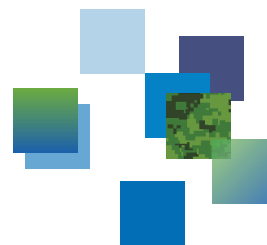Defence Research and Development Canada
Recherche et développement pour la défense Canada

# DRDC | RDDC

Post HCM/FELEX First of Class Standardization and Manoeuvring/ Controllability Trials on HMCS CALGARY

*Volume 1 of 4: Trial Summary*

Eric Thornhill

**Defence Research and Development Canada**

Canada

# Post HCM/FELEX First of Class Standardization and Manoeuvring/Controllability Trials on HMCS CALGARY

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# Abstract

The Halifax Class frigates are currently undergoing a midlife modernization as part of the FELEX program. An existing data set for standardization and manoeuvring/controllability for the HALIFAX Class frigates is from a trial in 1991 on HMCS HALIFAX when the ships were newly built. The ships now operate at a deeper displacement and have undergone a number of appendage changes. In order to update manoeuvring data for the post-refit ships a sea trial was conducted on HMCS CALGARY in September 2013. This report presents a summary description of this standardization and manoeuvring/controllability sea trial. Instrumentation, conditions, and data processing are discussed. The analysis and results from the trial are given in separate reports.

# Significance for defence and security

The Halifax Class ships are in the process of a midlife modernization. Upon completion of the refit, the Halifax Class will operate at a deeper displacement and will have a number of appendage changes. Historical data for the vessels goes back to 1991 when the original standardization and manoeuvring/controllability trials were done, but it is somewhat limited due to a number of problems encountered during the trials at that time. New standardization and manoeuvring/controllability trials were conducted on HMCS CALGARY in September 2013 off the coast of British Columbia. These results document the performance of the ships post FELEX/HCM refit, which is of primary concern to operators, and will also provide more complete and up-to-date information for ship simulators and research/ operations modelling.

# Résumé

Les frégates de la classe HALIFAX font actuellement l'objet d'une modernisation de mi-durée dans le cadre du programme FELEX. L'ensemble des données existantes sur la normalisation et la manoeuvrabilité/pilotabilité des frégates de la classe HALIFAX provient d'un essai effectué en 1991 sur le NCSM HALIFAX, alors que les navires venaient d'être construits. Ce sont maintenant des navires à déplacement plus lourd et leurs appendices ont subi de nombreuses modifications. Pour mettre à jour les données de manoeuvrabilité des navires après radoub, on a procédé, en septembre 2013, à un essai en mer du NCSM CALGARY. Ce rapport présente une description sommaire de cet essai de normalisation et de manoeuvrabilité/pilotabilité en mer. Les instruments de bord, les conditions de navigation et le traitement des données font l'objet d'une discussion. L'analyse et les résultats de cet essai figurent dans des rapports distincts.

# Importance pour la défense et la sécurité

Les navires de la classe Halifax sont en processus de modernisation de mi-durée. Après le radoub, les navires de la classe Halifax seront à déplacement plus lourd et leurs appendices auront subi de nombreuses modifications. Les données historiques sur les navires remontent à 1991, année où on a procédé aux premiers essais de normalisation et de manoeuvrabilité/pilotabilité, mais elles sont quelque peu limitées en raison des nombreux problèmes survenus à l'époque au cours de ces essais. En septembre 2013, on a procédé à de nouveaux essais de normalisation et de manoeuvrabilité/pilotabilité sur le NCSM CALGARY, au large des côtes de la Colombie Britannique. Ces résultats documentent les performances des navires après le radoub FELEX/MCH, lequel revêt une importance capitale pour les exploitants, et fourniront également des renseignements plus complets et plus actualisés pour les simulateurs de navires et la recherche/modélisation des opérations.

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# 1   Introduction

The twelve HALIFAX Class Frigates, launched during the period 1988 to 1995, form the backbone of the Royal Canadian Navy (RCN). The ships were designed in the late 1970's and early 1980's to accomplish the Cold War Anti-Submarine Warfare (ASW) and Anti-Surface Warfare (ASUW) missions primarily in the open ocean environment.

The operational profile of the HALIFAX Class has changed. Current and evolving threat systems are faster, stealthier, more manoeuvrable and are moving from open-ocean areas to the littoral environment.

The HALIFAX Class Frigates are undergoing a mid-life refit managed under the FELEX/ Halifax Class Modernization (HCM) project. In addition to the necessary maintenance and sustainment work involved in the mid-life refit, the modernization of the ships will see the implementation of new capabilities to meet the new threats and changing operating environments [2].

A number of the Engineering Changes (ECs) planned for the refits will affect the displacement of the vessels and see the addition or removal of some hull appendages. Such changes can have an impact on the speed, acceleration and manoeuvring / controllability of a ship.

Lightship displacement is expected to increase by 5% from 4086 t to 4294 t from the time of the last inclining to post-FELEX. This will result in a draft increase of 0.139 m at the deep departure displacement. In addition to a stern flap that is being added to the design in order to improve fuel economy, there are plans to remove the masking belt and related canoe fairings.

Standardization and manoeuvring/controllability trials were performed in 1991 when the original ships were delivered to the RCN from Saint John Shipbuilding Limited (SJSL), but the resulting data is somewhat limited due to a number of technical problems encountered during the trial at that time. In this report, the 1991 trial on HMCS HALIFAX is refereed to as 'HAL1991'. Likewise, the current 2013 trial on HMCS CALGARY is referred to as 'CAL2013'.

In order to document the performance of the post FELEX/HCM refit ships, as well as provide more complete and up to date information for ship simulators and research/operations modelling, a standardization and manoeuvring/controllability sea trial [3] was conducted on HMCS CALGARY off the coast of British Columbia in September 2013. This report contains a summary of activities related to the preparation, execution, and data analysis for this trial.

The trial was conducted by personnel from the Naval Platform Operational Limits (NPOL) Group of the Warship Performance (WP) Section from DRDC Atlantic. This work was assigned to DRDC with a MARCORD Task Request initiated by DNPS 2-3.

# 2 Trial summary

The date & time references in this report are with respect to GPS time (also referred to in this report as UTC[1]), unless otherwise stated as being a local time. Local time was that for Victoria, British Columbia which uses Pacific Daylight Time (PDT). During the trial, local time was UTC minus 7 hours (e.g. 12:00 Local Time = 19:00 UTC).

## 2.1 Operational area

The trial was conducted off the west coast of Vancouver Island approximately 100 - 200 nmi from Canadian Forces Base Esquimalt. This location met the requirements of an unconfined area with steady (non-fluctuating) ocean currents free from shipping traffic with water deeper than 50 m. This location had the added advantages of being in the vicinity of Ocean Data Acquisition System (ODAS) buoys and Differential GPS (DGPS) towers. The complete track from the trial is shown in Figure 1 along with the DGPS towers and ODAS buoys listed in Table 1.

*Table 1:* *Weather buoys and DGPS towers near proposed operational area*

| DGPS Towers | | |
|---|---|---|
| Name | Latitude | Longitude |
| Amphitrite Pt. | 48.92°N | 125.55°W |
| Eliza Dome [4] | 49.87°N | 127.12°W |
| Richmond | 49.18°N | 123.12°W |
| ODAS Buoys | | |
| Name | Latitude | Longitude |
| La Perouse Bank - 46206 | 48.83°N | 126.00°W |
| South Brooks - 46132 | 49.73°N | 127.92°W |
| Neah Bay - 46087 | 48.49°W | 124.73°W |

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[1]Technically, GPS time is not the same as UTC (a.k.a., GMT or Zulu time). UTC is occasionally adjusted by leap-seconds intended to keep it synchronized with mean solar time, while GPS time has not. At the time of the trial, the culmination of leap-second corrections resulted in GPS time being ahead of UTC by 16 seconds. This 16 second difference was not applied to any of the trial data time stamps. They were only synchronized to the GPS time reference, even if stated as being UTC.

*Figure 1:* GPS track for CAL2013
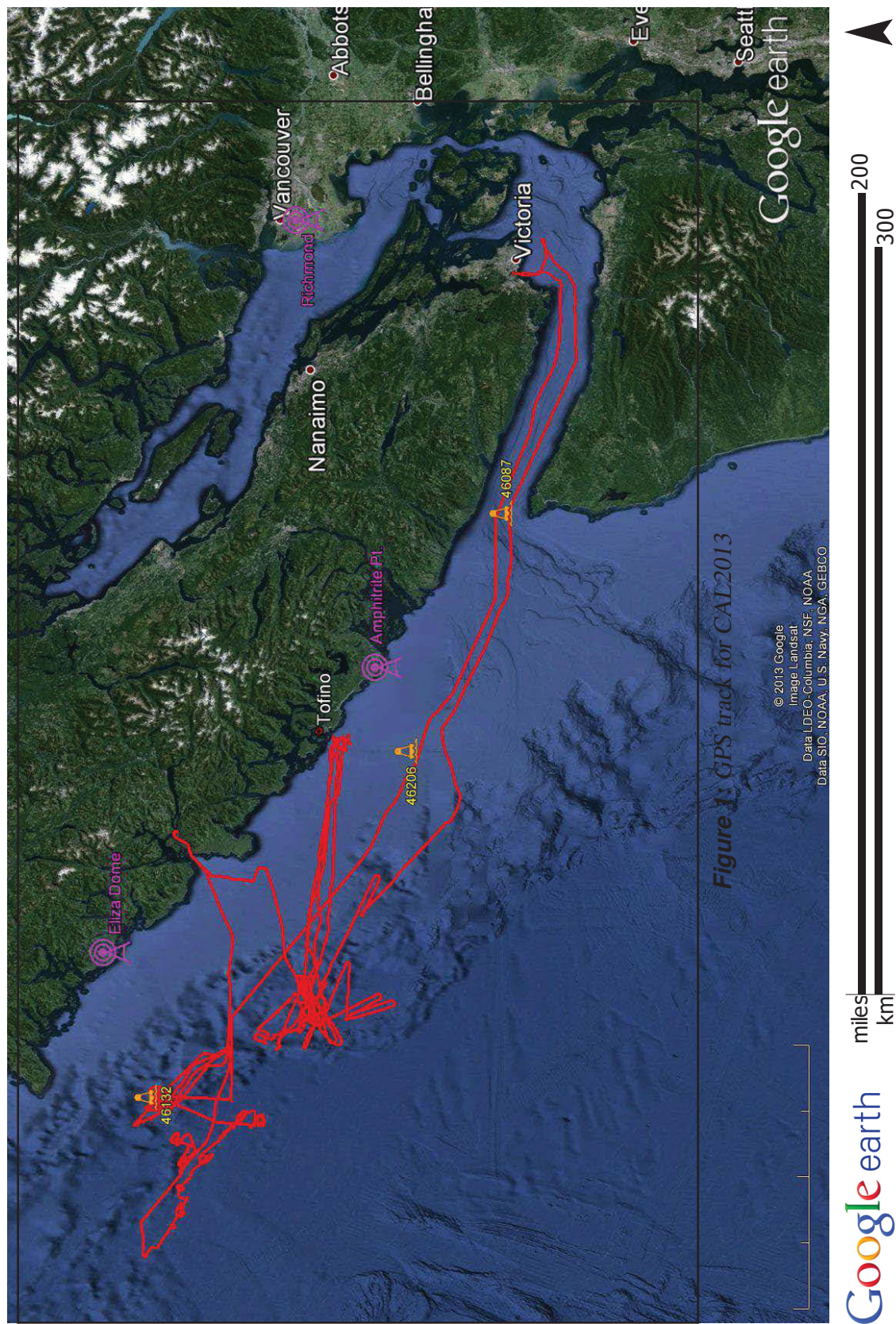
## 2.2 Sea state

Standardization and Manoeuvring/Controllability trials should be conducted in mild environmental conditions. The trials agendas [5], [6] indicate that the Sea State must be 2 or less as defined by Table 2, while International Towing Tank Conference (ITTC) recommended procedures [7] suggest maximum conditions of Sea State 3. Some guidelines for correcting trial results for environmental conditions are given in [8], but [9] notes that "*these correction methods are developed somewhat more intuitively than scientifically*" and explicitly indicates that for sea states of 5 or more that corrections are not reliable.

Although a directional wave buoy (Section 3.12) was brought, it was not deployed. Wind and wave conditions were mild and favourable throughout the trial. Wave measurements from moored ISDM buoys in the vicinity of the operational area are given in Section 3.15.

**Table 2:** *Sea state table for the open North Atlantic (NATO, 1993) [1]*

| Sea State Number | Significant Wave Height (m) | | Sustained Wind Speed (knots)[1] | | Percentage Probability of Sea State | Modal Wave Period (s) | |
|---|---|---|---|---|---|---|---|
| | Range | Mean | Range | Mean | | Range[2] | Most Probable[3] |
| 0-1 | 0 - 0.1 | 0.05 | 0 - 6 | 3 | 0.70 | - | - |
| 2 | 0.1 - 0.5 | 0.3 | 7 - 10 | 8.5 | 6.89 | 3.3 - 12.8 | 7.5 |
| 3 | 0.5 - 1.25 | 0.88 | 11 - 16 | 13.5 | 23.70 | 5.0 - 14.8 | 7.5 |
| 4 | 1.25 - 2.5 | 1.88 | 17 - 21 | 19 | 27.80 | 6.1 - 15.2 | 8.8 |
| 5 | 2.5 - 4 | 5 | 22 - 27 | 24.5 | 20.64 | 8.3 - 15.5 | 9.7 |
| 6 | 4 - 6 | 5 | 28 - 47 | 37.5 | 13.15 | 9.8 - 16.2 | 12.4 |
| 7 | 6 - 9 | 7.5 | 48 - 55 | 51.5 | 6.05 | 11.8 - 18.5 | 15.0 |
| 8 | 9 - 14 | 11.5 | 56 - 63 | 59.5 | 1.11 | 14.2 - 18.6 | 18.64 |
| >8 | >14 | >14 | >63 | >63 | 0.05 | 18.0 - 23.7 | 20.0 |

[1] Ambient wind sustained at 19.5 m above surface to generate fully developed seas.
To convert to another altitude, $H_2$, apply $V_2 = V_1 (H_2/19.5)^{1/7}$.
[2] Minimum is 5th percentile and maximum is 95th percentile for periods given wave height range.
[3] Based on periods associated with central frequencies included in Hindcast Climatology.

## 2.3 Engine Configurations

The HALIFAX Class frigates are twin screw, single rudder ships powered by two GT engines and one PDE in a Combined Diesel or Gas (CODOG) plant arrangement (shown in Figure 2). Power can be delivered to one or both propeller shafts using the PDE, a single GT, or both GTs. Normal modes of operation are those in which the engine power is distributed to the shafts through a cross-connected (XCON) gearbox which maintains equal shaft rotation rates to the port and starboard propellers [10].

The trials agenda [6] called for certain runs to be performed using a single driving pro-

# Plant Layout (CODOG)
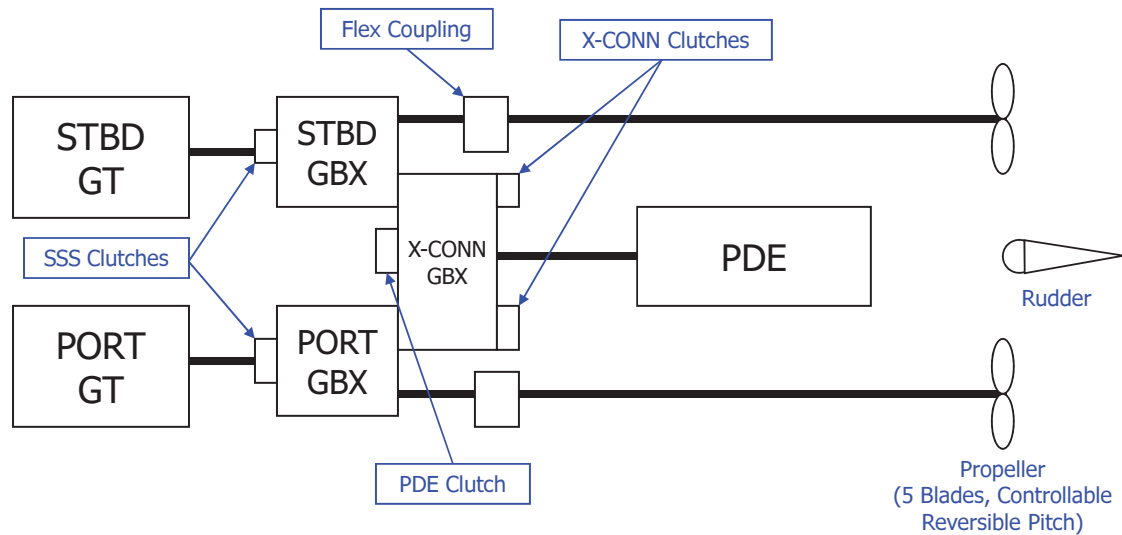


**Figure 2:** *Engine and propulsion configuration*

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peller shaft. There are two possibilities for the non-driving shaft; locked or trailing. A locked shaft requires significant effort (1.5 - 2 hours) to engage the locking mechanism and is limited to a maximum torque. Trailing a shaft involves disengaging one of the cross-connection clutches, allowing the engine to drive a single shaft directly. The trailing shaft must maintain some rotation in order to ensure proper lubrication in its bearings. References to a single driving shaft in this trial report refer to the trailing shaft configuration only. No shaft was locked during the trial.

# 3 Instrumentation, data collection, and processing

Considerable data was collected about the ship and environmental conditions. Some data was logged manually, some logged with native ship systems, while others required specialized instrumentation.

The data acquisition was set-up as a number of self-contained units throughout the ship (they were not networked together). Data collection units were located in: the passageway to the Chiefs & Petty Officers (POs) servery (near the ship's CG), the chart room, the steering gear compartment, on-deck at the bow, the hanger, on-deck aft of the flight deck, and in the engine room (forward and aft). Approximate positions for various instruments are given in Table 3. The 'ship centre' or OSRP, used by the NDDS as the reference for GPS coordinates was set in accordance with the "2007 Manual of Trim and Stability Deep Departure".

Data coverage during the trial is illustrated in Figure 3. The top plot shows the periods during which the various run types were performed. The bottom plot shows the data coverage for the various sensors used on the trail.

With the exception of the fuel flow meters (Section 3.9), all trial related equipment was installed by the DRDC trials team on the weekend prior to the trial departure and was completely removed at the end of the trial.

***Table 3:*** *Instrument locations (approximate)*

| Instrument | X [m] | Y [m] | Z [m] |
|---|---|---|---|
| Own Ship Reference Point (OSRP) | 59.63 | 0.02 | 6.56 |
| NAV420 Motion Sensors | 67 | 0 | 8.6 |
| NRC 3m Bow Anemometer | 132 | 0 | 15.8 |
| NRC 5m Bow Anemometer | 132 | 0 | 17.8 |
| Ship Port Anemometer | 81 | 3.75 | 28.5 |
| Ship Starboard Anemometer | 81 | -3.75 | 28.5 |
| Bow DGPS | 132 | 0 | 15.8 |
| Aft DGPS | 5 | 0 | 13 |
| Handheld GPS | 22 | 7.5 | 13 |
| NRC Meteorological Sensors | 96.5 | -5.5 | 18.75 |

Longitudinal X is relative to the AP. Lateral Y is relative to the ship centreline (port is positive, starboard is negative). Vertical Z is relative to the baseline (keel). The AP is defined at the intersection of the transom with the waterline at a level draft of 5.00 m.
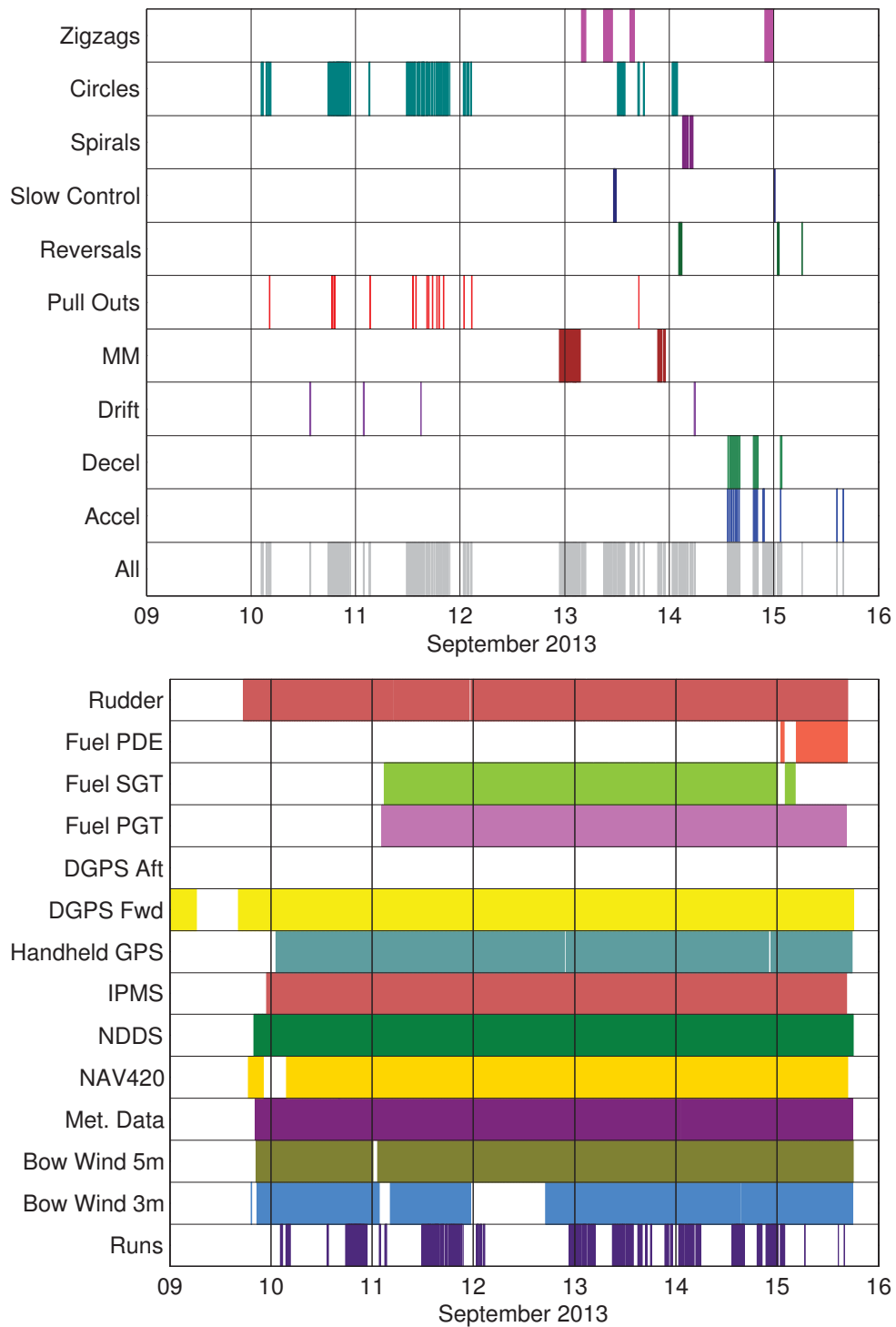
**Figure 3:** *Run times and data coverage*

## 3.1 Time synchronization

Conducting a sea trial with multiple independent data logging computers requires careful attention to time synchronization between the systems. Generally, the internal clocks used in most laptop and desktop computers stray over time (sometimes as much as seconds per day). To correct this, time servers were connected to each standalone computer or to groups of networked computers. Two brands of time servers were used on this trial: the ORCA Model GS-101 [11], and the CNS Clock II [12].

