New Lakers.

Table 4.1: Sample Mean Error and Standard Deviations

Ship Type	**Lake St. Louis Transits**			
	Tuck		**Eryuzlu et al.**	
	Mean Error (m)	Stand. Dev. (m)	Mean Error (m)	Stand. Dev. (m)
New Laker	**0.02**	**0.08**	0.07	0.09
Trad. Laker	**0.08**	**0.13**	0.13	0.17
Chem. Tanker	0.08	0.09	**0.01**	**0.07**
Salty Bulker	**0.04**	**0.10**	0.02	0.13
Salty Laker	**0.05**	**0.09**	0.09	0.11

Ship Type	**South Shore Canal Transits**					
	Tuck		**Barrass 2**		**Tothill**	
	Mean Error (m)	Stand. Dev. (m)	Mean Error (m)	Stand. Dev. (m)	Mean Error (m)	Stand. Dev. (m)
New Laker	-0.03	0.08	0.08	0.09	**0.02**	**0.10**
Trad. Laker	0.02	0.08	0.12	0.09	**0.01**	**0.11**
Chem. Tanker	0.08	0.08	**0.04**	**0.06**	-0.08	0.09
Salty Bulker	0.04	0.11	**0.03**	**0.11**	-0.14	0.14
Salty Laker	-0.04	0.14	**0.04**	**0.13**	-0.08	0.17

For the extended reach, the recommended models are different for some cases. Specifically, in Lake St. Francis, Barrass 3 provides the best representation of the measured squat for the New Laker and Traditional Laker. In most of the other cases, the difference between Eryuzulu et al. and Tuck are small. Barrass 2 does not compare well at all for the Wiley-Dondero Canal; however, Eryuzulu et al. is comparable to Tuck and Tothill. Table 4.2 summarizes the sample mean error and standard deviations for the best-fit models for the extended reach measurements.

Table 4.2: Sample Mean Error and Standard Deviations for the Best-Fit Models for the Extended Reach Measurements

Ship Type	**Lake St. Francis Transits**					
	Tuck		**Eryuzlu et al.**		**Barrass 3**	
	Mean Error (m)	Stand. Dev. (m)	Mean Error (m)	Stand. Dev. (m)	Mean Error (m)	Stand. Dev. (m)
New Laker	-0.28	0.08	-0.28	0.08	**-0.01**	**0.13**
Trad. Laker	-0.37	0.10	-0.29	0.09	**0.10**	**0.13**
Salty Bulker	**0.00**	**0.07**	**0.00**	**0.07**		
					Eryuzlu & Hausser	
Salty Laker	0.14	0.07	**-0.08**	**0.08**	**0.05**	**0.08**

Ship Type	**Wiley-Dondero Canal Transits**					
	Tuck		**Eryuzlu et al.**		**Tothill**	
	Mean Error (m)	Stand. Dev. (m)	Mean Error (m)	Stand. Dev. (m)	Mean Error (m)	Stand. Dev. (m)
New Laker	**0.01**	**0.12**	-0.01	0.10	0.02	0.12
Trad. Laker	**0.04**	**0.18**	0.04	0.18	-0.07	0.14
Salty Bulker	0.07	0.17	**0.01**	**0.15**	-0.09	0.11
Salty Laker	0.09	0.27	**0.07**	**0.26**	-0.03	0.23

The numerical methods identified in Tables 4.1 and 4.2 are detailed in section 2.6 and are repeated here for ease of reference. Please refer to section 2.6 for details not noted here.