These devices were synchronized with GPS time by connecting them to a GPS receiver. If they maintain a connection to a GPS receiver, they can automatically stay synchronized. If however they cannot remain connected to a GPS, such was the case for several units on this trial, they can maintain time using accurate internal clocks that can keep sub-millisecond precision for several months.

Two issues with time synchronization occurred during the trial. The first was with data logged by the ship's IPMS (Section 3.3) and the other was with rudder angle (Section 3.8). Both issues required post-trial corrections.

## 3.2 NDDS logging

The Navigational Data Distribution System, (NDDS) is used to provide various navigational and environmental data streams throughout the ship. DRDC connected a standalone data logging computer (laptop) to this system through a network connection located in the Aft Sonar Integrated Space (Aft SIS). NMEA style sentences were timestamped with DRDC time (see Section 3.1) and saved to file as they were received. Sentences $WIMTW and $PAXDR were not available on this ship for this trial. GPS position data were reported with respect to OSRP as defined in Table 3.

The following data was logged through port 14041 (mean sampling rate given in brackets):

a. $GPGGA - GPS position & time (1 Hz);

b. $GPGSA - GPS Dilution of Precision and active satellites (1 Hz);

c. $GPVTG - Course and speed (10 Hz);

d. $INDBT - Water depth below transducer (0.25 Hz);

e. $INGLL - Latitude and longitude (1 Hz);

f. $INHDT - Ship heading (True) (10 Hz);

g. $INROT - Ship rate of turn (10 Hz);

h. $INVHW - Heading and Speed Through Water (10 Hz);

i. $INVTG - Course Over Ground & Speed Over Ground (10 Hz);

j. $INXDR - Heading, roll, pitch (10 Hz);

k. $INZDA - GPS date & time (1 Hz);

l. $P1MWV - Port anemometer apparent wind & angle (1 Hz);

m. $P2MWV - Port anemometer true wind speed & angle (1 Hz);

n. $P2MWD - Port anemometer true wind speed & direction (1 Hz);

o. $P3MWV - Stbd anemometer apparent wind & angle (1 Hz);

p. $P4MWV - Stbd anemometer true wind speed & angle (1 Hz);

q. $P4MWD - Stbd anemometer true wind speed & direction (1 Hz);

r. $SDDBT - Water depth below transducer (0.5 Hz);

s. $SDDPT - Water depth and offset (1 Hz);

t. $WIMTW - Water temperature (unavailable);

u. $PAXDR - Air temperature, pressure, and humidity (unavailable).

## 3.3   IPMS logging

The Integrated Platform Management System, (IPMS) (also known as Halifax Class IPMS or HCI) was used to access and log data streams related to the machinery and propulsion systems during the trial.

The IPMS was configured to log at 1 Hz for the duration of the trial. The following data was logged by the IPMS and transferred to the DRDC trials team at the end of each day (IPMS logging code in brackets):

a. Port Shaft RPM (PROGBX10001);

b. Starboard Shaft RPM (PROGBX10161);

c. Port propeller pitch setting (ANCCPP10200);

d. Starboard propeller pitch setting (ANCCPS10200);

e. Port GT PLA (PROGTP10200);

f. Starboard GT PLA (PROGTS10200);

g. Port shaft torque (PROGBX10041);

h. Starboard shaft torque (PROGBX10201);

i. Port shaft power (PROGBX10080);

j. Starboard shaft power (PROGBX10240);

k. Drive mode; identification of operating engines and gearing configuration (dm_drive_mode_0).

During the trial, there was discrepancy of 1 - 2 minutes between the clock used by the IPMS system and UTC time (used for the trial data). This could not be easily corrected on the ship, so a log of the discrepancies was made at least once a day. This was done by manually marking down the times as seen on the IPMS clock and a GPS clock at the same instant. These times are listed in Table 4 and plotted in Figure 4 along with a linear best-fit line. The equation for this regression line was then used to determine the correct time shift to apply to the raw IPMS data when it was processed for analysis. This method of correcting the IPMS time discrepancy to UTC is likely only accurate to approximately $\pm 1$ second.

*Table 4: Logged times for IPMS and UTC*

| UTC | IPMS | Lag [s] |
|---|---|---|
| 10-Sep-2013 14:12:00 | 10-Sep-2013 14:10:14 | 106 |
| 10-Sep-2013 01:15:45 | 10-Sep-2013 01:13:57 | 108 |
| 12-Sep-2013 17:05:30 | 12-Sep-2013 17:03:48 | 102 |
| 13-Sep-2013 08:08:00 | 13-Sep-2013 08:06:22 | 98 |
| 13-Sep-2013 04:13:00 | 13-Sep-2013 04:11:22 | 98 |
| 13-Sep-2013 20:50:20 | 13-Sep-2013 20:48:43 | 97 |
| 14-Sep-2013 23:55:00 | 14-Sep-2013 23:53:28 | 92 |
| 15-Sep-2013 16:32:00 | 15-Sep-2013 16:30:32 | 88 |
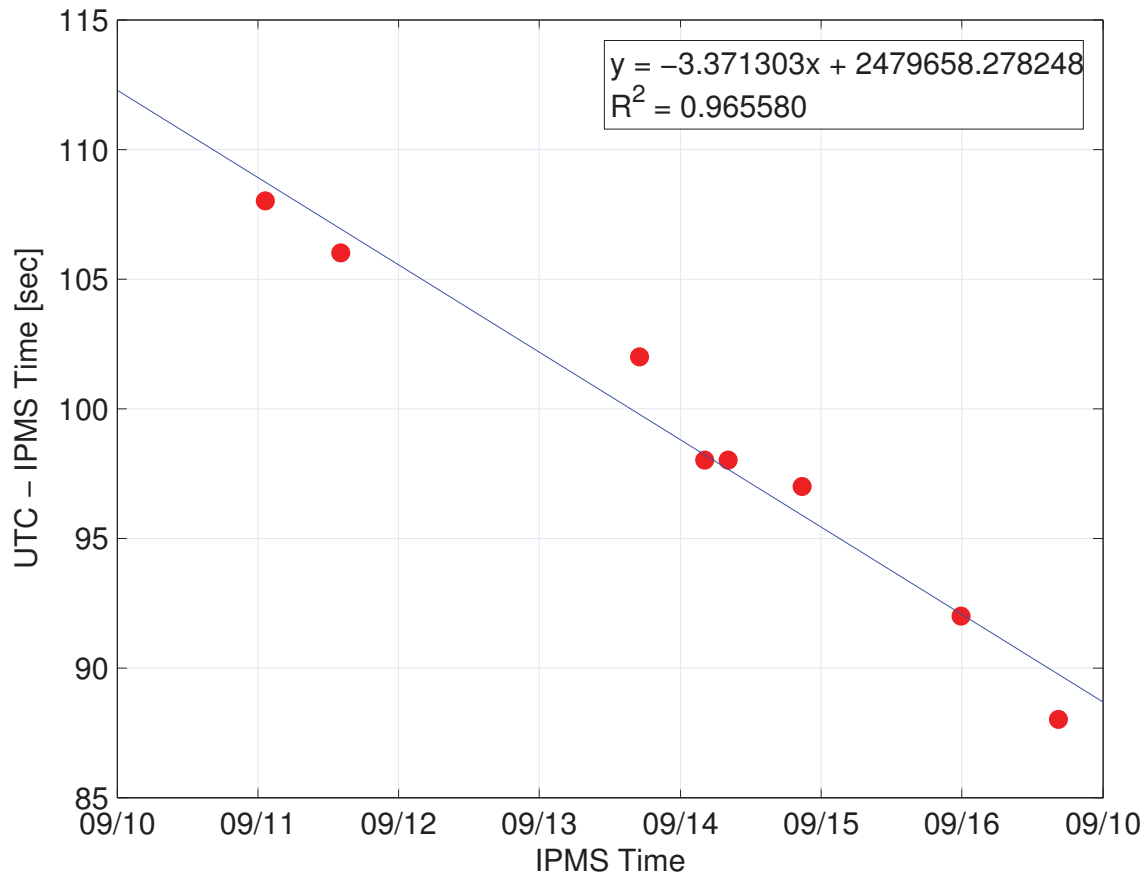
The *x*-axis is expressed as Matlab serial date numbers which are in units of days.
The Matlab date number corresponding to 12:00 pm on 10-September-2013 is 735486.5.

**Figure 4:** *IPMS time lag relative to UTC*

## 3.4 ECPINS logging

At the end of the trial, a copy of the Electronic Chart Precise Integrated Navigation System (ECPINS) data was provided by the ship to serve as a backup to other similar data sets such as from the NDDS (Section 3.2).

## 3.5 GLM data

GHS Load Monitor (GLM) reports [13], which detail the ship's weight, drafts, and hydrostatic stability, were generated twice each day by ship staff. Copies of these reports were given to the DRDC trial team at the end of the trial. Selected GLM data is summarized in Annex C.

## 3.6  Ship motions

Ship motions were recorded using a Crossbow® NAV420CA-100 [14] sensor which measures accelerations, angles, and angular rates along each of the three principal axes. The sensor was mounted to an aluminium plate which was then clamped to the flange of a structural beam in the deckhead of the passageway to the Chiefs and PO's servery (this is near the ship's centre of gravity). The data was logged at 20 Hz using a nearby laptop located in the Electrical Workshop as shown in Figure 5. Raw NAV420 data was converted to a forward-port-up coordinate system (see Figure 6 and Table 5) commonly used in ship seakeeping for analysis.

Ship roll & pitch were also recorded from the NDDS (Section 3.2) as measured by the ship's gyrocompass. These are more accurate than those from the NAV420 and were subsequently used for the analysis of runs. Roll angle, reported by the NDDS as positive stbd. down/port up, was converted during processing to stbd. up/port down in compliance with Figure 6.
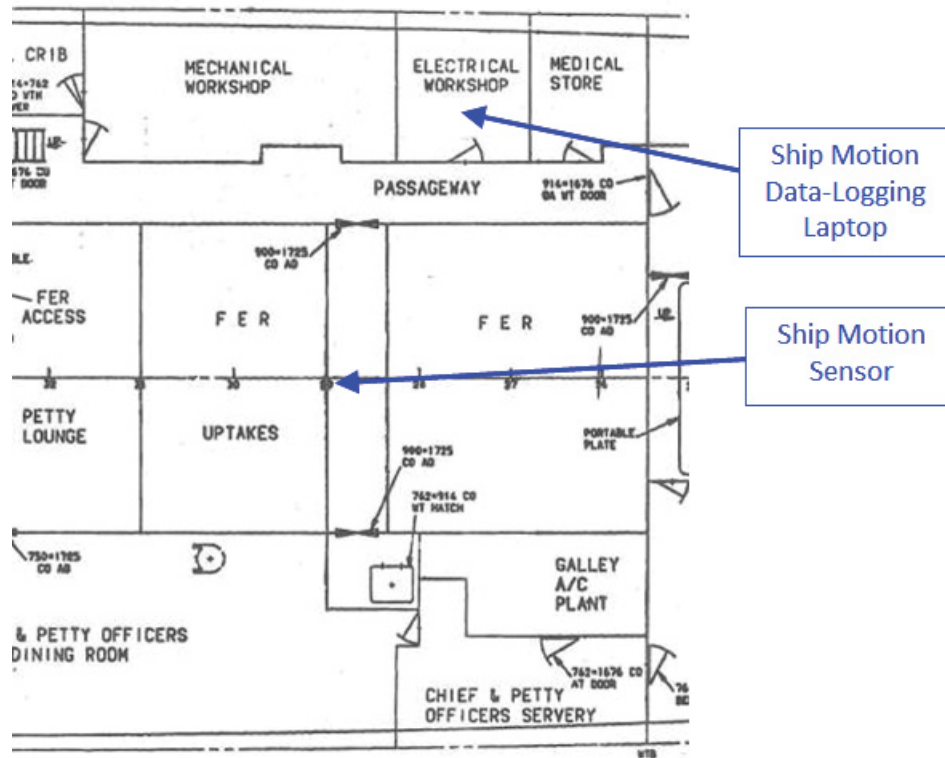


***Figure 5:*** *Motion sensor location on deck 2 (near ship CG)*
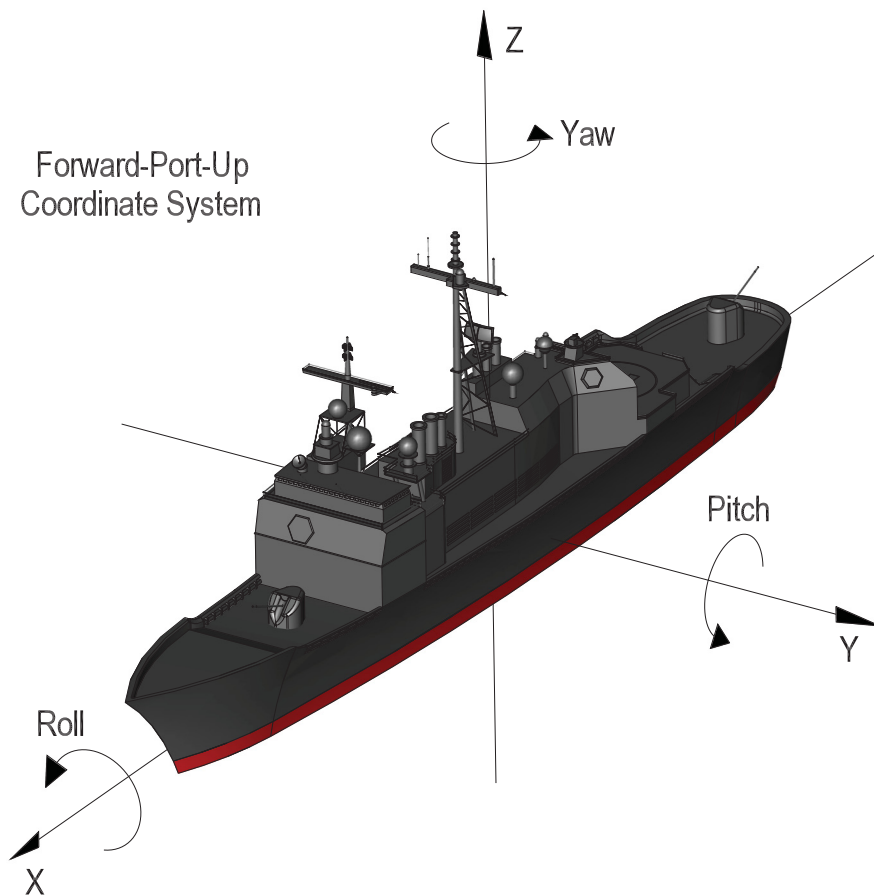
**Figure 6:** *Coordinate system*

**Table 5:** *NAV420 and ship coordinate system definitions*

| Axis/Rotation | NAV420 Coordinates | Ship Coordinates |
|---|---|---|
| $x$ axis | positive bow to stern | positive stern to bow |
| $y$ axis | positive towards port | positive towards port |
| $z$ axis | positive downwards | positive upwards |
| Roll (about $x$) | positive stbd up, port down | positive stbd down, port up |
| Pitch (about $y$) | positive stern up, bow down | positive stern up, bow down |
| Yaw (about $z$) | positive turning to stbd. | positive turning to port |

## 3.7   Differential GPS

In order to obtain the best possible accuracy for the ship position and orientation, two Differential GPS (DGPS) units were installed on the ship for the trial. Each unit consisted of a dual-frequency GNSS receivers (Novatel FlexPak$^{TM}$-V2-L1) connected to ring-style antenna (Novatel GPS-701-GG). One set was located on the anemometer bow pole (see Section 3.13), and the other mounted on the quarterdeck (see Figure 7). Both units were aligned with the centre-line of the ship. Data for the forward unit was logged by a Raspberry Pi Computer (RASP-PI) in the bridge wing Pelican case shown in Figure 29. A similar case was used to log the aft unit (Figure 8) with its own RASP-PI/ORCA pair.

Unfortunately, data from the aft unit was not available for analysis. During the morning of 09-Sep-2013 prior to departure, there was a power outage on the ship which reset various trial equipment, including the aft DGPS data acquisition. When this happened, the RASP-PI which had been configured to receive DGPS data from port 1 and the ORCA time signal from port 2 reset so that it was receiving both data and time on port 1. This fact was not noticed at the time because it did not generate an error and log files were being created as expected. Also, because the DGPS logged binary data that needed to be post-processed by Novatel's GrafMov software to produce the required latitude/longitude tracks, the data could not be checked on ship. Checks on the system were simply to see that it was still running and that new log files were being created, which they were. It was not until the end of the trial when all of the data was being collected onto a single computer that it was noticed that there was a large discrepancy in the size of the files generated by the forward unit relative to the aft unit. After returning to DRDC Atlantic, an attempt was made to post-process this data and it became apparent that the aft DGPS data only contained a small fraction of the required data. The port conflict on the RASP-PI had interfered with logging to the point that none of the data was usable.

Data from the forward unit was unaffected by this issue and was successfully post-processed and corrected using reference data from the Eliza Dome station [4] (see Section 2.1), yielding latitude / longitude track data at 2 Hz.

**Figure 7:** Aft DGPS antenna on quarterdeck


**Figure 8:** Pelican case for aft DGPS data acquisition

## 3.8   Rudder angle

As rudder angle is not logged by any of the ship's native systems, a custom set-up was therefore required for this trial. Rudder angle was measured and recorded by two identical stand-alone systems located in the rudder compartment (primary and secondary backup). As illustrated in Figure 9, each system consisted of a cable-extension transducer (Celesco Transducer Products Inc. Model PT101), an Analog-to-Digital (A/D) converter (NI Model 9239), and a laptop computer. The bases of the transducers were fixed to positions near the top of the rudder stock as shown in Figure 10. The transducer cables were attached to the rudder stock such that the cable was partially wrapped along the stock's outer perimeter. As the rudder changed angle, the cables extended or retracted an amount linearly proportionate to the change in rudder angle. The transducers' analogue voltage output passed through A/D converters before being recorded on a laptop computer (shown in Figure 11). Calibration parameters between transducer output voltage and rudder angle were determined alongside before the trial as given in Annex B.
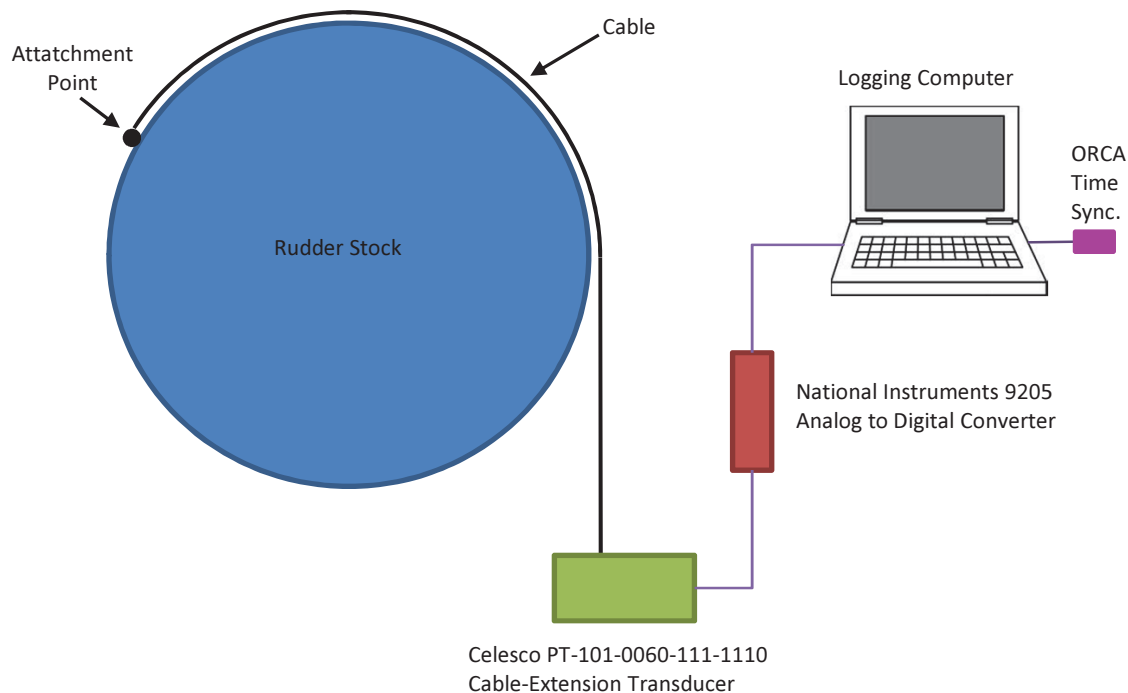


*Figure 9:* *Rudder angle measurement setup*

**Figure 10:** *Port (left) and starboard (right) linear transducers*
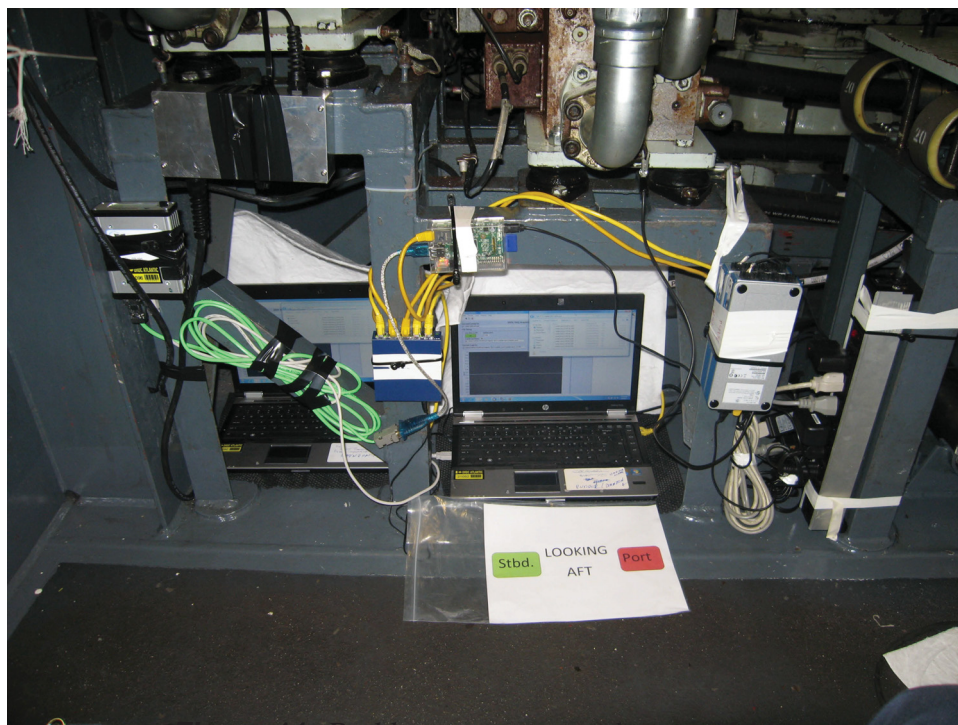


**Figure 11:** *Rudder compartment data acquisition*

The helm was set to use the 'follow-up' mode for the trial, which is consistent with normal operation. This mode activates a control system on the rudder movement which causes the slew rate to slow as the rudder approaches the requested angle. An example of this behaviour can be seen in Figure 13 which shows a rudder being ordered from midships to port 20°. At first the slew rate is constant, but as it approaches −20°, it slows down. There were two channels that can engage the follow-up mode; port and starboard. The trial was conducted entirely using the port follow-up channel, as the ship was having issues with the starboard channel. The ship is also equipped with two pumps to power the rudder hydraulics. The trial was conducted using a single pump, as per usual practice. Most of the trial relied on the starboard pump (which for this ship was believed to have a faster slew rate), although there were periods when the port pump was used.

During the set up phase for the trial, it was discovered that the DRDC's stock NI model 9205 A/D converters [15] were susceptible to drift error and would not perform satisfactory for rudder angle measurements. It was therefore decided to use the newer model 9239 converters [16] which could better compensate for this problem. One major difference between the two systems, not known at the time, was that the model 9239 had an internal clock.

With the older model 9205 system, time-stamps in the output data files used computer time, which was accurately set to UTC using an ORCA/RASP-PI combination (as described in Section 3.1). After first powering up the components, it would often take approximately 1 - 2 hours before a usable NTP time signal was available. Data files generated during this period would be discarded.

The model 9239 system uses its internal clock for generating time-stamps in the output data files. This clock is set to computer time when the converter is first powered up. It retains this time reference until it is reset by powering down and back up again; where it would again set itself to computer time.

During the trial, this difference in time handling was not known and the starboard rudder sensor A/D converter was powered up before its acquisition computer was properly synchronized to UTC by the ORCA. It therefore set its internal clock to an incorrect computer time which lagged UTC by ~135 seconds. When discovered after the trial during post-processing, a 135 second correction was made to the affected starboard sensor data, but an additional smaller correction was still required to properly align it to the port sensor data. This was done on a run-by-run basis.

The port sensor had a different issue with its data where, at times, it would not properly track the rudder position (as shown in Figure 12). At several times in the plot, the starboard sensor (corrected for time shift) shows a constant rudder angle while the port sensor shows a sloping line (such as between 19:05-19:12). This behaviour could be explained by some sort of slippage, sticking, or stretching of the cable connecting the transducer to the rudder post. This also affected the relationship between cable position and rudder angle

established during calibration, as illustrated by the offset between the starboard and port sensors. The degree to which the two sensors differed varied throughout the trial and was corrected on a run-by-run basis.
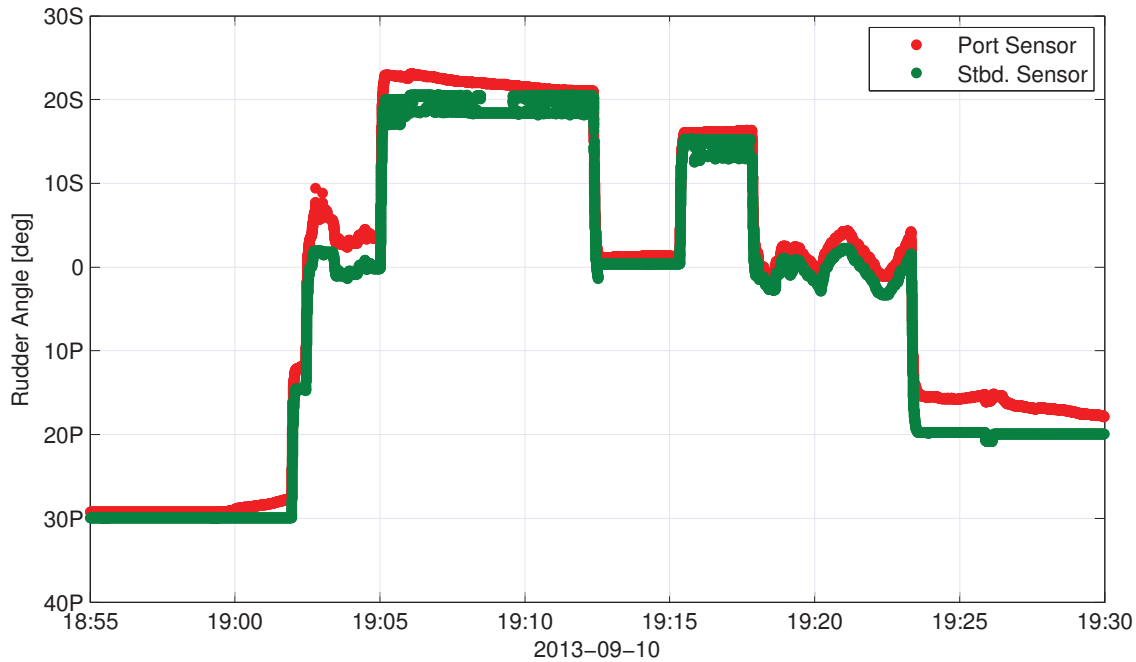


**Figure 12:** *Port rudder sensor slippage*

As discussed, there were issues with both of the sensors used to acquire rudder position during the trial. However, as the issues were different, corrected rudder angle could be determined by using data from both sensors. For each run in the trial, the following procedure was used to obtain this data:

   a. When reading from raw data files, 135 seconds was automatically added to any starboard sensor data with timestamps earlier than 00:00:00 on 11-Sep-2013.

   b. Rudder data from both sensors was then plotted for a range of ~1 - 2 minutes around the rudder execute time[2] (top plot in Figure 13).

   c. Using cross-hairs in a GUI, the rudder start swing time for both the port and starboard sensors were identified (top plot in Figure 13), to give the shift correction Eqn. (1).

---

[2]For runs without a specific rudder execute time, such as a measured mile, some other appropriate reference movement was used.

d. Port sensor time was assumed correct. The starboard sensor data was shifted using Eqn. (2) to match the port sensor data using the difference between the two rudder start swing times (middle plot in Figure 13).

e. Starboard sensor data was assumed to have the correct calibration. The port sensor data was adjusted for bias and scale using Eqn. (3) to best match the angles measured by the starboard sensor (bottom plot in Figure 13).

f. After these corrections, the two data sets would then be nominally equivalent (bottom plot in Figure 13).

g. For each individual run, the two corrected data sets would be plotted together and the one which appeared to have the least noise or other issues was selected as the rudder data for that run.

h. In the few instances where both sensors had a significantly large degree of noise, the least noisy data was chosen and passed through a smoothing filter before being used in further analysis.

$$t_{shift} = t_{portRef} - t_{stbdRef} \tag{1}$$

$$t_{stbdCorr} = t_{stbdRaw} + t_{shift} \tag{2}$$

$$\delta_{portCorr} = P_{scale}\,\delta_{portRaw} + P_{bias} \tag{3}$$

where,

$t_{shift}$ = Time shift of port rudder sensor relative to starboard sensor.
$t_{portRef}$ = Reference time in raw port rudder data.
$t_{stbdRef}$ = Reference time in raw port rudder data.
$t_{stbdRaw}$ = Raw starboard rudder sensor time.
$t_{stbdCorr}$ = Corrected starboard rudder sensor time.
$\delta_{portRaw}$ = Raw port rudder sensor angles.
$\delta_{portCorr}$ = Corrected port rudder sensor angles.
$P_{scale}$ = Scale factor applied to port rudder sensor angles.
$P_{bias}$ = Shift applied to port rudder sensor angles.
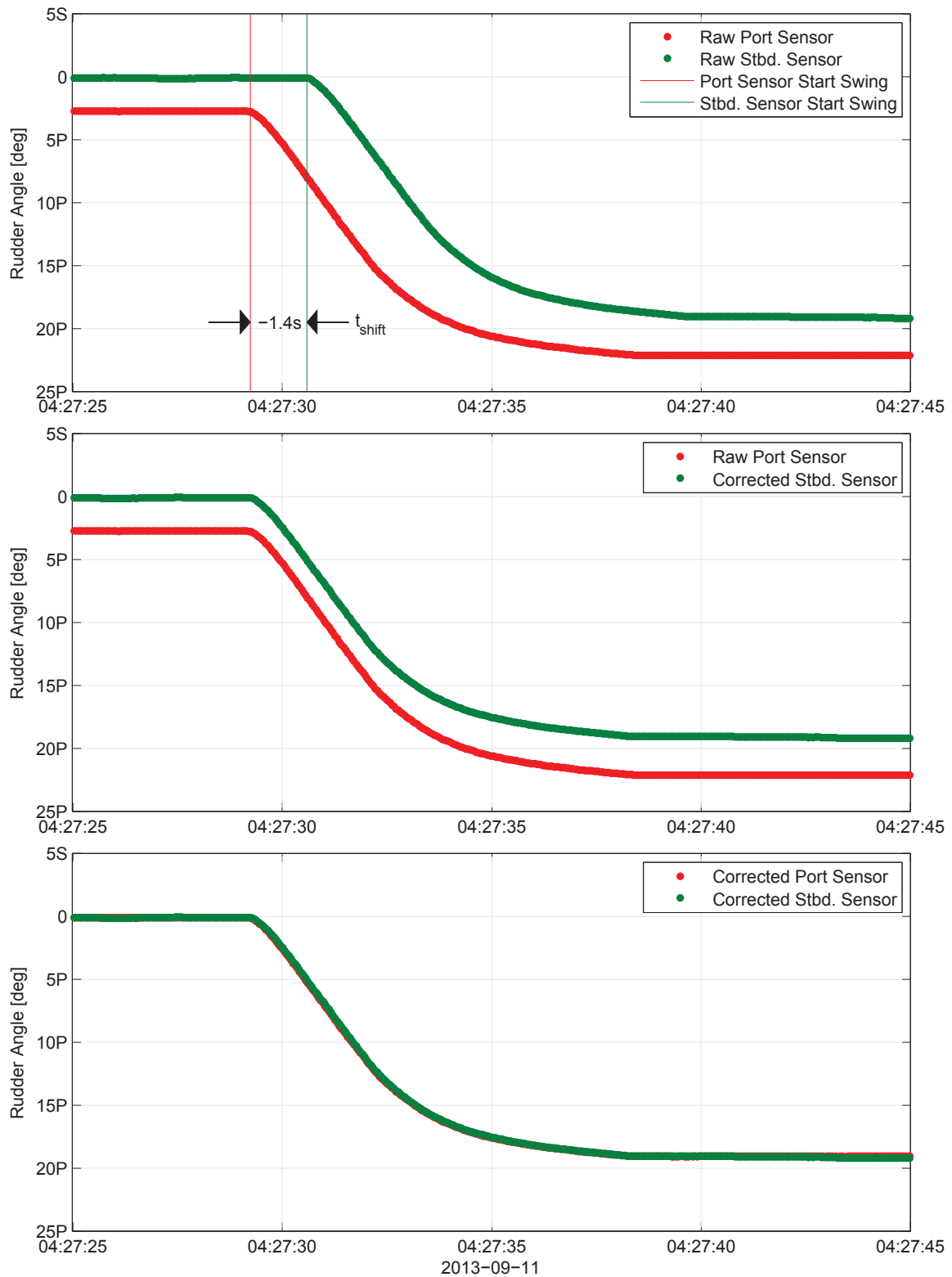
**Figure 13:** *Both rudder sensors corrected*

In many cases after correction, both the port and starboard sensor data sets where essentially identical (starboard sensor data was usually used). However, there were cases where either one data set or the other was noisy or even unusable, as shown in the following examples (data was first corrected as described in the above procedure). Figure 14 shows an example of good starboard sensor data while the port sensor was erratic. Figure 15 likewise shows a clean port sensor signal, but noisy starboard sensor data. Figure 16 shows a situation where both sensors had issues. The port sensor was erratic and the starboard sensor was noisy. Also shown in this example is the ordered rudder angle, and the starboard sensor data after being passed through a smoothing filter. Although sufficient rudder data was acquired to conduct the required analyses for the trial, the acquisition set-up used has room for improvement. It is recommended that manoeuvring trials should always have redundant systems for rudder angle measurement as it key to determining metrics. Methods other than the cable transducer should also be explored. Ideally, rudder angle should be included in the HCI system and logged by the ship.
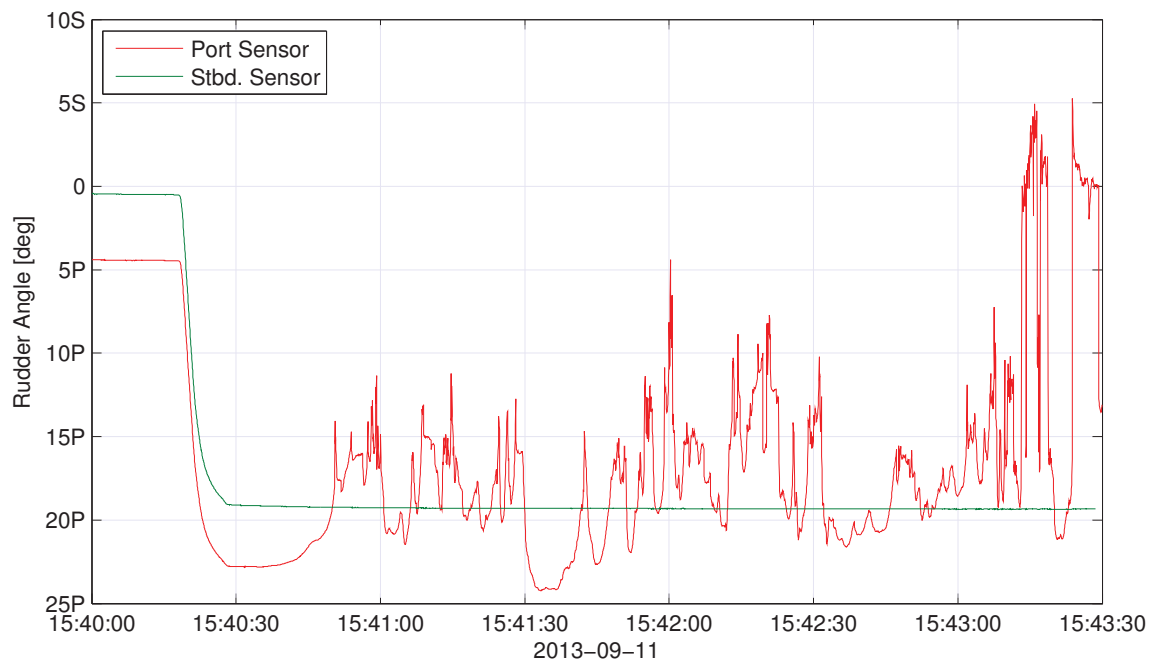


**Figure 14:** *Unusable port sensor data, good stbd. sensor data*
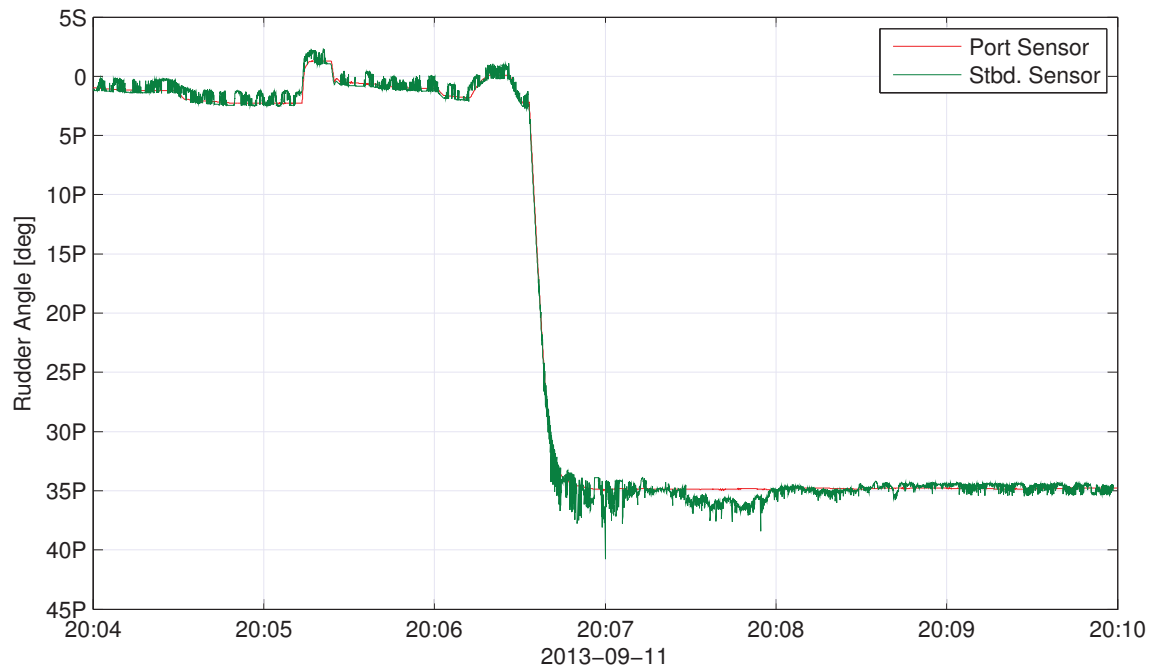
**Figure 15:** *Good port sensor data, noisy stbd. sensor data*
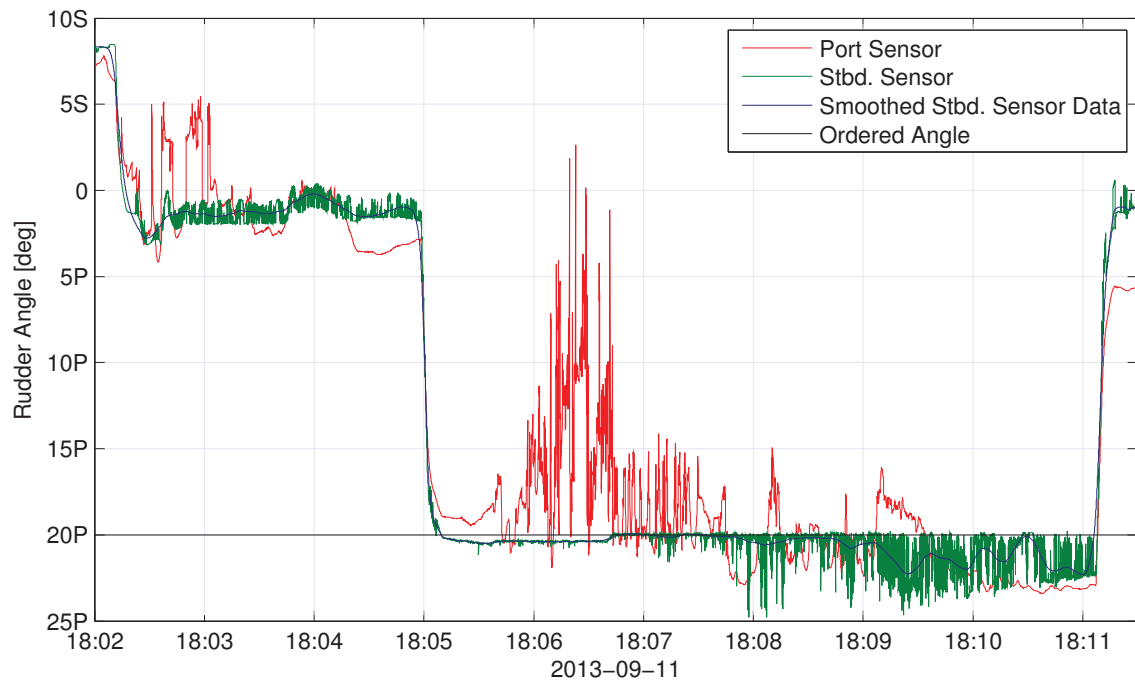


**Figure 16:** *Noisy port and starboard sensor data*

## 3.9 Fuel flow meters

Fuel consumption on the trial was measured using three Siemens FUP1010 ultrasonic flow meters [17] (Figure 17) selected and installed by NETE through a contract with DNPS 3-8. Separate sensors were installed on each of the fuel feeds to the port (S/N U13456) and starboard (S/N U13455) GTs[3]. A third unit (S/N 31677) equipped with two sensors was used to measure the PDE fuel feed and return lines (PDE fuel consumption is the difference between these measurements). DRDC was responsible for logging the output of each meter which was done using a RASP-PI for acquisition and an ORCA for time synchronization. As the gas turbines were in the same compartment, a single ORCA was used to provide time to the two RASP-PI data loggers (one for each GT). NETE did not provide enough of the proprietary serial cables for the flow meters (two cables were provided to use with three meters), so each time there was a switch from using two GTs to the PDE (or vice versa), one of the cables had to be disconnected from a meter, moved, and reconnected to a meter in another compartment. This switch-over process took about 1.5 hours to complete each time.

Figure 18 shows the two RASP-PIs used to log the fuel meters in the GT compartment along with ORCA time server shown in Figure 19. Figures 20 and 21 show the sensors on the fuel feeds to the port and starboard GTs. Figures 22 and 23 show the sensors attached to the PDE fuel feed and return lines.

There were issues with the initial configuration of the meters in the GT compartment. Unlike the meter in the PDE compartment, the GT meters would not enable logging. A NETE technician was on-board the morning of departure (09-Sep-2013) and could not correct the problem. Several emails were sent from the ship to NETE, but without a solution being found. It was not until late in the second day at sea that rigorous trial-and-error attempts by the trial team to re-configure the meters were successful and the logging options were finally enabled.

---

[3]At departure for the trial on 09-Sep-2013, the port GT had 372.42 operating hours and the starboard GT had 4514.43 operating hours.