Barrass 2

$$S_{\max} = \frac{C_b S_2^{2/3} V_k^{2.08}}{30}$$

Barrass 3

$$S_{\max} = \frac{C_b V_k^2}{50} \text{ for confined water} \quad \text{or} \quad S_{\max} = \frac{C_b V_k^2}{100} \text{ for open water}$$

Tuck

$$S_b = 1.46 \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} K_S + 0.5 L_{pp} \sin\left(\frac{\nabla}{L_{pp}^3} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} K_S\right)$$

Eryuzlu et al.

$$S_b = 0.298 \frac{h^2}{T} F_{nh}^{2.289} \left(\frac{h}{T}\right)^{-2.972} K_b \qquad \text{where} \qquad 1.1 < \text{h/T} < 2.5$$

$$K_b = \frac{3.1}{\sqrt{W/B}} \quad \text{when} \quad \frac{W}{B} < 9.61 \qquad \text{or} \qquad K_b = 1 \quad \text{when} \quad \frac{W}{B} \geq 9.61$$

Eryuzlu & Hausser

$$S_b = 0.113 \left[\frac{T}{H}\right]^2 BF_{nh}^{1.8} \qquad\qquad 1.08 < \text{h/T} < 2.75$$

Tothill

$$S_b = S_m + 0.5(Trim) \qquad\qquad S_m = 1.25 C_b \left(\frac{V^2}{2g}\left(PAR\_A - 1\right)\right)$$

$$PAR\_A = \left[\frac{\mathrm{A}_c}{\mathrm{A}_c - BT - W\left(\frac{V^2}{2g}\right)\left(\left(\frac{\mathrm{A}_c}{\mathrm{A}_c - BT}\right)^2 - 1\right)}\right]^2$$

$$Trim = 2S_m(PAR_{ch})(PAR\_h/T)$$

$$PAR_{ch} = (C_b^{(2+PAR\_A)} - 0.15(1 + PAR\_A^2) - K_b^T - K_{TR}^T - K_{in}^T) * PAR\_h/T$$

It can be seen that some of these six methods require knowledge of numerous channel and ship parameters. Below are listed the parameters and measures required to apply each of the methods:

Barrass 2:	Ship block coefficient Ship speed Cross-sectional area of vessel midship section Net underwater cross-sectional area of channel
Barrass 3:	Ship block coefficient Ship speed

Tuck:	Ship volume displacement
	Ship length between perpendiculars
	Ship speed
	Water depth
	Cross-sectional area of vessel mid-ship section
	Cross-sectional area of channel
	Channel-type parameter
Eryuzlu et al.:	Water depth
	Mean ship draft
	Ship beam
	Ship speed
	Channel width (toe-to-toe)
Eryuzlu & Hausser:	Mean ship draft
	Ship beam
	Ship speed
	Channel width (toe-to-toe)
Tothill:	Ship block coefficient
	Ship beam
	Ship speed
	Mean ship draft
	Draft forward
	Draft aft
	Channel width (toe-to-toe)
	Cross-sectional area of channel
	Transom stern (yes or no) width
	Bulbous bow (yes or no)
	Water depth

For simplicity during Seaway operational decisions, the Barrass 2 formula would provide a reasonable estimation for all ship types in the South Shore Canal section of the channel if some of the information for the Tothill formula is not available. The recommended methods for the Lake St. Louis section are both fairly easy to apply. The recommended methods for Lake St. Francis and the Wiley-Dondero Canal should be used with caution as the data on which the recommendations are based did not represent adequate coverage of the channels.

4.1 Future Work

The extensive data that were collected during this study represent an available unique source for continuing work related to vessel squat in the St. Lawrence Seaway. With additional time and data collection, further enhancement of the results of this study could be accomplished. Listed below are recommended areas of future analysis.

- Provide additional hydrographic surveys for more extensive channel cross section data, including waterway outside of navigation channel, especially in South Shore Canal Lower Pool and the extended reaches.
- Collect additional water level measurements along the channel to determine the effect of surges and fluctuations in water level surface and to define more accurately the water surface elevations along the navigation canal in the extended reaches.
- Perform further analysis of the EC data to compare these data with the SLSMC water surface levels and channel bottom values.
- Obtain more complete water surface, current and channel bottom elevation data for Lake St. Francis and the Wiley-Dondero Canal to be used in further analysis of the squat data collected during the extended runs.
- Determine the effect of ship traffic and moored vessels in the canal on squat through further investigation of videotapes, ship logs and SLSMC traffic records.
- Develop a customized formula for calculation of squat in the St. Lawrence Seaway.