**Figure 17:** *Siemens FUP1010 flow meter (attached to starboard GT)*
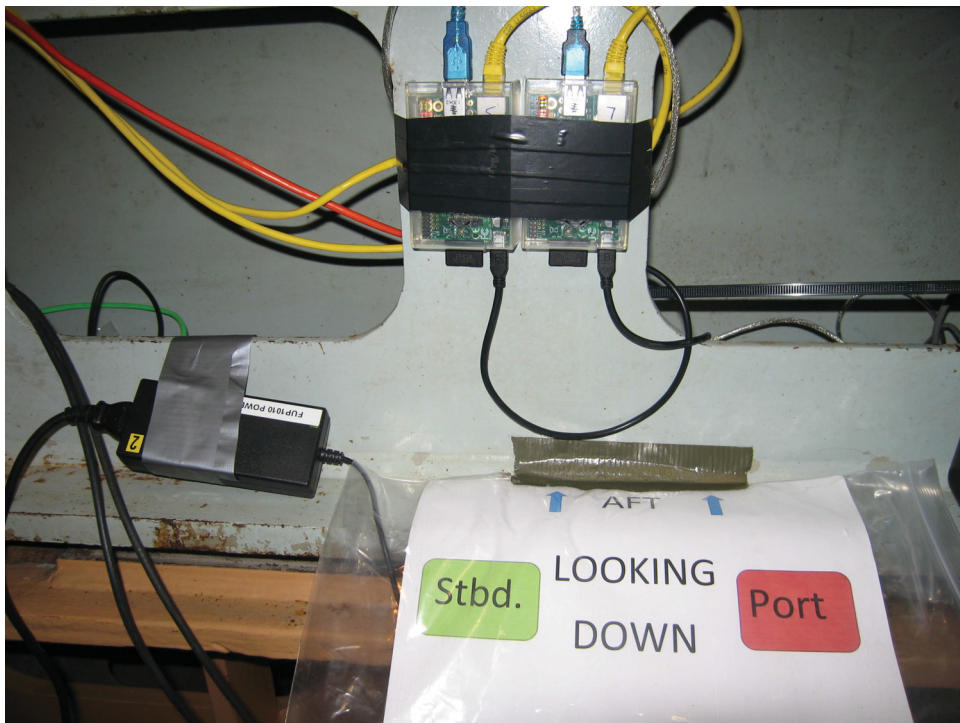


**Figure 18:** *Port & starboard GT Raspberry Pi logging computers*

***Figure 19:*** *ORCA time server in GT compartment*



***Figure 20:*** *Sensor on port GT fuel feed*

**Figure 21:** *Sensor on starboard GT fuel feed*
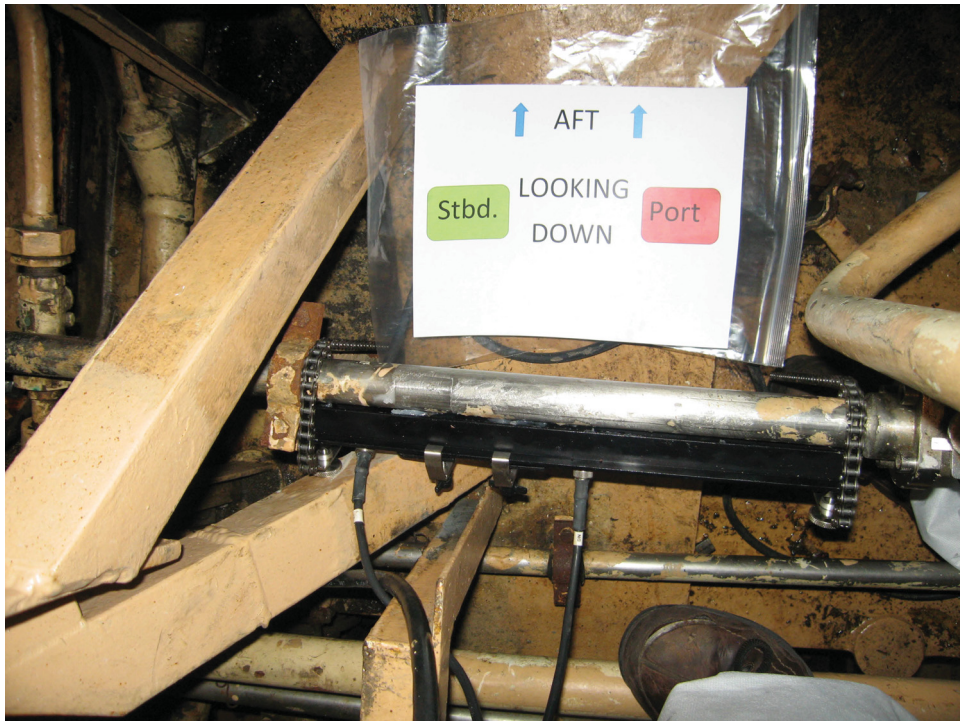


**Figure 22:** *Sensor on PDE fuel feed*

**Figure 23:** *Sensor on PDE fuel return*

## 3.10   Weather logging

A meteorological technician was present on the ship for the trial and kept a log of weather conditions. A copy of this log is provided in Annex D.

## 3.11   Water density

ITTC recommended procedures [7, 8] for ship trials require that the ocean water density be measured. This was performed daily by testing a sample of sea water on-board ship using a sea water hydrometer (Aqua Medic® refractometer). This device uses light refraction to determine salinity against a temperature compensated scale.

**Table 6:** *Water density log*

| Date & Time [UTC] | S.G. [-] | Salinity [PPT] | Comment |
|---|---|---|---|
| 09-Sep-2013 16:10 | 1.030 | 40 | At jetty. Sample may have been contaminated by residue in water collection cup. |
| 10-Sep-2013 23:46 | 1.028 | 37 | In open water. |
| 11-Sep-2013 20:55 | 1.028 | 37 | In open water. |
| 13-Sep-2013 17:11 | 1.025 | 35 | Near shore at Tofino. |
| 13-Sep-2013 21:00 | 1.027 | 36 | In open water. |
| 15-Sep-2013 16:45 | 1.027 | 36 | At jetty. |

## 3.12   Wave buoy & tracker GPS

Activities in this trial required relatively mild sea conditions. It was therefore important to have the ability to accurately measure the sea conditions should they become significant enough to affect the various trial manoeuvres. To accomplish this, a free floating Triaxys$^{TM}$ directional wave buoy was brought on ship for the trial (see Figure 25 and Table 7). A VHF receiver for the buoy was located inside the ship's hanger with an antenna mounted outside on the port deck railing (see Figure 26). The receiver was connected to a laptop computer running Triaxys WaveView software which can be used to view sea state parameters as they are received from the buoy.

At times when the buoy is deployed, it is important to be able to track its position relative to the ship. To accomplish this, a hand-held GPS unit (Garmin 72) was used. Its antenna was mounted on the port flight-deck railing and logged with an additional laptop computer located in the hanger. This laptop could also run charting software (Fugawi) showing the track of the ship. Buoy positions could be manually entered as they are received (see Figure 24).

This buoy measures the full directional sea spectrum (along with its current location) every 30 minutes from which wave height, wave direction, and other parameters can be extracted. Data is stored in the buoy and also transmitted via VHF to the receiver on the ship. It is also possible to communicate with the buoy via satellite (requires an internet connection) should it get out of VHF range.

Fortunately for this trial, the sea state conditions were sufficiently calm that the wave buoy was not deployed.

**Table 7:** *Triaxys directional wave buoy dimensions*

| Item | Description |
|---|---|
| Diameter | 1.10 m (43.5 inches) |
| Outside bumper diameter | 0.91 m (36 inches) |
| Weight | 197 kg (435 lb) |
| Obstruction Light | Amber LED. Programmable ODAS flash sequence with three miles visibility. |
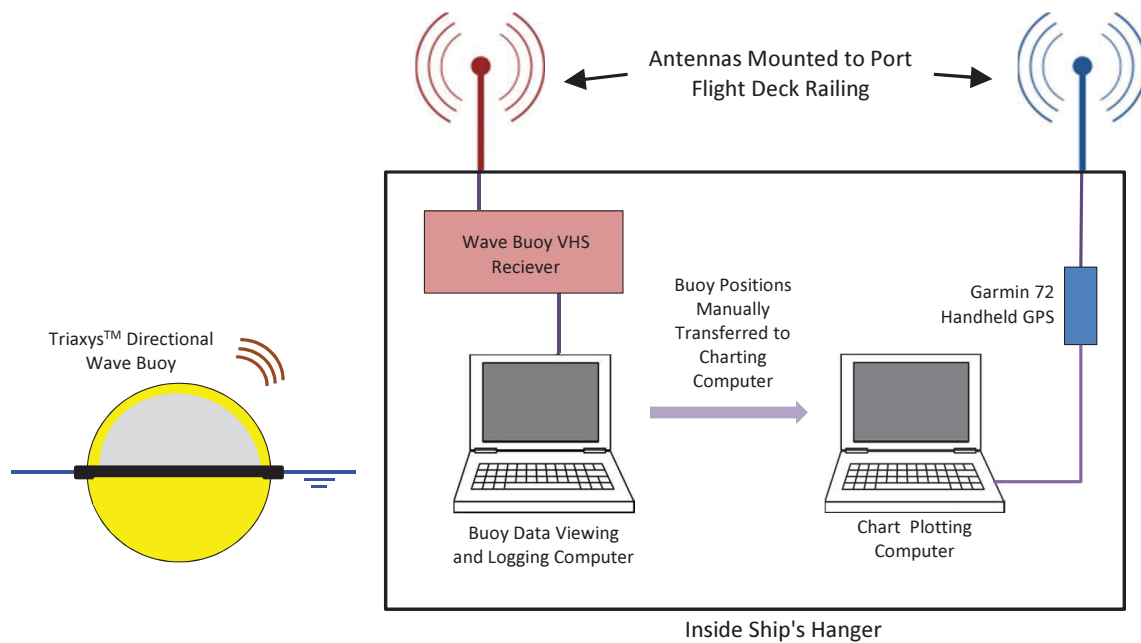


**Figure 24:** *Wave buoy setup*

***Figure 25:*** *Recovery of wave buoy on HMCS KINGSTON*
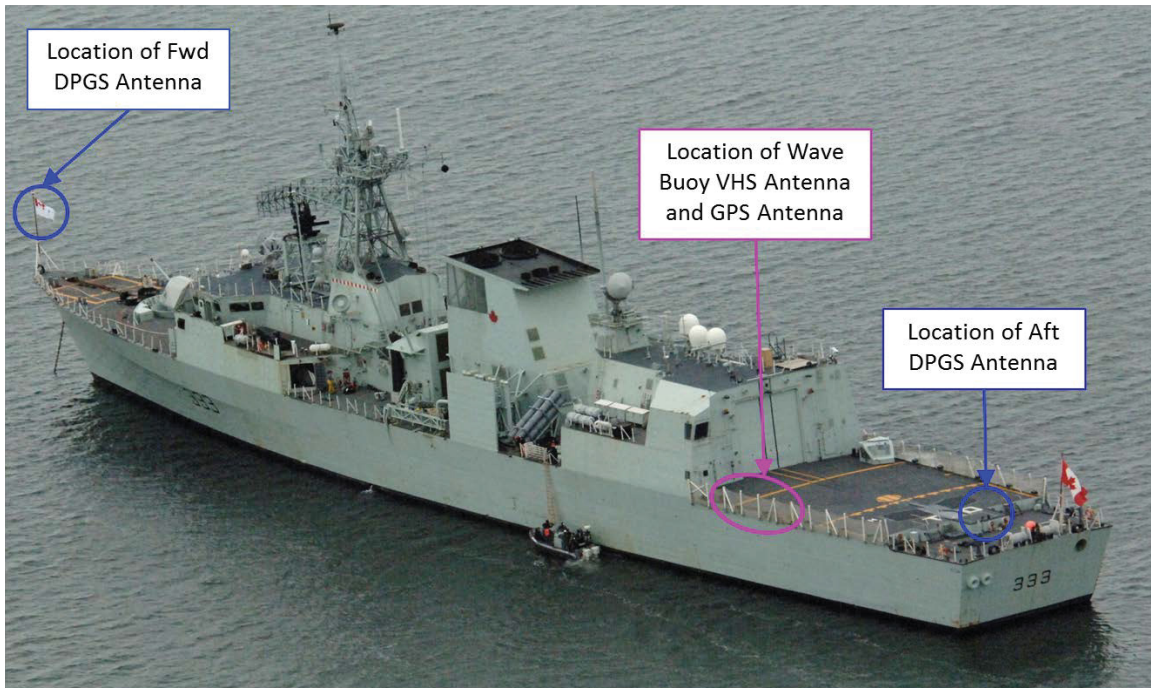

***Figure 26:*** *DRDC antenna locations*

## 3.13 Supplementary anemometers

In support of separate project regarding the Ship-Helicopter Operational Limits (SHOL) envelope for the CH124 Sea King on post-FELEX/HCM ships, supplementary anemometers were used on this trial. The purpose of using these sensors was to: perform shakedown tests at-sea prior to using them on a dedicated SHOL sea trial (planned for December 2013), and to provide full scale wind data to the NRC who were performing wind tunnel model tests of the post-refit ship.

Two RM Young® Model 81000 ultrasonic anemometers [18] were installed on a custom-built aluminium pole designed to fit the mounts for the ship's flagstaff at the bow. They were mounted at 3 and 5 m above the deck. The pole also included a mount for the forward DGPS antenna (see Section 3.7). Cables from these sensors led back to a weatherproof enclosure (Pelican™ case) located outside on the bridge wing (see Figure 28) containing a time server and data acquisition computer. These sensors provided relative wind data in three components ($x$,$y$,$z$) as well as magnitude and direction. They were mounted so that the 'North' indicator symbol on the units faced forward. Data was sampled at ~30 Hz.

During post-processing of the anemometer data, there were some minor issues with the timestamping. Duplicate timestamps would appear for several steps every few minutes. This was identified as a software issue and was corrected for use on future trials.

After the trial, data for periods when the ship was on a straight track at constant speed were identified and various data (supplementary anemometers, ship's anemometers, ship motions, ship heading & speed, etc.) were compiled and transferred to the NRC for analysis. The goal was to evaluate the ship's wind readings in the mast to those of a 'truth' source at the bow, as well as to compare this data to wind tunnel experiments. These results are important for supporting SHOL development for both the Sea King and the Cyclone on the post-refit HALIFAX class.
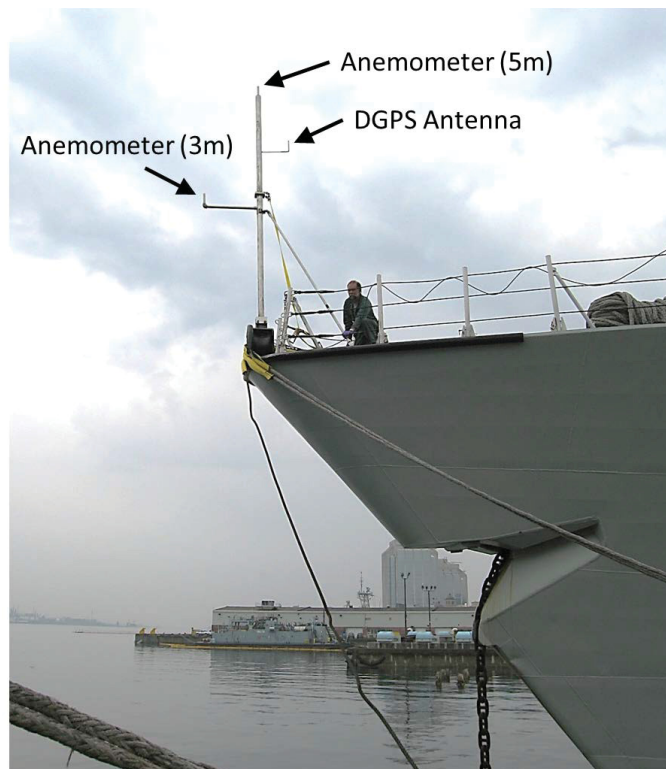
**Figure 27:** *Bow anemometer pole showing mounting locations*
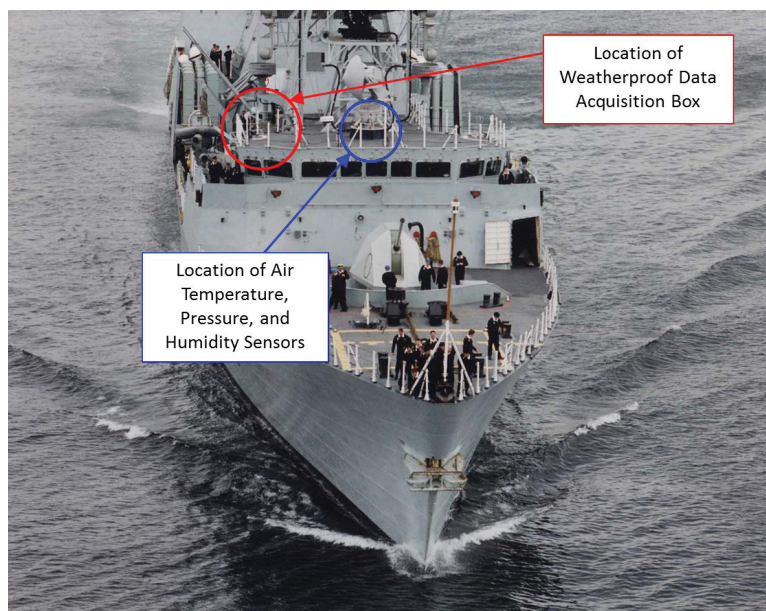


**Figure 28:** *Bridge top equipment*

**Figure 29:** *Pelican case on starboard bridge wing*

## 3.14 Meteorological sensors

Also in support of the CH124/HCM SHOL project mentioned in Section 3.13, meteorological sensors from the NRC were used on this trial to provide at-sea shakedown testing prior to a dedicated SHOL sea trial (planned for December 2013).

The sensors were installed on the starboard side of the bridge top as shown in Figure 30. These included a HC2-S3-L multi-sensor [19] for air temperature and relative humidity (S/N #0061012374), and a 61302V barometric sensor [20] to measure atmospheric pressure (S/N #H4960027). Cables from these sensors fed to the same Pelican case in the starboard bridge wing as used by the supplementary anemometers (Figure 29) for data acquisition.

There were two issues encountered during the trial with these sensors. The first was that data was being recorded at a rate of ~1600 Hz as opposed to the expected rate of 20 Hz. This turned out to be an issue with the newer A/D converters being used. The acquisition software was updated to correct for this for use on future trials. For the current trial, the data was decimated down to 20 Hz when read from the raw data files for analysis.

The second problem was that the barometric pressure sensor was being affected by the navigational S-band radar (the emitter was also on the bridge top, only a few meters from the meteorological sensors). An example of this effect is given in Figure 31 which shows the pressure dropping off and then recovering every few seconds (consistent with the rotation rate of the radar emitter). This effect was confirmed on the trial; the drop-outs stopped when this radar was switched off. In post processing, an attempt was made to automatically remove the drop-outs, but this was not completely effective. As a result, any mean barometric pressure reported by the sensor would be lower than the actual pressure due to the inclusion of the drop-outs or partial drop-outs missed by the filtering process. On future trials, this sensor should be placed in a location that is protected from radar emissions.

**Figure 30:** *NRC meteorological sensors on bridge top*
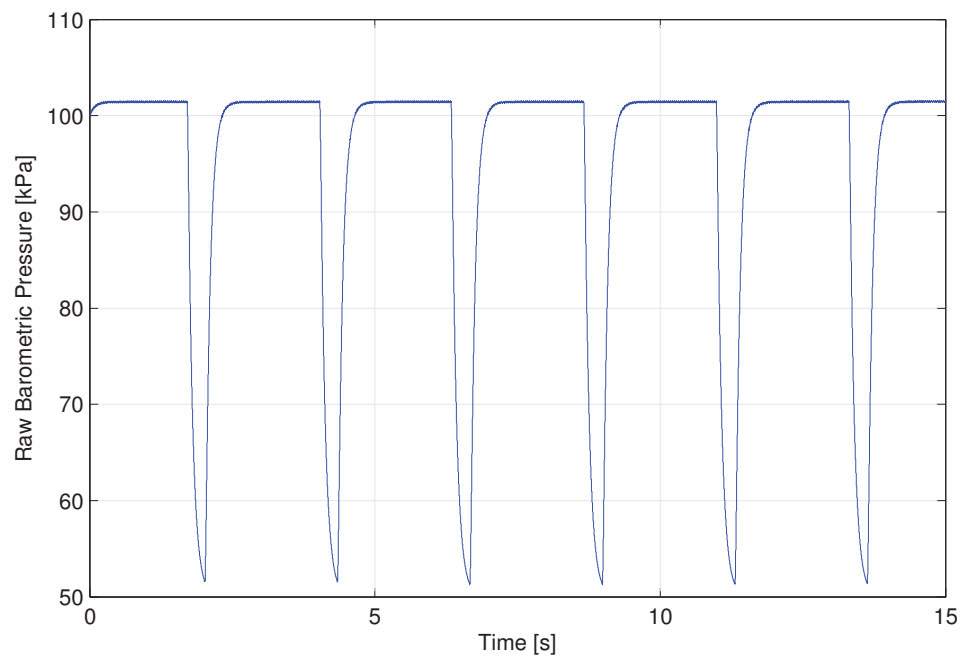


**Figure 31:** *Raw data from NRC barometric sensor*

## 3.15 ISDM Buoy Data

Although a wave buoy was brought on the ship for the trial, the conditions were sufficiently mild that it was not deployed. Instead, wave conditions were obtained after the trial from the moored environmental monitoring buoys in the area (see Table 1 and Figure 1). Data from buoys 46132 and 426206 were obtained from the ISDM (formally known as the Marine Environmental Data Service, MEDS) website operated by Fisheries and Oceans Canada [21] and data from buoy 46087 was obtained from the US National Buoy Data Center (NBDC) website [22].

Wave height and peak period from the buoys are shown in Figure 32 (wave data from buoy 46087 was not available for this time period). At the bottom of the figure are the distances from each buoy to the ship for the trial period. The ship left Esquimalt late in the day (UTC) on September 9 and transited to the operational area near buoy 46132, arriving mid-day on September 10th. Wave heights were reducing to ~1 m, briefly rising to 2 m on September 12th and then reduced again to 1 m for the remainder of the trial. For much of the trial, these conditions were ideal for manoeuvring activities.

Results for wind speed & direction from the buoys and the supplementary anemometers for the trial is shown in Figure 33. Air temperature and humidity results[4] are given in Figure 34.

---

[4]Atmospheric pressure results from the NRC sensor are lower than actual due to interference from the navigational radar (see Section 3.14).
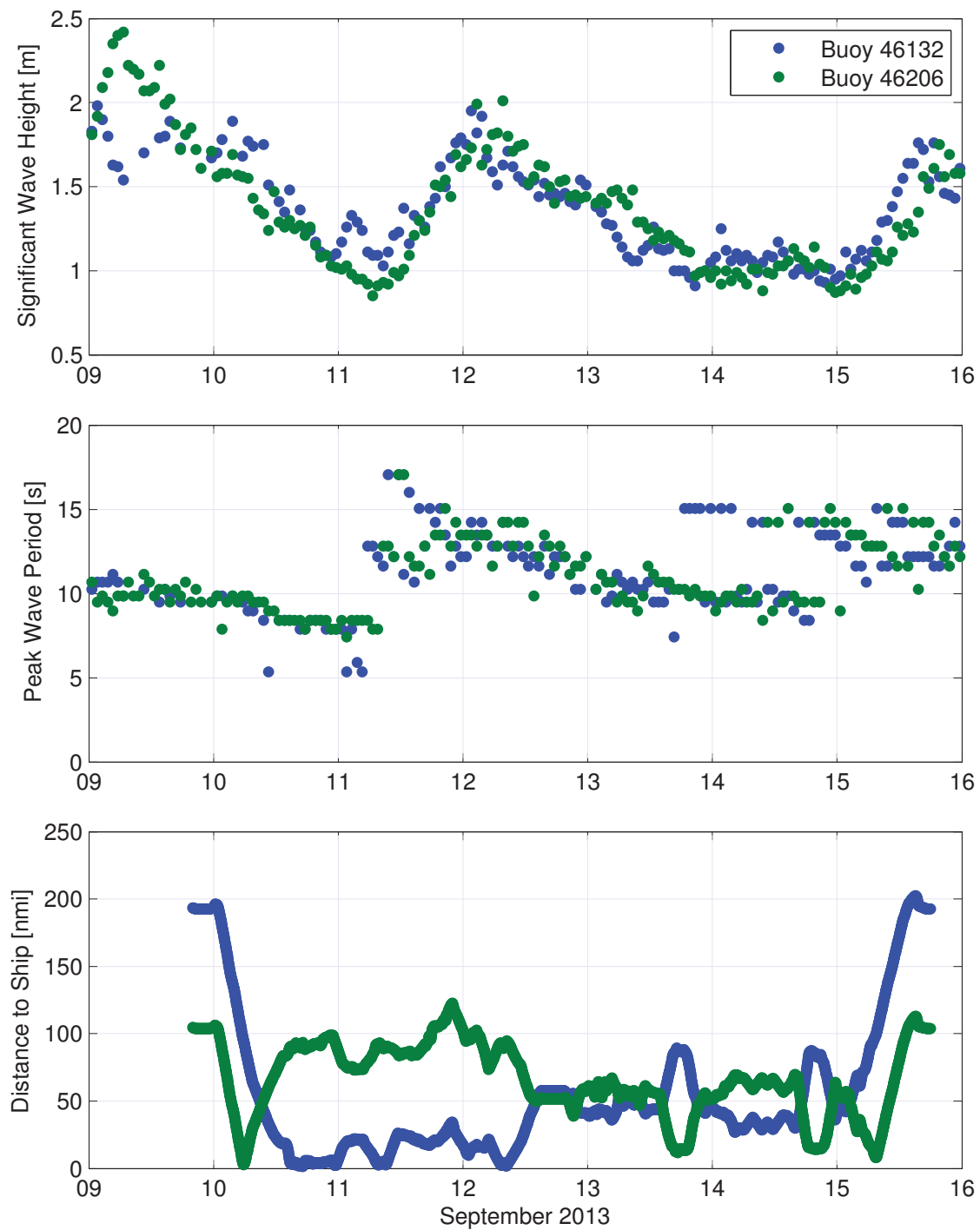
**Figure 32:** *Wave height & period from environmental monitoring buoys*
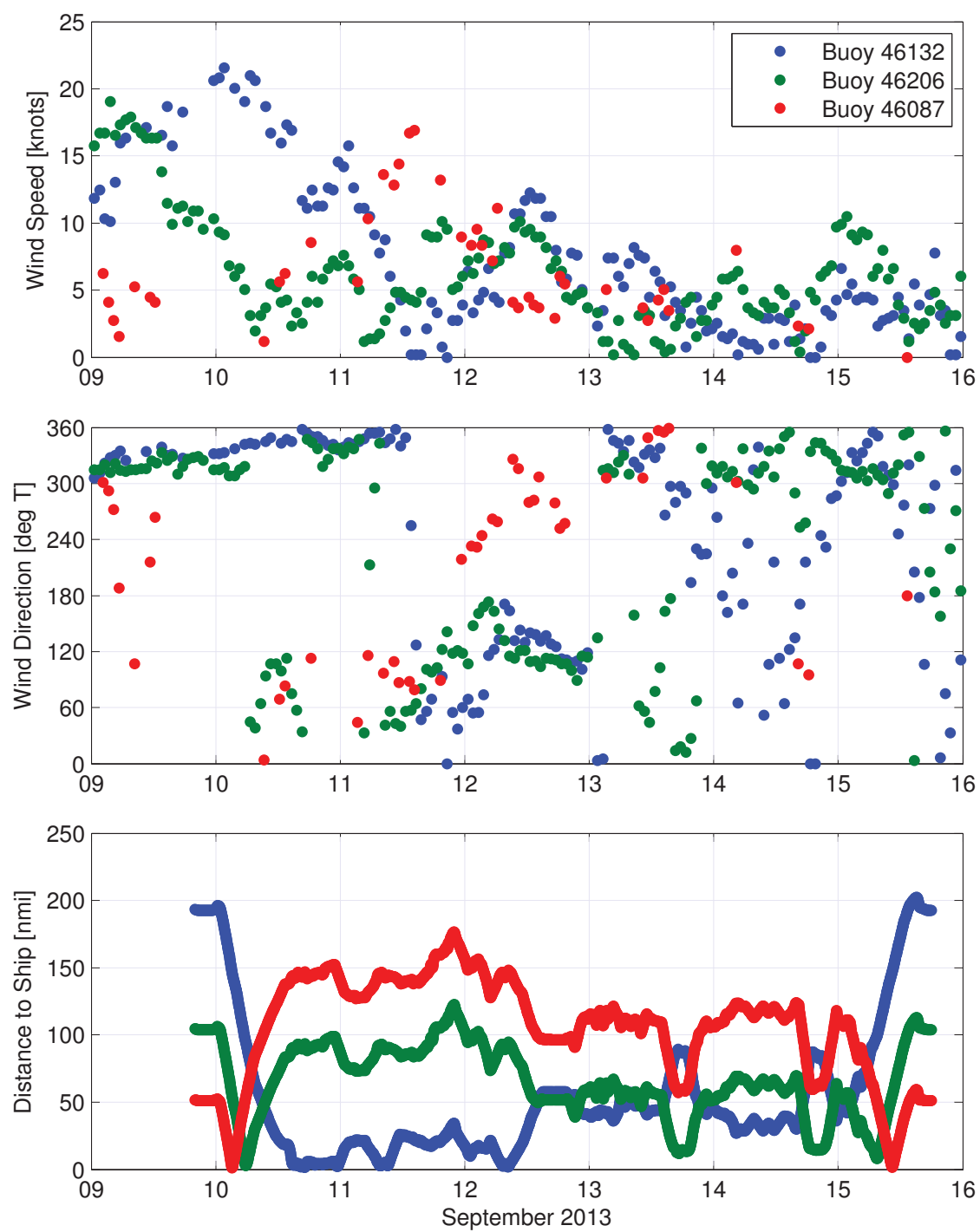
***Figure 33:*** *Wind speed & direction from environmental monitoring buoys*
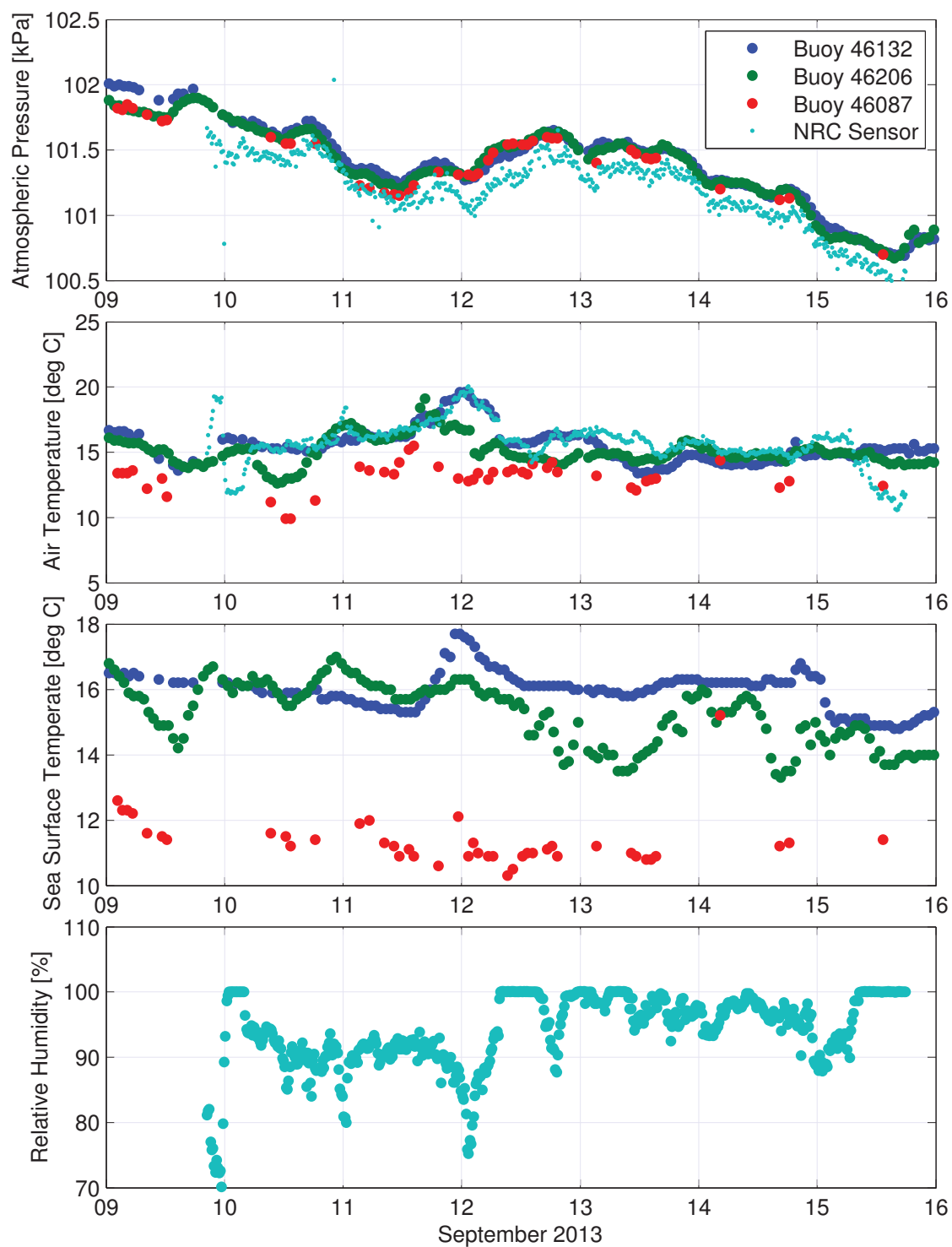
***Figure 34:*** *Air pressure, air temperature, water temperature, and relative humidity*

# 4 Data and processing

This section describes some of the data processing that was applied to the runs prior to being analysed. This processing is in addition to that which may have been applied to data as it was read in from the raw data files and is primarily related to the ship's track during a run. Also note that any circular type data (e.g. compass headings) were processed as described in Annex A.

## 4.1 Latitude/longitude to planar coordinates

In the report for the 1991 trial [23], a Universal Transverse Mercator (UTM) projection was used to transform GPS data into planar coordinates. This method requires an angular correction to be made in order to account for the fact that grid lines in the projected space (referred to as grid north) are not always parallel to true north (which is associated with the direction of meridians or lines of longitude). The angular difference between grid north and true north is referred as the grid declination or Grid Convergence Angle (GCA).

For example, the 2013 trial was conducted off the coast of British Columbia which put it in UTM zone '9U' which spans latitudes 48°N–56°N and longitudes 126°W–132°W. This zone's central meridian is therefore at 129°W. The GCA at this point is 0° and increases to approximately $\pm 2.5°$ at the east and west limits of the zone (GCA can be calculated for any point in a UTM zone using Eqn. (4)). This is significant particularly when comparing ship heading from a gyro-compass or COG from the GPS data and that calculated using projected $(x, y)$ data.

$$GCA = \arctan(\sin(\Phi)\tan(\lambda_c - \lambda)) \tag{4}$$

where,

$$
\begin{aligned}
GCA &= \text{Grid Convergence Angle.} \\
\Phi &= \text{Latitude.} \\
\lambda &= \text{Longitude} \\
\lambda_c &= \text{Central meridian of UTM zone}
\end{aligned}
$$

Although the UTM system does have minimal distortion with respect to linear distances, the GCA correction can complicate analysis (unless the ship happened to be at or near the zone's central meridian). Given that each run in a manoeuvring trial may cover only a few kilometres at most, a simpler approach is to perform an azimuthal projection using a plane tangent to the centre of each run. This will produce planar $(x, y)$ data with minimal distortion as with a UTM projection, but with the added advantage that no GCA correction is required because the central meridian for the projection will always be through the centre of the run track.

The equations used for this projection are given in Eqn. (5)[5] . First, the reference position is calculated using the means of the GPS latitude and longitude data. These are then used to calculate the planar data points. Finally, the planar data are adjusted so that points are made relative to a given reference position (in this case the start of the manoeuvre).

$$
\begin{aligned}
\Phi_0 &= \overline{\Phi} \\
\lambda_0 &= \overline{\lambda} \\
x_p &= R_E \cos(\Phi) \sin(\lambda - \lambda_0) \\
y_p &= R_E \cos(\Phi_0) \sin(\Phi) - R_E \cos(\Phi) \sin(\Phi_0) \cos(\lambda - \lambda_0) \\
x_p &= x_p - x_p \big|_{x_p = Manoeuvre\,Start} \\
y_p &= y_p - y_p \big|_{y_p = Manoeuvre\,Start}
\end{aligned}
\tag{5}
$$

where,

$$
\begin{aligned}
x_p, y_p &= \text{Easting \& northing track coordinates of raw GPS data.} \\
R_E &= \text{Radius of the Earth (6,371 km).} \\
\Phi &= \text{Latitude.} \\
\Phi_0 &= \text{Reference latitude.} \\
\lambda &= \text{Longitude.} \\
\lambda_0 &= \text{Reference longitude.}
\end{aligned}
$$

## 4.2 Referencing position to OSRP

Once the GPS data has been converted into planar coordinates, an additional adjustment is required so that $(x, y)$ data are referenced to the ship centre or Own Ship Reference Point (OSRP) (see Table 3), as opposed to the location of the GPS antenna. This is done by using the body-to-inertial transformation equations based on Euler angles. This transformation works by performing rotations about the three principle axes $(x, y, z)$, Eqn. (6), in successive order. For a body-to-inertial transformation ${}^I_B\mathbf{R}$, rotations are first performed about the *x*-

---

[5]This are based on the Matlab function `latlon2xy.m` from the JLAB+JDATA v1.0 toolbox [24].

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axis, then the *y*-axis, followed by the *z*-axis; as defined by Eqn. (7).

$$\mathbf{R}_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}$$

$$\mathbf{R}_y = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \tag{6}$$

$$\mathbf{R}_z = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where,

$\phi = $ Euler roll angle (rotation about *x*-axis)
$\theta = $ Euler pitch angle (rotation about *y*-axis)
$\psi = $ Euler yaw angle (rotation about *z*-axis)
$\mathbf{R}_x = $ Rotational transformation about *x*-axis
$\mathbf{R}_y = $ Rotational transformation about *y*-axis
$\mathbf{R}_z = $ Rotational transformation about *z*-axis

$$^I_B\mathbf{R} = R_z R_y R_x$$

$$^I_B\mathbf{R} = \begin{bmatrix} \cos\theta\cos\psi & \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \tag{7}$$

where,

$^I_B\mathbf{R} = $ Body-to-Inertial transformation matrix

These equations require data in a right-handed coordinate system. This report uses the forward-port-up convention (see Figure 6). As mentioned in Section 3.6, roll, pitch, & yaw (ship heading) data was used from NDDS instead of the NAV420 sensor system for analysis. This data needs to be adjusted to be consistent with the forward-port-up convention before it can be used in the transformation equations. Raw roll data from the NDDS was reported as positive starboard-up/port-down. Therefore the negative of this data was used as $\phi$ to make it positive starboard down/port up. No change was required for the pitch data.

The raw heading data required two adjustments. The first was that raw heading data (given relative to True North) is positive turning to starboard. Therefore the negative of this data was used to make it positive turning to port. Next, as the convention used when converting GPS coordinates to planar coordinates had the $x$-axis aligned with the easting direction and the $y$-axis aligned with the northing direction, the ship at $0°$ heading would be aligned with the $y$-axis instead of the $x$-axis. A $90°$ adjustment was therefore also needed to get the Euler $\psi$ angles. These adjustments are summarized in Eqn. (8).

$$
\begin{aligned}
\phi &= -(\text{Raw NDDS Roll Data}) \\
\theta &= (\text{Raw NDDS Pitch Data}) \\
\psi &= 90° - (\text{Raw NDDS Heading Data})
\end{aligned}
\tag{8}
$$

The procedure for re-referencing the ship track from the sensor location to the OSRP was as follows:

a. Convert latitude/longitude data to planar easting/northing track data $(x_r, y_r)$ as described in Section 4.1.

b. Resample NDDS roll, pitch, and heading to match sampling times used for the track data.

c. Adjust roll, pitch, and heading data to be consistent with Euler angles $(\phi, \theta, \psi)$ definitions in the forward-port-up coordinate system using Eqn. (8).

d. Calculate the distance from the GPS sensor reference location to the OSRP in body coordinates[6] $(\delta X, \delta Y, \delta Z)$ using Eqn. (9).

e. For every point in the track, use Eqn. (7) to calculate the distance from the GPS sensor reference location to the OSRP in world coordinates $(\delta x, \delta y, \delta z)$ using Eqn. (10).

f. Adjust every point in the raw track $(x_r, y_r)$ by $(\delta x, \delta y)$ to get the OSRP referenced track $(x_s, y_s)$ using Eqn. (11).

$$
\begin{bmatrix} \delta X \\ \delta Y \\ \delta Z \end{bmatrix} =
\begin{bmatrix} X_{OSRP} - X_{sensor} \\ Y_{OSRP} - Y_{sensor} \\ Z_{OSRP} - Z_{sensor} \end{bmatrix}
\tag{9}
$$

---

[6]The $x_B$-axis is parallel to the ship's centreline, equal to 0 at the AP, and increases in the direction of the FP. The $y_B$-axis is in the ship's transverse direction, equal to 0 at the centreplane, and increases towards the port side. The $z_B$-axis is vertical, equal to 0 at the ship's keel, and increases upwards.

$$\begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} = {}_{B}^{I}\mathbf{R} \begin{bmatrix} \delta X \\ \delta Y \\ \delta Z \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} x_s \\ y_s \end{bmatrix} = \begin{bmatrix} x_r + \delta x \\ y_r + \delta y \end{bmatrix} \tag{11}$$

where,

| | |
|---|---|
| $X_{OSRP}, Y_{OSRP}, Z_{OSRP}$ | $=$ Location of the OSRP in ship reference frame (body) coordinates. |
| $X_{sensor}, Y_{sensor}, Z_{sensor}$ | $=$ Location of GPS sensor reference location in ship reference frame (body) coordinates. |
| $\delta X, \delta Y, \delta Z$ | $=$ Difference between OSRP and sensor reference location in ship reference frame (body) coordinates. |
| $\delta x, \delta y$ | $=$ Difference between OSRP and sensor reference location in inertial or world coordinates. |
| $x_r, y_r$ | $=$ Easting & northing track coordinates of the raw GPS data. |
| $x_s, y_s$ | $=$ Easting & northing track coordinates referenced to the OSRP. |

No correction was required for the NDDS GPS data as it is already given with respect to the OSRP. Corrections were made for the bow DGPS unit and the hand-held Garmin GPS located on the flight deck port railing. Problems with the logging of the aft DGPS unit meant that this data was not available for analysis. The top plot in Figure 35 shows an example of raw GPS after conversion to planar coordinates. The relative positions of the three GPS sensors are clearly distinguished. The bottom plot in Figure 35 shows the same data after re-referencing it using the above procedure. All tracks are nominally coincident but for the inherent uncertainty in the measurements. Tracks points from the three sensors were typically within ~1 - 2 m of each other.
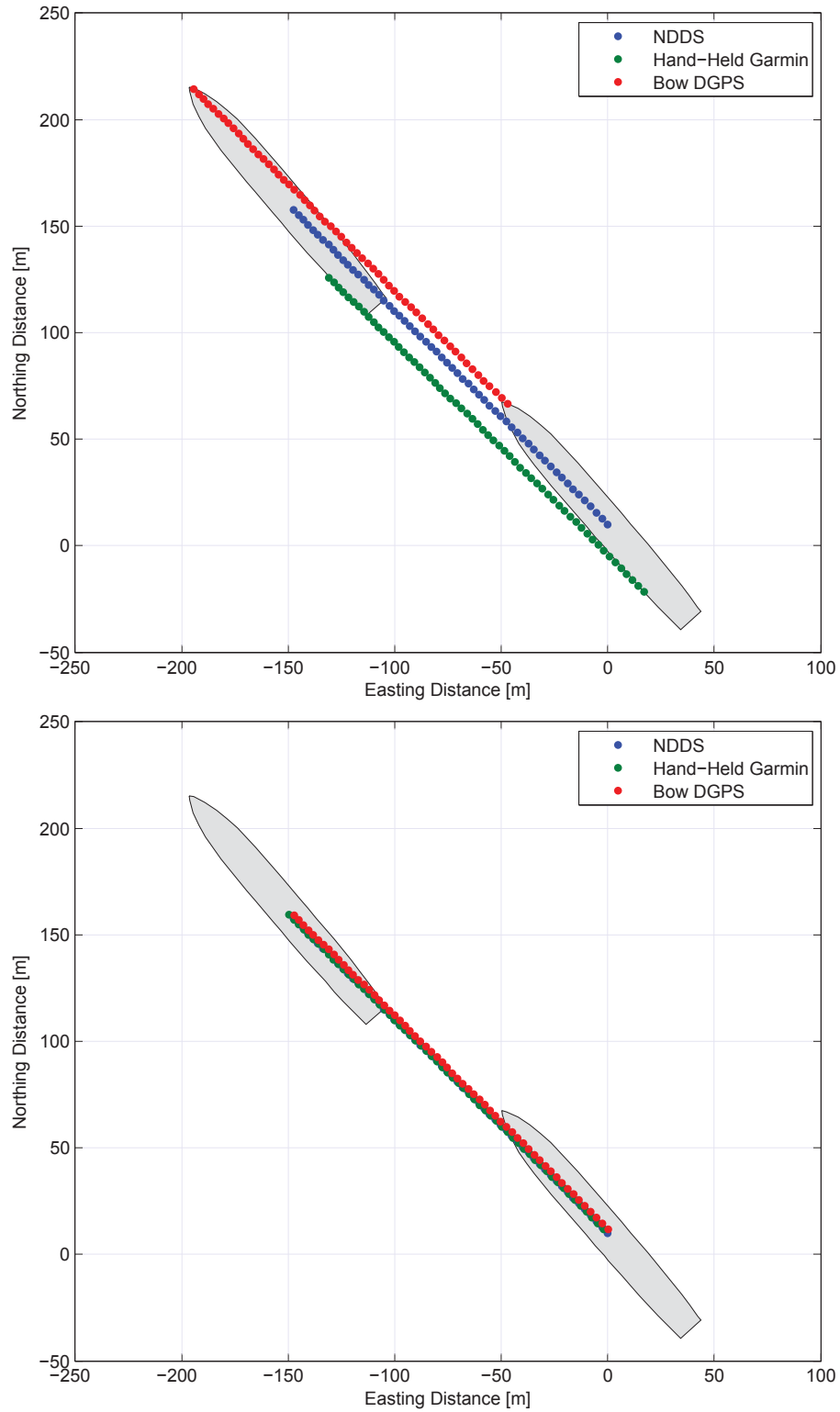
***Figure 35:*** *GPS data in planar coordinates, before (top) and after (bottom) transformation to ship's CG*

## 4.3 Wander correction

The ship's track is often influenced by environmental conditions such as wind, waves, and current. This effect is often called 'drift', but is instead referred to as 'wander' in this report to avoid confusion with 'drift angle' or $\beta$ (the difference between ship heading and course). Although wander can change with time throughout a run, and can also be a function of heading (e.g. effects from wind are larger on the side of ship than the front or back), it was modelled by a velocity vector of constant magnitude ($W$), and direction ($\eta$). For example, an un-powered ship's speed-over-ground and course-over-ground would be the same as the wander velocity and direction. Determination of the values of the $W$ and $\eta$ was performed on a run-by-run basis using a method appropriate for that run. The track would then be corrected with Eqn. (12) to remove the effect of wander prior to further analysis.

Wander was checked periodically throughout the trial by performed a 'dead drift' run where the ship would sit un-powered for several minutes. The resulting track would reveal the current wander. The results of the dead drift runs are given in Annex E.

$$x_c = x_s - (t - t_{start})W\cos(90° - \eta)$$
$$y_c = y_s - (t - t_{start})W\sin(90° - \eta)$$

(12)

where,

$t$ = Time.

$t_{start}$ = Time at the beginning of the run.

$x_s, y_s$ = Easting & northing track coordinates referenced to the OSRP.

$x_c, y_c$ = Easting & northing coordinates of wander-corrected track.

$W$ = Magnitude of wander velocity.

$\eta$ = Direction of wander velocity (relative to true North).

## 4.4 Track related data

After the track has been corrected for wander, quantities such as speed and course generated by the GPS must be recalculated to properly reflect the properties of the new track. Many of these quantities require derivatives found by a basic difference approach given by Eqn. (13). Speed-over-ground for the corrected track was calculated with Eqn. (14) followed by course-over-ground given by Eqn. (15). Calculation of corrected ship heading, $\psi_c$, assumes that the drift angle, $\beta$, is the same for the raw and corrected tracks. First $\beta$ is determined using Eqn. (16) then applied in Eqn. (17) to get $\psi_c$.

Data series produced using differencing will be of length $(n-1)$ given initial data of length $n$. In order to make the new data consistent in length with other data sets, either the last

point in the calculated data was linearly extrapolated, or a slightly larger initial data set was used so that the calculated data could be truncated to the correct length.

Before being used in further analysis, data from the corrected speed, heading, and course were passed through a smoothing filter which applies a best-fit polynomial spline. An advantage of this filter is that it also returns the first derivative of the smoothed output data, thereby giving rates of change for speed, heading, and course (Eqns. (18) to (20)).

$$\delta\,(\text{var})_i = (\text{var})_{i+1} - (\text{var})_i \tag{13}$$

$$V_{ci} = \frac{\sqrt{\delta x_{ci}^2 + \delta y_{ci}'^2}}{\delta t_i} \tag{14}$$

$$\chi_{ci} = 90° - \arctan\left(\frac{\delta y_i}{\delta x_i}\right) \tag{15}$$

$$\beta = \psi - \chi \tag{16}$$

$$\psi_c = \chi_c + \beta \tag{17}$$

$$\left[V_c, \dot{V_c}\right] = f_{\text{smooth}}\left(t, V_c\right) \tag{18}$$

$$\left[\psi_c, \dot{\psi_c}\right] = f_{\text{smooth}}\left(t, \psi_c\right) \tag{19}$$

$$\left[\chi_c, \dot{\chi_c}\right] = f_{\text{smooth}}\left(t, \chi_c\right) \tag{20}$$

where,

$t$ = Time.

$x_c, y_c$ = Easting & northing coordinates of wander-corrected track.

$V_c$ = Ship speed-over-ground on wander-corrected track.

$\dot{V_c}$ = Ship acceleration on wander-corrected track.

$\beta$ = Drift angle, the difference between ship heading and course.

$\psi$ = Ship heading on raw track (from gyro-compass).

$\psi_c$ = Ship heading on wander-corrected track.

$\dot{\psi_c}$ = Rate of change of ship heading on wander-corrected track.

$\chi$ = Ship course-over-ground on raw track (from GPS).

$\chi_c$ = Ship course-over-ground on wander-corrected track.

$\dot{\chi_c}$ = Rate of change of ship course-over-ground on wander-corrected track.

## 4.5 Normalized track

Once the track for a given run has been corrected, it is then re-oriented using Eqn. (21) to a normalized position such that: the course at the start of the manoeuvre is $0°$, the position at the start of the manoeuvre is (0,0), and the time at the start of the manoeuvre is 0 seconds. Other track related data for the normalized track are determined using Eqn. (22). Metrics for the various manoeuvres were calculated using data from the normalized track.

$$
\begin{aligned}
t' &= t - t_0 \\
\chi_0 &= \chi_c|_{t_0} \\
x' &= (x_c - x_c|_{t_0})\sin(\chi_0) + (y_c - y_c|_{t_0})\cos(\chi_0) \\
y' &= (x_c - x_c|_{t_0})\cos(\chi_0) - (y_c - y_c|_{t_0})\sin(\chi_0)
\end{aligned}
\tag{21}
$$

$$
\begin{aligned}
V' &= V_c \\
\dot{V}' &= \dot{V}_c \\
\beta' &= \beta \\
\chi' &= \chi_c - \chi_0 \\
\dot{\chi}' &= \dot{\chi}_c \\
\psi' &= \psi_c - \chi_0 \\
\dot{\psi}' &= \dot{\psi}_c
\end{aligned}
\tag{22}
$$

where,

$t_0$ = Time at the beginning of the manoeuvre.
$t'$ = Time referenced to the start of the manoeuvre.
$\chi_0$ = Ship course $\chi_c$ at $t_0$.
$x', y'$= Advance and transfer of normalized track.
$V'$ = Ship speed on normalized track.
$\dot{V}'$ = Ship acceleration on normalized track.
$\beta'$ = Drift angle for ship on normalized track.
$\psi'$ = Ship heading on normalized track.
$\dot{\psi}'$ = Rate of change of ship heading on normalized track.
$\chi'$ = Ship course on normalized track.
$\dot{\chi}'$ = Rate of change of ship course on normalized track.

# 5   Data and processing: 1991 re-analysis

Data from the 1991 trial (referred to as 'HAL1991') was made available to DRDC from the NRC who originally conducted the trial. Raw data was taken out of archives and combined into an individual ASCII .csv file for each run. The data was resampled at 5 Hz to give a common time reference. A list of the data types in these files is given in Table 8. The 1991 report [23] noted issues with the quality of the propulsion data; some of it may not be usable. One important missing data set in these files was ship heading. This meant that drift angle, and parameters dependent on drift angle, could not be determined.

Much of the data processing for HAL1991 runs was conducted using the same methods as given by Section 4, with some exceptions described in Sections 5.1 and 5.2.

*Table 8:* HAL1991: Available Data

| Data | Units |
|---|---|
| Time | [s] |
| Rudder Angle | [deg] |
| Roll Angle | [deg] |
| Pitch Angle | [deg] |
| Port Shaft Torque | [kN-m] |
| Port Shaft Thrust | [kN] |
| Stbd. Shaft Torque | [kN-m] |
| Stbd. Shaft Thrust | [kN] |
| Port Shaft | [RPM] |
| Stbd. Shaft | [RPM] |
| Port Propeller Pitch Angle | [deg] |
| Stbd. Propeller Pitch Angle | [deg] |
| GPS Time* | [sec] |
| Latitude | [rad] |
| Longitude | [rad] |
| Altitude | [m] |
| Latitude Velocity | [rad/s] |
| Longitude Velocity | [rad/s] |

* Seconds since 1980-01-06 (the GPS epoch).

## 5.1 Latitude/longitude to planar coordinates: 1991 re-analysis

The original 1991 analysis [23] used a UTM projection with GCA corrections to convert GPS data to planar coordinates. However, for re-analysis, the method described in Section 4.1 was applied. The GPS data at the time was not as accurate as it is currently and therefore produced tracks with a much higher degree of variability from point to point. To improve further analysis with these tracks, they were first passed through a smoothing filter to reduce this variability. An example of HAL1991 track data before and after smoothing is given in Figure 36. Smoothing was not used for the raw CAL2013 track data.
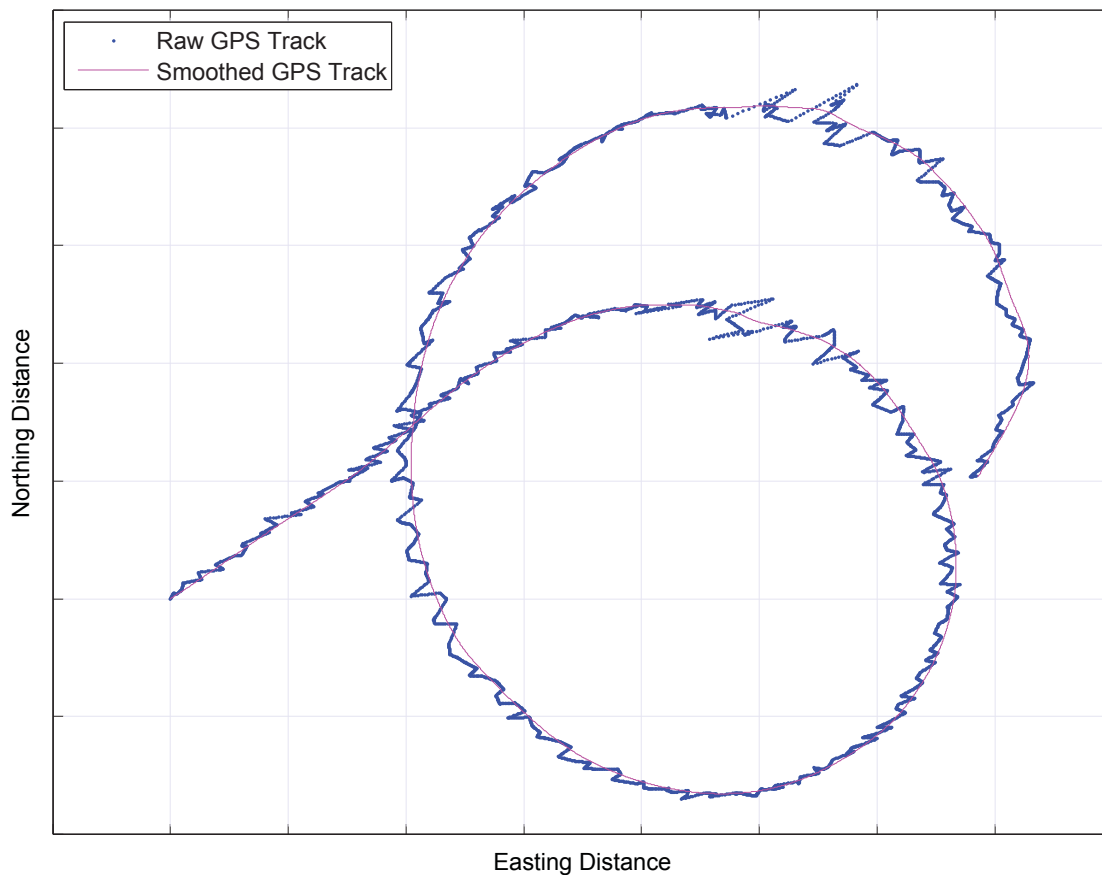


***Figure 36:*** *Example 1991 GPS track before and after smoothing*

## 5.2 Referencing position to ship CG: 1991 re-analysis

The HAL1991 GPS data also had to be re-referenced to the ship's centre of gravity. On that trial they had only a single GPS unit whose antenna was fitted on a 2 m post located on the starboard side of the quarterdeck at approximately frame 61 (0.1 m forward of the AP, 6.29 m starboard of the centreline, and 12.45 m above the keel). The reference CG used for HAL1991 was 59.43 m forward of the AP, on the ship centreline, and 6.32 m above the keel. In the original 1991 analysis, the track data was re-referenced using a similar method as described in Section 4.2, but neglecting the influence of pitch. For the current re-analysis, the approach described in Section 4.2 was applied, with the exception that as ship heading was not available, ship COG was used instead.

As COG was not provided in the HAL1991 data set, it was first calculated from the raw track data $(x_p, y_p)$ using the same approach as used in Section 4.4.

The use of COG in place of heading for re-referencing the GPS track introduces an error in the resulting track that increases with the magnitude of the drift angle. This is illustrated by Figure 37 which shows two resulting ship and CG positions generated from the same raw GPS point using COG with and without accounting for drift. For a drift angle of 10°, the absolute error in the resulting CG position was ~10.4 m. For turning circles, using COG instead of heading will result in an increase in the apparent turning diameter by approximately twice the track error given by Eqn. (23).

$$D_{\text{error}} \approx \delta X \sin(\beta) \tag{23}$$

where,

$D_{\text{error}} =$ Approximate magnitude of track error.

$\delta X =$ Longitudinal distance from the GPS reference location to the OSRP in ship reference frame coordinates (~60 m).

$\beta =$ Drift angle, the difference between ship heading and course.
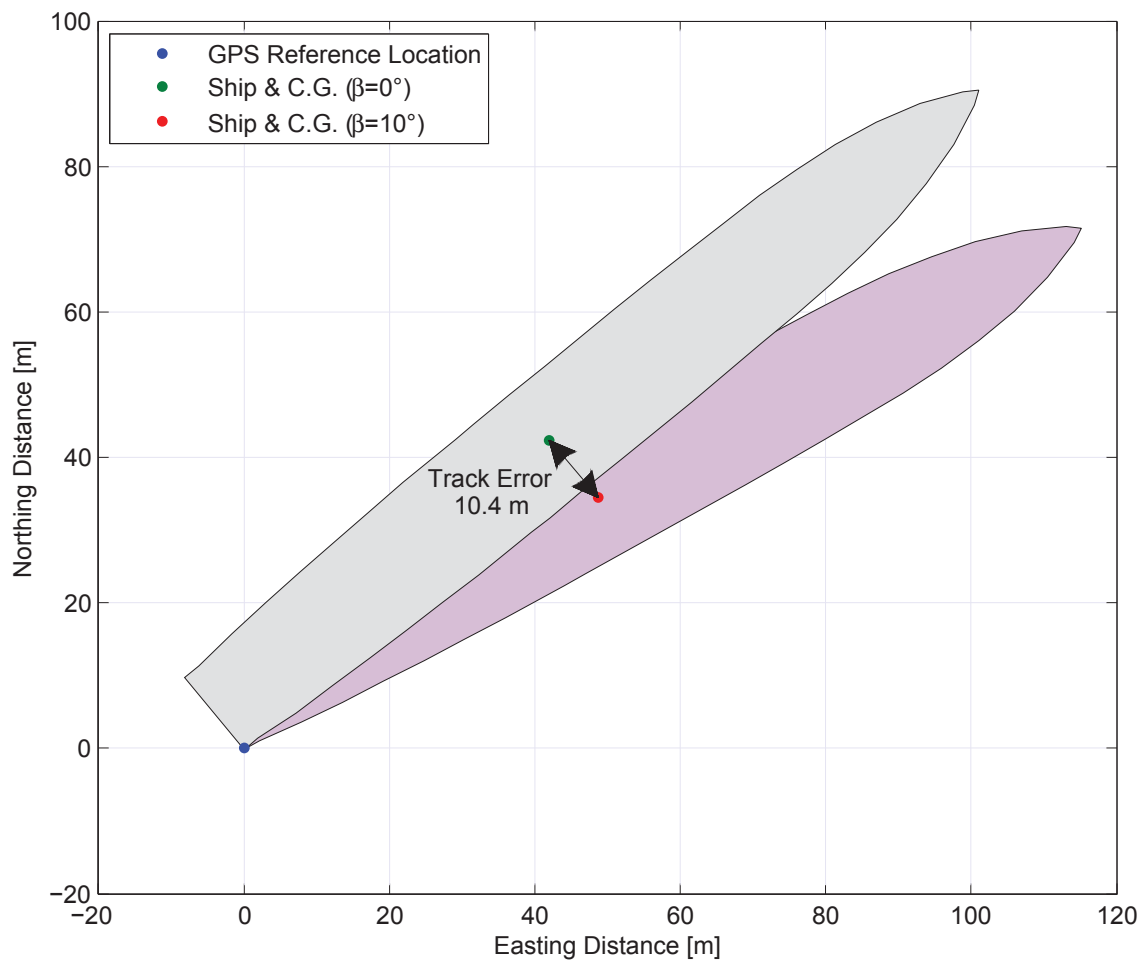
***Figure 37:*** *Effect of drift angle on track*

# 6 Conclusions

The HALIFAX Class Frigates are undergoing a mid-life refit managed under the HCM/FELEX project. A number of the ECs planned for the refits will affect the displacement of the vessels and see the addition or removal of some hull appendages. Such changes can have an impact on ship manoeuvring characteristics.

A sea trial [3] was conducted on HMCS CALGARY (which has completed its refit) in September 2013 with the objective of collecting data to be used to update the manoeuvring characteristics for the class. A series of runs were completed as listed in Table 9. This report describes the instrumentation setup along with basic data processing methods.

Overall, equipment worked well. There were, however, a few issues encountered from which lessons could be learned to improve future similar trials:

- When using the NI A/D converters with an internal clock, be sure that the acquisition computer time is properly synchronized to UTC before powering the converter up, or correct the acquisition software to ignore the converter's time and force it to use the acquisition computer time (assuming it is has a reliable time signal).

- The NI A/D converters used to acquire the meteorological data were not being properly controlled w.r.t. sampling rates. This may require changes to the acquisition software.

- The ship IPMS data should be acquired by a system that can be synchronized to UTC.

- The barometric sensor used on the trial was affected by the navigational radar. It should be moved to a protected location.

- The DGPS data acquisition software should be modified to better handle unexpected power interruptions.

- Slow speed / small rudder angle turning circles were time consuming and ultimately of limited value. These could be reduced, omitted, or replaced by alternate manoeuvres.

- Measured miles or legs of a baseline run should be at least 10 minutes in duration.

- Astern slow speed controllability runs did not produce much useful information and could be omitted.

- During a pullout run, the rudder should be held at midships for a longer duration in order to better determine resulting steady state yaw rate (at least 5 minutes).

- Redundant measurements of rudder angle should always be made during manoeuvring trails. Alternate means of rudder angle measurement should be explored.

- Full speed runs may be better performed using unitized gearbox mode instead of cross-connected.

Much of the analysis and results from the runs has been classified CONFIDENTIAL and has been issued in separate reports. Table 9 gives a list of how many of each run type were performed along with a citation which contains the details and results on the analysis.

Overall the data collected on the trial was high quality owing to modern data acquisition systems and cooperative weather conditions. The data was successfully used to determine the required performance characteristics of the post-refit HALIFAX class.

**Table 9:** *Runs summary*

| Run Type | Details |
|---|---|
| Turning Circle | 62 turning circle runs were completed: 50 runs with both shafts, 8 runs with a single powered shaft, and 4 astern runs. |
| Measured Mile | 16 ahead measured miles and 6 astern measured miles were performed using both GTs with XCON gearing. |
| Baseline | 5 baseline runs were completed; 2 were performed using 2GT (only one was usable for analysis), one run using 1GT, and two runs using the PDE (only one had fuel flow measurements). |
| Acceleration | 15 acceleration runs were performed; 7 using 2GT, 6 using 1GT, and 2 using the PDE. 12 of the runs accelerated from a full stop (9 to ahead speed, 3 to astern speed) and 3 runs accelerated from a steady forward speed. |
| Coasting | 13 coasting runs were conducted at various initial speeds; 7 runs were performed by tripping the engines, and 6 runs used a zero-speed order. |
| Speed Reversal/ Crash Stop | 9 speed reversal runs were performed; 5 using 2GT, 3 using 1GT, and 1 using the PDE. 7 of the runs reversed from an ahead speed to an astern speed, and 2 runs reversed from an astern speed to an ahead speed. Separate runs for crash stop runs were not performed; data was instead taken from the appropriate speed reversal run. |
| Zigzag | 42 zigzag runs were performed ranging in speeds from 10‑30 knots and included runs starting with both port and starboard turns using helm/rudder angles of 10°, 15°, 20°, and 30°. |
| Pullout | 15 pullout runs were performed at various speeds from 10‑30 knots and included runs starting with both port and starboard turns using rudder angles of 5° to maximum. |
| Direct Spiral | 3 direct spiral manoeuvres were performed on the trial, one each for the ship speeds 10, 20 and 30 knots. |
| Slow Speed Controllability | 11 slow speed controllability runs were conducted for ahead speeds descreasing from 6 to 1 knots and astern speeds descreasing from 6 to 2 knots. |

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# Acronyms

| | |
|---|---|
| **A/D** | Analog-to-Digital |
| **Aft SIS** | Aft Sonar Integrated Space |
| **a.k.a.** | also known as |
| **AP** | Aft Perpendicular |
| **ASCII** | American Standard Code for Information Interchange |
| **ASUW** | Anti-Surface Warfare |
| **ASW** | Anti-Submarine Warfare |
| **BML** | Vertical Distance from the C.B. to the Longitudinal Metacentre |
| **BMT** | Vertical Distance from the C.B. to the Transverse Metacentre |
| **C.B.** | Centre of Buoyancy |
| **CG** | Centre of Gravity |
| **CODOG** | Combined Diesel or Gas |
| **COG** | Course Over Ground |
| **csv** | Comma Separated Values |
| **DGPS** | Differential GPS |
| **DNPS** | Directorate of Naval Platform Systems |
| **DOP** | Dilution of Precision |
| **DRDC** | Defence Research and Development Canada |
| **EC** | Engineering Change |
| **ECPINS** | Electronic Chart Precise Integrated Navigation System |
| **ESP** | Emergency Steering Position |
| **FELEX** | Frigate Life Extension |
| **FP** | Forward Perpendicular |
| **GCA** | Grid Convergence Angle |
| **GHS** | General Hydrostatics |
| **GLM** | GHS Load Monitor |
| **GML** | Vertical Distance from the CG to the Longitudinal Metacentre |
| **GMT** | Vertical Distance from the CG to the Transverse Metacentre |
| **GNSS** | Global Navigation Satellite System |
| **GPS** | Global Positioning System |
| **GT** | gas turbine |
| **GUI** | Graphical User Interface |
| **HCI** | Halifax Class IPMS |
| **HCM** | Halifax Class Modernization |
| **HMCS** | Her Majesty's Canadian Ship |
| **IPMS** | Integrated Platform Management System |
| **ISDM** | Integrated Science Data Management |
| **ITTC** | International Towing Tank Conference |
| **LCB** | Longitudinal Centre of Buoyancy |
| **LCF** | Longitudinal Centre of Flotation |

| | |
|---|---|
| **LCG** | Longitudinal Centre of Gravity |
| **LED** | Light-Emitting Diode |
| **MEDS** | Marine Environmental Data Service |
| **MetOc** | Meteorology and Oceanography |
| **MSL** | Mean Sea Level |
| **NBDC** | National Buoy Data Center |
| **NDDS** | Navigational Data Distribution System |
| **NETE** | Naval Engineering Test Establishment |
| **NI** | National Instruments |
| **NI-DAQ** | National Instruments Data Acquisition |
| **NMEA** | National Marine Electronics Association |
| **NPOL** | Naval Platform Operational Limits |
| **NRC** | National Research Council |
| **NTP** | Network Time Protocol |
| **ODAS** | Ocean Data Acquisition System |
| **OSRP** | Own Ship Reference Point |
| **PDE** | Propulsion Diesel Engine |
| **PDT** | Pacific Daylight Time |
| **PLA** | Power Level Angle |
| **PO** | Petty Officer |
| **PPT** | parts per thousand |
| **PSP** | Primary Steering Position |
| **RAI** | Rudder Angle Indicator |
| **RASP-PI** | Raspberry Pi Computer |
| **RCN** | Royal Canadian Navy |
| **RPM** | Rotations Per Minute |
| **S.G.** | specific gravity |
| **SHOL** | Ship-Helicopter Operational Limits |
| **SJSL** | Saint John Shipbuilding Limited |
| **SOG** | Speed Over Ground |
| **SS** | Sea State |
| **SSS** | Synchronous Self-Shifting |
| **STW** | Speed Through Water |
| **TCB** | Transverse Centre of Buoyancy |
| **TCF** | Transverse Centre of Flotation |
| **TCG** | Transverse Centre of Gravity |
| **US** | United States |
| **UTC** | Coordinated Universal Time |
| **UTM** | Universal Transverse Mercator |
| **VCB** | Vertical Centre of Buoyancy |
| **VCG** | Vertical Centre of Gravity |
| **VHF** | Very high frequency |

| | |
|---|---|
| **WP** | Warship Performance |
| **WPA** | Water-Plane Area |
| **w.r.t.** | with respect to |
| **XCON** | cross-connected |

# Annex A: Circular data processing

Frequently, processing and analysis requires operations such filtering, resampling, determination of statistical properties (mean, standard deviation, etc.), interpolation, etc. that most be modified to account for circular data. Circular data, such as wind direction or ship heading, wraps around a discontinuity (either through $360°$ to $0°$ or $-180°$ to $180°$) that causes problems with conventional analysis methods which assume continuous data. For example, the correct average of the angles $355°$ and $3°$ is $359°$. An average using a method that does not account for wrapping would instead give the incorrect angle of $179°$.

Calculation of statistical properties for circular data for this trial was done with a custom Matlab toolbox [25] developed based on methods described in [26].

For filtering, resampling, and interpolation operations, circular data was first decomposed into two components based on its sine and cosine function values. The given processing operation would then be performed separately on each component. The resulting processed components would then be recombined using an inverse tangent function[7] (see Eqn. (A.1)).

$$
\begin{aligned}
s &= \sin(\varepsilon) \\
c &= \cos(\varepsilon) \\
s' &= F(s, \dots) \\
c' &= F(c, \dots) \\
\varepsilon' &= \arctan\left(\frac{s'}{c'}\right)
\end{aligned}
\tag{A.1}
$$

where,

$\varepsilon =$ Arbitrary circular data.
$F =$ Arbitrary processing function (e.g. filtering).
$\dots =$ Additional function inputs.
$\varepsilon' =$ Processed circular data.

Circular data may be wrapped (may contain discontinuities) or unwrapped (discontinuities removed) without affecting the meaning of the angular values. Figure A.1 shows an example of wind direction data in both wrapped and unwrapped forms. In this report and related reports, circular data is generally shown in the unwrapped form.

---

[7]Note that references to the inverse tangent function with two inputs, such as $\arctan\left(\frac{y}{x}\right)$, imply the use of the Matlab function `atan2(y,x)` which returns an angle in the correct quadrant given the signs of the two input values. This differs from the `atan(x)` function with one input which only returns angles in range of $-90°$ to $90°$.
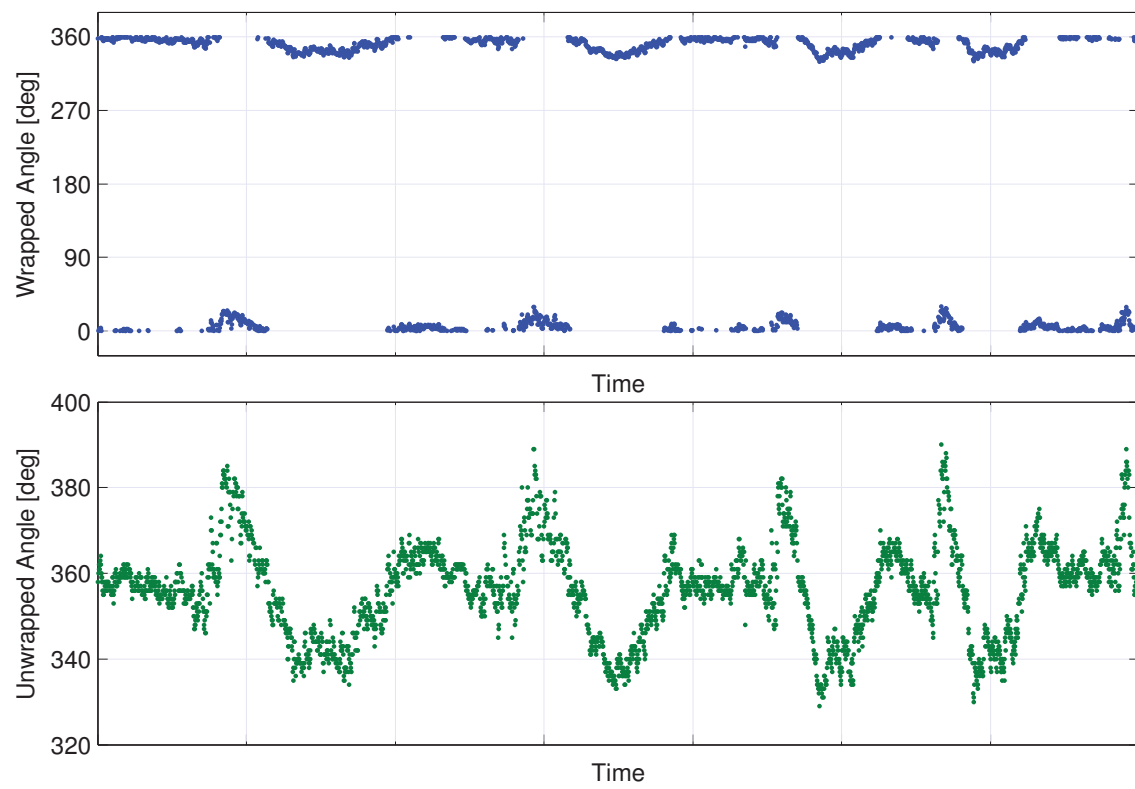
**Figure A.1:** *Example of wrapped and unwrapped circular data*

# Annex B: Rudder calibration

Rudder angle was measured using linear cable transducers attached to the rudder post (see Section 3.8). Two systems were used such that when the rudder was turning in a given direction, one transducer would have its cable retracting while the other had its cable extending. Transducer output was converted from an analogue voltage to a digital signal and acquired by a computer. A calibration was required to convert the measured voltages to rudder angles. This calibration was performed at the beginning of the trial while alongside at Esquimalt harbour. The rudder was systematically moved from full port to full starboard twice (in 5° increments). Measurements were logged for: the angle reported by the Primary Steering Position (PSP) on the bridge, the angle reported by the Emergency Steering Position (ESP) in the rudder compartment, the angle indicated by a graduated brass ring on the rudder post (Figure B.1), the voltage from the port sensor NI-DAQ, the voltage from the starboard sensor NI-DAQ, the voltage from a hand-held meter for the port sensor, and the voltage from a hand-held meter for the starboard sensor. The time history of the NI-DAQ voltages is shown in Figure B.2 and the logged results are given in Table B.1 (negative angles are to port). The noisy signal shown for the port sensor in Figure B.2 was caused by a faulty connector that was repaired before leaving harbour. NI-DAQ Calibrations were based on the brass ring readings and shown in Figure B.3.
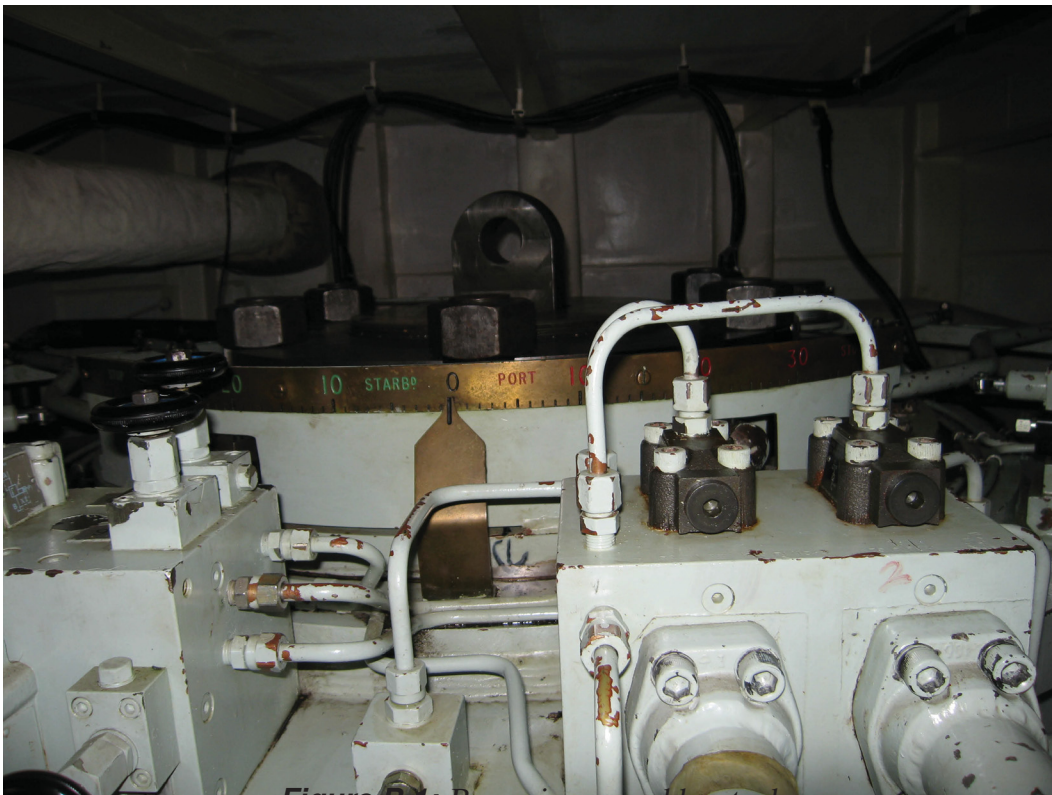


**Figure B.1:** *Brass ring on rudder stock*

***Figure B.2:*** *Rudder calibration time history*
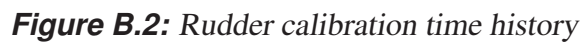
**Table B.1:** *Rudder calibration data*

| Approx. Time 2013-09-09 [UTC] | PSP RAI [deg] | ESP RAI [deg] | Brass Ring [deg] | Port NI-DAQ [volts] | Stbd. NI-DAQ [volts] | Port Meter [volts] | Stbd. Meter [volts] |
|---|---|---|---|---|---|---|---|
| 18:05 | -35.0 | -35.0 | -35.0 | 4.30 | 2.50 | 4.270 | 2.519 |
| 18:12 | -30.0 | -30.0 | -30.2 | 4.18 | 2.65 | 4.180 | 2.635 |
| 18:14 | -25.0 | -25.0 | -25.3 | 4.10 | 2.75 | 4.070 | 2.756 |
| 18:15 | -20.0 | -20.0 | -20.1 | 3.95 | 2.90 | 3.940 | 2.885 |
| 18:15 | -15.0 | -15.0 | -14.8 | 3.85 | 3.05 | 3.820 | 3.014 |
| 18:20 | -10.0 | -10.0 | -9.8 | 3.70 | 3.15 | 3.700 | 3.139 |
| 18:23 | -5.0 | -5.0 | -4.6 | 3.58 | 3.28 | 3.570 | 3.260 |
| 18:27 | -3.0 | -2.5 | -2.7 | 3.55 | 3.30 | 3.530 | 3.320 |
| 18:28 | 0.0 | -0.2 | 0.3 | 3.45 | 3.40 | 3.450 | 3.390 |
| 18:32 | 3.0 | 3.4 | 3.3 | 3.38 | 3.48 | 3.380 | 3.470 |
| 18:34 | 5.0 | 5.3 | 5.3 | 3.35 | 3.50 | 3.330 | 3.510 |
| 18:36 | 10.0 | 10.1 | 10.3 | 3.20 | 3.65 | 3.213 | 3.640 |
| 18:38 | 15.0 | 15.2 | 15.2 | 3.10 | 3.75 | 3.095 | 3.760 |
| 18:40 | 20.0 | 20.2 | 20.3 | 2.95 | 3.90 | 2.969 | 3.890 |
| 18:51 | 25.0 | 25.0 | 24.8 | 2.85 | 4.05 | 2.858 | 4.010 |
| 18:53 | 30.0 | 30.5 | 30.0 | 2.75 | 4.15 | 2.734 | 4.130 |
| 18:56 | 35.0 | 35.2 | 35.0 | 2.60 | 4.28 | 2.613 | 4.260 |
| 19:01 | -34.6 | -34.5 | -34.5 | 4.35 | 2.53 | 4.310 | 2.520 |
| 19:03 | -30.0 | -30.0 | -30.0 | 4.20 | 2.65 | 4.200 | 2.631 |
| 19:06 | -25.0 | -24.5 | -25.0 | 4.10 | 2.75 | 4.070 | 2.759 |
| 19:08 | -20.0 | -19.5 | -20.2 | 3.95 | 2.88 | 3.950 | 2.885 |
| 19:10 | -15.0 | -14.5 | -15.0 | 3.85 | 3.05 | 3.820 | 3.014 |
| 19:12 | -10.0 | -9.5 | -9.8 | 3.70 | 3.15 | 3.700 | 3.138 |
| 19:15 | -5.0 | -4.6 | -4.7 | 3.58 | 3.25 | 3.570 | NaN |
| 19:18 | -3.0 | -2.5 | -2.7 | 3.55 | 3.35 | 3.520 | 3.310 |
| 19:21 | 0.0 | 0.3 | 0.3 | 3.45 | 3.40 | 3.440 | 3.390 |
| 19:23 | 3.0 | 3.2 | 3.3 | 3.35 | 3.50 | 3.370 | 3.470 |
| 19:25 | 5.0 | 5.2 | 5.4 | 3.35 | 3.57 | 3.320 | 3.520 |
| 19:27 | 10.0 | 10.2 | 10.2 | 3.20 | 3.65 | 3.201 | 3.640 |
| 19:29 | 15.0 | 15.2 | 15.3 | 3.10 | 3.78 | 3.079 | 3.770 |
| 19:35 | 20.0 | 20.2 | 20.2 | 2.95 | 3.90 | 2.957 | NaN |
| 19:38 | 25.0 | 25.5 | 25.1 | 2.85 | 4.00 | 2.845 | 4.010 |
| 19:40 | 30.0 | 30.5 | 29.8 | 2.75 | 4.15 | 2.727 | 4.130 |
| 19:41 | 35.0 | 35.5 | 35.0 | 2.60 | 4.30 | 2.602 | 4.260 |
| 19:46 | -35.0 | -34.5 | -34.3 | 4.30 | 2.50 | 4.290 | 2.520 |

**Figure B.3:** *Port (top) and starboard (bottom) sensor rudder calibration*

# Annex C: GLM data

**Table C.1:** *Data extracted from GLM reports*

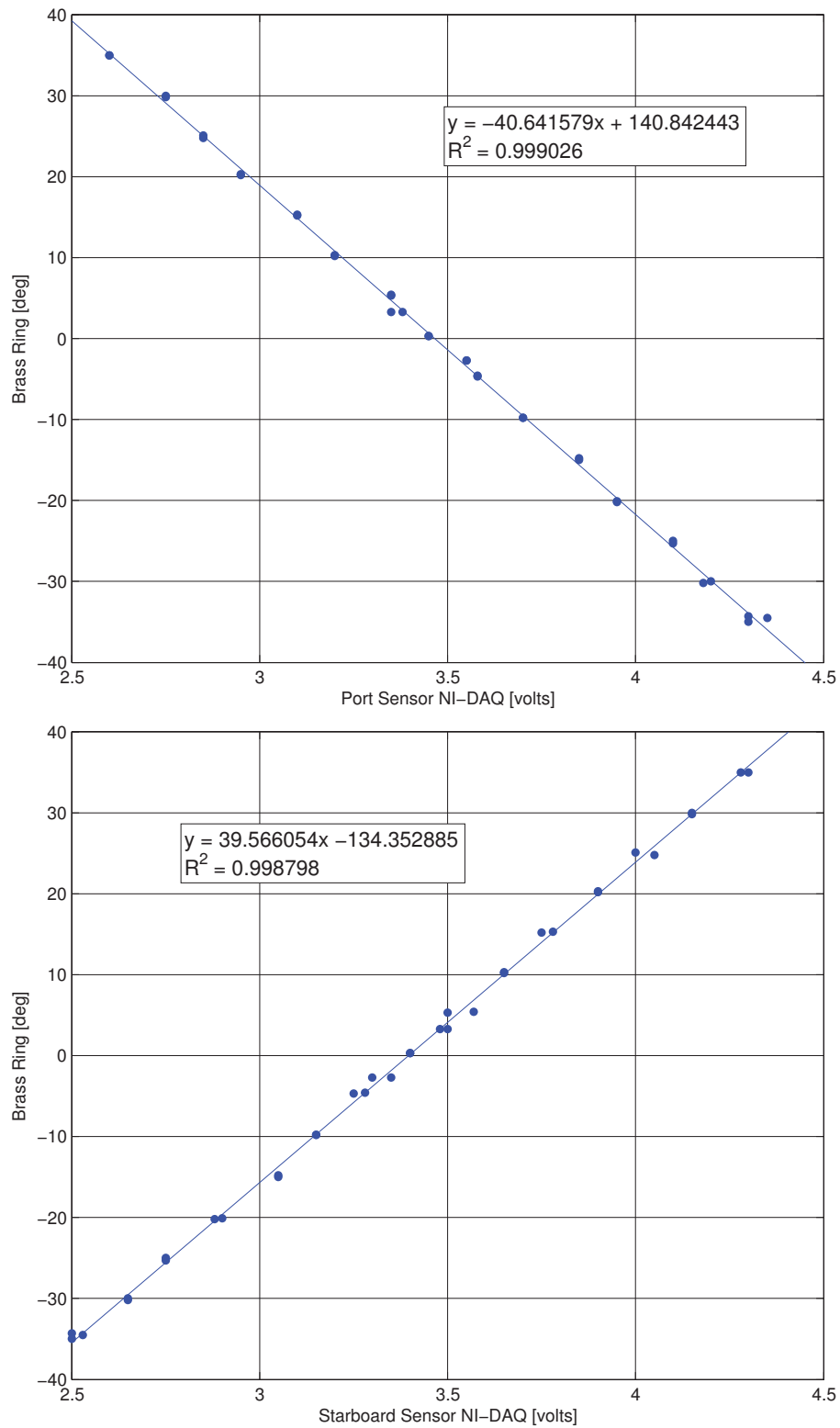| Date & Time [UTC] | 9 Sept Sailing | 10 Sept 12:00 | 11 Sept 14:00 | 11 Sept 23:30 | 12 Sept 12:00 | 12 Sept 23:30 | 13 Sept 12:00 | 13 Sept 23:30 | 15 Sept 12:00 | 15 Sept 00:00 | 15 Sept 02:15 | 15 Sept 03:30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FP Draft | 5.086 | 5.078 | 5.052 | 4.943 | 4.978 | 5.075 | 5.109 | 5.03 | 4.988 | 4.87 | 5.077 | 4.867 |
| Midship Draft [m] | 5.119 | 5.113 | 5.085 | 5.056 | 5.045 | 5.057 | 5.048 | 5.003 | 4.988 | 4.939 | 5.002 | 5.005 |
| AP Draft [m] | 5.151 | 5.147 | 5.119 | 5.169 | 5.112 | 5.04 | 4.987 | 4.976 | 4.988 | 5.008 | 4.927 | 5.144 |
| Trim* [m] | -0.065 | -0.068 | -0.226 | -0.067 | 0.135 | 0.036 | 0.122 | 0.054 | 0.000 | -0.138 | 0.149 | -0.277 |
| Heel** (deg) | -0.7 | -0.08 | -0.58 | -0.58 | -0.69 | -1.29 | -0.99 | 0.13 | -0.06 | 0.57 | 0.19 | 0.22 |
| Displacement [MT] | 4,901.28 | 4,892.42 | 4,851.34 | 4,822.99 | 4,799.17 | 4,800.43 | 4,778.36 | 4,717.30 | 4,700.90 | 4,641.09 | 4,707.48 | 4,753.20 |
| LCG [m] | -3.136 | -3.134 | -3.088 | -3.429 | -3.192 | -2.802 | -2.576 | -2.662 | -2.772 | -3.029 | -2.426 | -3.476 |
| TCG [m] | -0.012 | 0 | -0.009 | -0.009 | -0.011 | -0.022 | -0.017 | 0.004 | 0 | 0.011 | 0.005 | 0.005 |
| VCG [m] | 6.467 | 6.48 | 6.502 | 6.526 | 6.535 | 6.523 | 6.538 | 6.589 | 6.606 | 6.67 | 6.605 | 6.602 |
| LCB [m] | -3.137 | -3.136 | -3.09 | -3.436 | -3.196 | -2.799 | -2.57 | -2.661 | -2.772 | -3.034 | -2.422 | -3.484 |
| TCB [m] | -0.052 | -0.005 | -0.043 | -0.044 | -0.053 | -0.099 | -0.076 | 0.012 | -0.003 | 0.047 | 0.017 | 0.018 |
| VCB [m] | 3.142 | 3.138 | 3.122 | 3.111 | 3.1 | 3.102 | 3.093 | 3.067 | 3.06 | 3.037 | 3.063 | 3.082 |
| WPA [m²] | 1455.3 | 1454.7 | 1452.5 | 1450.6 | 1449.5 | 1450.1 | 1448.9 | 1444.9 | 1443.9 | 1440.6 | 1445.2 | 1446.6 |
| LCF [m] | -8.081 | -8.086 | -8.089 | -8.229 | -8.154 | -8.001 | -7.931 | -7.989 | -8.039 | -8.17 | -7.932 | -8.282 |
| TCF [m] | -0.083 | -0.009 | -0.068 | -0.069 | -0.081 | -0.152 | -0.117 | 0.015 | -0.007 | 0.066 | 0.022 | 0.025 |
| BML [m] | 288.88 | 289.21 | 290.61 | 291.31 | 292.51 | 292.79 | 293.89 | 295.98 | 296.56 | 298.78 | 296.98 | 293.9 |
| BMT [m] | 4.324 | 4.328 | 4.349 | 4.373 | 4.388 | 4.386 | 4.407 | 4.456 | 4.476 | 4.508 | 4.423 | 4.29 |
| GML [m] | 285.56 | 285.87 | 287.23 | 287.89 | 289.08 | 289.37 | 290.44 | 292.45 | 293.02 | 295.15 | 293.44 | 290.38 |
| GMT [m] | 0.999 | 0.986 | 0.969 | 0.957 | 0.953 | 0.965 | 0.962 | 0.934 | 0.931 | 0.875 | 0.882 | 0.77 |

Longitudinal positions relative to midships (negative = aft).
Transverse positions relative to centreline (negative = port).
*Trim = FP Draft - AP Draft
**Negative = Heel to port (port down/starboard up).

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# Annex D: MetOc log

**Table D.1:** *CAL2013 MetOc log sheet*

| Day [UTC] | Time [UTC] | Quadrant | Latitude | Longitude | Sky Conditions | Visibility | Weather | MSL Press. [mBar] | Dry Bulb [°C] | Wet Bulb [°C] | Dew Point [°C] | Sea Temp. [°C] | Wind Direction [°True] | Wind Speed [knots] | Altimiter Setting [" Hg] | Cloud Type & Opacity (Sky Divided into 8ths) | Wave Period [s] | Wave Height [m] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 0300 | 7 | 48.5 | 124.6 | Vertical Visibility 200' | 1/4 | Fog | 1016.9 | 12.2 | 12.2 | 12.2 | 15.0 | 31 | 10 | 30.03 | Fog 8/8 | 4 | 1 |
| 10 | 0400 | 7 | 48.5 | 125.2 | Broken Cloud 900' | 12 | | 1016.9 | 13.5 | | 13.5 | | 32 | 12 | 30.03 | Stratocumulous 7/8 | 4 | 1 |
| 10 | 0800 | 7 | 49.0 | 126.6 | Few Cloud 2000' | 12 | | 1016.1 | 15.4 | | 14.6 | 13.1 | 32 | 10 | 30.01 | Cumulus 1/8 | 6 | 1 |
| 10 | 0600 | 7 | 49.0 | 126.6 | Few Cloud 2000' | 12 | | 1016.0 | 15.4 | | 14.7 | 15.2 | 32 | 10 | 30.00 | Cumulus 1/8 | 6 | 1 |
| 10 | 1100 | 7 | 49.4 | 127.4 | Clear Skies | 12 | | 1015.7 | 14.9 | | 14.0 | 14.7 | 34 | 12 | 29.99 | | 5 | 1 |
| 10 | 1200 | 7 | 49.4 | 127.6 | Clear Skies | 12 | | 1015.6 | 15.1 | | 13.9 | 15.0 | 33 | 13 | 29.99 | | 6 | 1 |
| 10 | 1300 | 7 | 49.4 | 127.8 | Few Cloud 2000' | 12 | | 1015.7 | 15.8 | | 13.8 | 16.6 | 34 | 14 | 29.99 | Cumulus 1/8 | 4 | 2 |
| 10 | 2100 | 7 | 49.7 | 128 | Clear Skies | 30 | | 1016.0 | 16.1 | | 14.7 | | 35 | 13 | 30.00 | | 5 | 1 |
| 10 | 2300 | 7 | 49.8 | 128.1 | Clear Skies | 30 | | 1014.8 | 16.1 | | 14.8 | | 25 | 14 | 29.97 | | 5 | 2 |
| 11 | 0000 | 7 | 49.7 | 127.9 | Clear Skies | 30 | | 1014.6 | 16.6 | | 15.2 | | 29 | 14 | 29.96 | | 5 | 2 |
| 11 | 0100 | 7 | 49.6 | 127.7 | Clear Skies | 30 | | 1013.9 | 16.1 | | 15.1 | 15.6 | 33 | 11 | 29.94 | | 5 | 2 |
| 11 | 0500 | 7 | 49.5 | 127.6 | Clear Skies | 12 | | 1013.2 | 16.2 | | 15.2 | 16.0 | 33 | 9 | 29.92 | | 6 | 1 |
| 11 | 0600 | 7 | 49.5 | 127.7 | Clear Skies | 12 | | 1013.1 | 16.1 | | 15.2 | 15.6 | 33 | 7 | 29.92 | | 6 | 1 |
| 11 | 0900 | 7 | 49.7 | 127.8 | Few Cloud 21000' | 12 | | 1012.5 | 15.9 | | 14.7 | 15.9 | 34 | 9 | 29.90 | Cirrus 1/8 | 7 | 1 |
| 11 | 1000 | 7 | 49.6 | 128 | Few Cloud 25000' | 12 | | 1012.3 | 16.5 | | 15.4 | 16.2 | 35 | 11 | 29.89 | Cirrus 1/8 | 7 | 1 |
| 11 | 1100 | 7 | 49.4 | 128 | Few Cloud 25000' | 12 | | 1012.3 | 16.4 | | 15.5 | 15.9 | 33 | 7 | 29.89 | Cirrus 1/8 | 7 | 1 |
| 11 | 2000 | 7 | | | Clear Skies | 30 | | 1013.6 | 18.3 | | 16.3 | 16.8 | 33 | 6 | 29.93 | | 7 | 1 |
| 11 | 2200 | 7 | | | Clear Skies | 30 | | 1013.2 | 18.5 | | 16.8 | 16.5 | 12 | 5 | 29.92 | | 8 | 1 |
| 11 | 2300 | 7 | | | Clear Skies | 30 | | 1013.0 | 19.1 | | 17.3 | 16.8 | 16 | 4 | 29.91 | | 8 | 2 |

*– Continued on Next Page –*

**Table D.1:** *Continued from previous page*

| Day [UTC] | Time [UTC] | Quadrant | Latitude | Longitude | Sky Conditions | Visibility | Weather | MSL Press. [mBar] | Dry Bulb [°C] | Wet Bulb [°C] | Dew Point [°C] | Sea Temp. [°C] | Wind Direction [°True] | Wind Speed [knots] | Altimeter Setting ["Hg] | Cloud Type & Opacity (Sky Divided into 8ths) | Wave Period [s] | Wave Height [m] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 0000 | 7 | 49.6 | 128.3 | Clear Skies | 30 | | 1012.7 | 19.2 | | 17.4 | 15.8 | 8 | 7 | 29.91 | | 8 | 2 |
| 12 | 0300 | 7 | 49.6 | 128.2 | Clear Skies | 30 | | 1012.2 | 18.7 | | 16.7 | 17.1 | 8.0 | 6.0 | 29.89 | | 8 | 1 |
| 12 | 0500 | 7 | 49.4 | 127.6 | Clear Skies | 12 | | 1013.1 | 18.2 | | 16.5 | 17.1 | 14.0 | 12.0 | 29.92 | | 8 | 1 |
| 12 | 0600 | 7 | 48.5 | 127.7 | Clear Skies | 12 | | 1013.1 | 17.9 | | 16.6 | 15.9 | 14.0 | 8.0 | 29.92 | | 8 | 1 |
| 12 | 0900 | 7 | 49.6 | 127.9 | Vertical Visibility 200' | 1/4 | Fog | 1014.1 | 16 | | 16.0 | 16.5 | 17.0 | 10.0 | 29.95 | Fog 8/8 | 8 | 1 |
| 12 | 1000 | 7 | 49.5 | 127.8 | Vertical Visibility 200' | 1/4 | Fog | 1014.3 | 16 | | 16.0 | 15.9 | 15.0 | 12.0 | 29.95 | Fog 8/8 | 8 | 2 |
| 12 | 1100 | 7 | 49.4 | 127.7 | Vertical Visibility 200' | 1/4 | Fog | 1014.2 | 15.8 | | 15.8 | 17.2 | 14.0 | 13.0 | 29.95 | Fog 8/8 | 8 | 2 |
| 12 | 2000 | 7 | 49.6 | 126.5 | Overcast Cloud 800' | 7 | | 1015.8 | 16.7 | | 15.7 | | 27.0 | 11.0 | 30.00 | Stratus 8/8 | 8 | 1 |
| 12 | 2100 | 7 | 49.3 | 126.6 | Overcast Cloud 800' | 2 1/2 | Mist | 1016.2 | 15.7 | | 15.6 | | 5.0 | 3.0 | 30.01 | Stratus 8/8 | 9 | 1 |
| 12 | 2200 | 7 | 49.2 | 127 | Overcast Cloud 800' | 2 1/2 | Mist | 1015.7 | 16.2 | | 16.2 | | 7.0 | 8.0 | 29.99 | Stratus 8/8 | 10 | 1 |
| 12 | 2300 | 7 | 49.1 | 127.4 | Overcast Cloud 400' | 1 | Mist | 1015.1 | 16.5 | | 16.5 | 15.5 | 8.0 | 4.0 | 29.98 | Stratus 8/8 | 8 | 1 |
| 13 | 0000 | 7 | 49.2 | 127.3 | Overcast Cloud 400' | 1 | Mist | 1014.7 | 16.3 | | 16.3 | 15.4 | 12.0 | 4.0 | 29.96 | Stratus 8/8 | 10 | 1 |
| 13 | 0300 | 7 | 49.2 | 127.3 | Overcast Cloud 1000' | 3 | Mist | 1014.2 | 16.3 | | 16.3 | 15.7 | 6.0 | 1.0 | 29.95 | Stratus 8/8 | 10 | 1 |
| 13 | 0500 | 7 | 49.2 | 127.6 | Overcast Cloud 1000' | 8 | | 1014.9 | 16.6 | | 16.6 | 17.2 | 9.0 | 1.0 | 29.97 | Stratus 8/8 | 10 | 1 |
| 13 | 0600 | 7 | 49.0 | 128.4 | Overcast Cloud 1000' | 5 | Mist | 1014.7 | 16.4 | | 16.4 | 15.4 | 0.0 | 0.0 | 29.96 | Stratus 8/8 | 10 | 1 |

# Annex E: Dead drift run results

## E.1 CAL2013-DeadDrift-01

**Table E.1:** *Run parameters: CAL2013-DeadDrift-01*

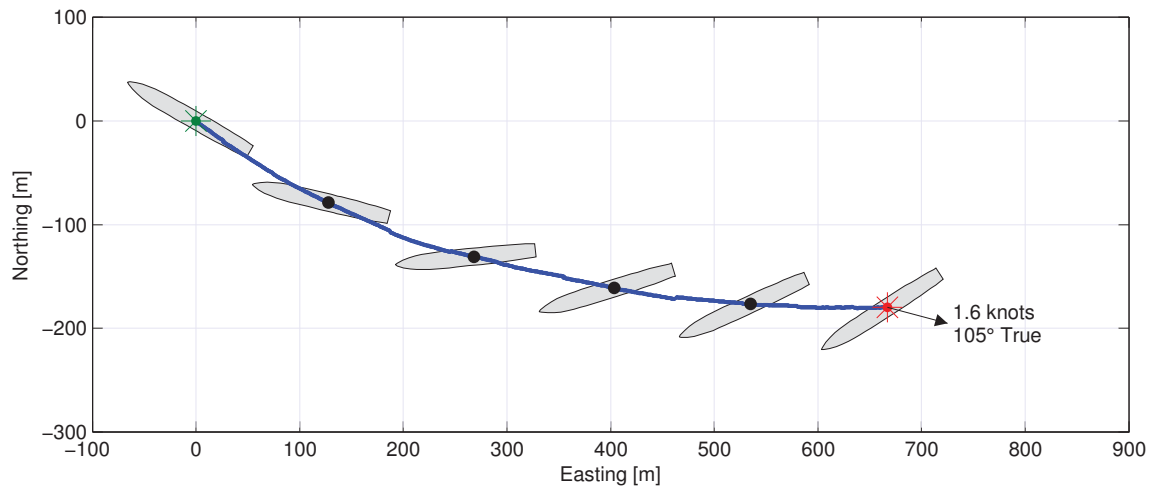| Run ID | CAL2013_DeadDrift_01 |
|---|---|
| Run Start | September 10, 2013 at 13:31:15 UTC |
| Run End | September 10, 2013 at 13:45:14 UTC |
| Run Duration | 13 minutes, 59 seconds |
| Wander | 1.60 knots at 105.1 deg.T |
| Track Length | 691 m (0.37 nmi) |
| Mean True Wind | 14.3 knots from 167.7 deg.T |
| Air Temp. & Humidity | 15.7 deg. C with 91.2% Relative Humidity |



**Figure E.1:** *Raw track: CAL2013-DeadDrift-01*

## E.2 CAL2013-DeadDrift-02

**Table E.2:** *Run parameters: CAL2013-DeadDrift-02*

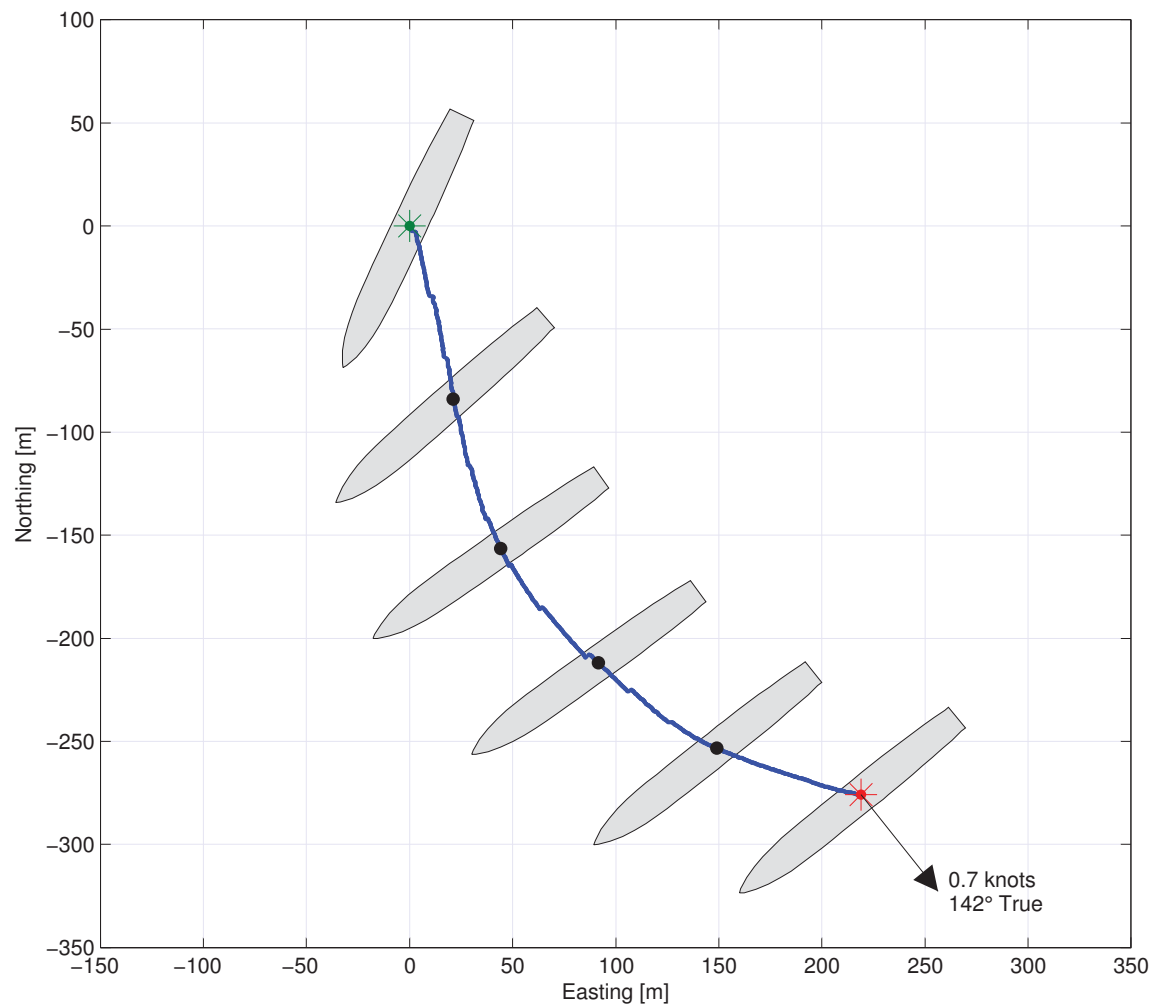| Run ID | CAL2013_DeadDrift_02 |
|---|---|
| Run Start | September 11, 2013 at 01:47:52 UTC |
| Run End | September 11, 2013 at 02:04:00 UTC |
| Run Duration | 16 minutes, 8 seconds |
| Wander | 0.71 knots at 141.5 deg.T |
| Track Length | 352 m (0.19 nmi) |
| Mean True Wind | 9.5 knots from 283.8 deg.T |
| Air Temp. & Humidity | 16.5 deg. C with 90.2% Relative Humidity |



**Figure E.2:** *Raw track: CAL2013-DeadDrift-02*

# E.3 CAL2013-DeadDrift-03

**Table E.3:** *Run parameters: CAL2013-DeadDrift-03*

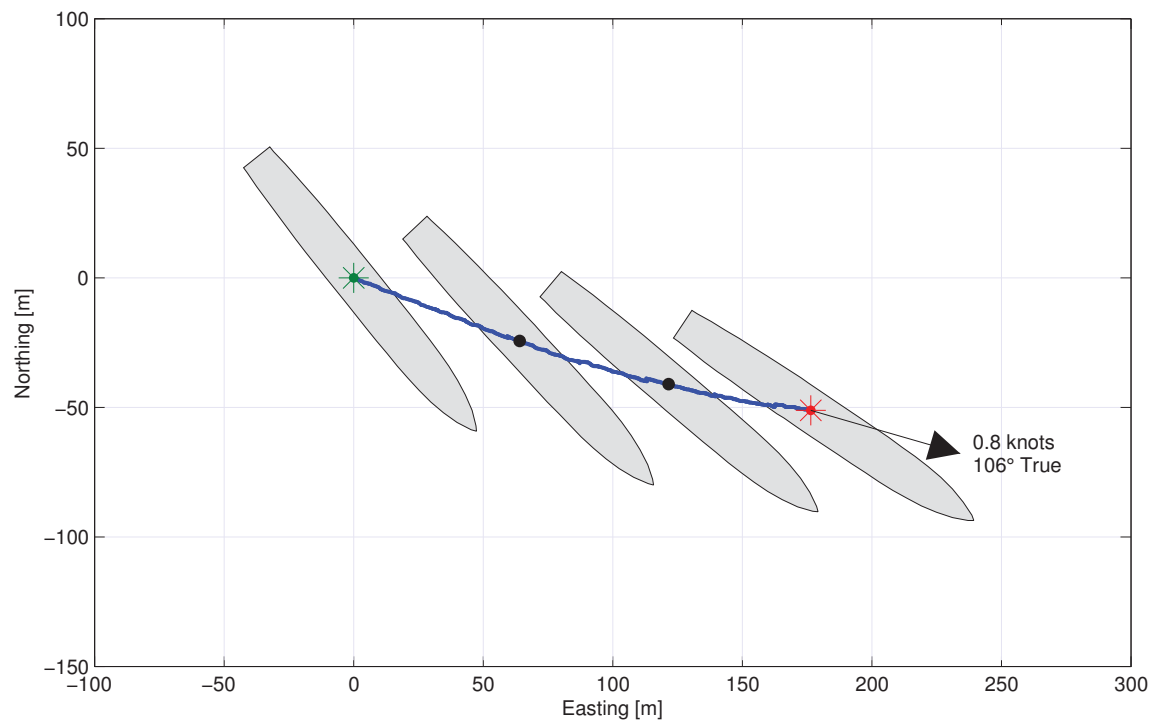| Run ID | CAL2013_DeadDrift_03 |
|---|---|
| Run Start | September 11, 2013 at 15:00:41 UTC |
| Run End | September 11, 2013 at 15:08:07 UTC |
| Run Duration | 7 minutes, 25 seconds |
| Wander | 0.80 knots at 106.2 deg.T |
| Track Length | 184 m (0.10 nmi) |
| Mean True Wind | 5.0 knots from 335.0 deg.T |
| Air Temp. & Humidity | 17.5 deg. C with 89.4% Relative Humidity |



**Figure E.3:** *Raw track: CAL2013-DeadDrift-03*

## E.4 CAL2013-DeadDrift-04

*Table E.4:* Run parameters: CAL2013-DeadDrift-04

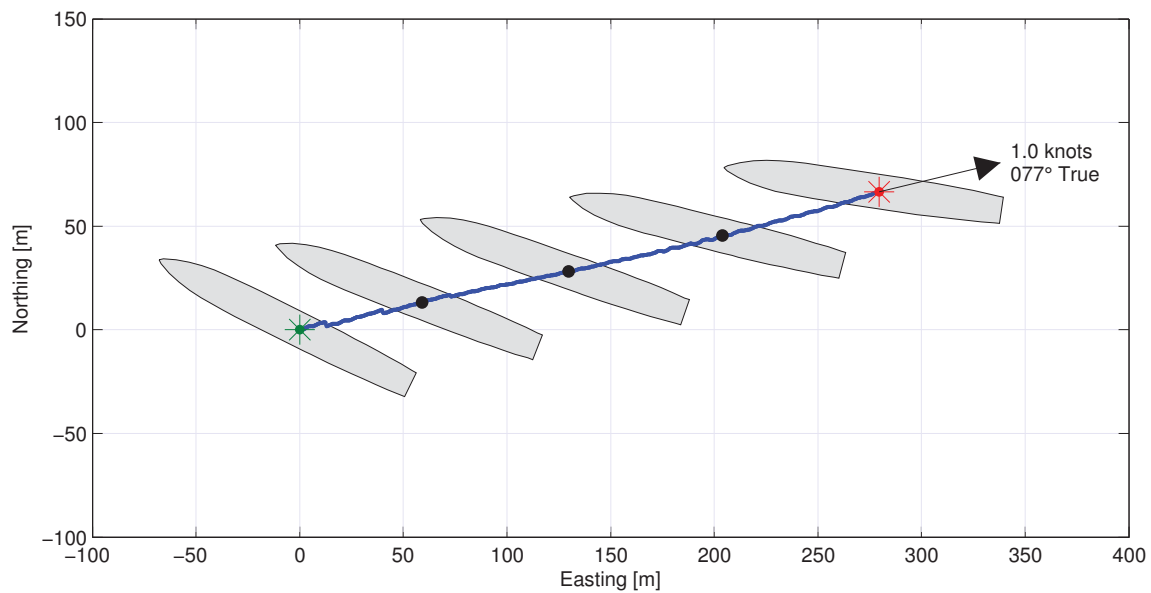| Run ID | CAL2013_DeadDrift_04 |
|---|---|
| Run Start | September 14, 2013 at 05:45:54 UTC |
| Run End | September 14, 2013 at 05:55:06 UTC |
| Run Duration | 9 minutes, 12 seconds |
| Wander | 1.01 knots at 76.6 deg.T |
| Track Length | 288 m (0.16 nmi) |
| Mean True Wind | 4.6 knots from 81.4 deg.T |
| Air Temp. & Humidity | 15.0 deg. C with 98.2% Relative Humidity |



*Figure E.4:* Raw track: CAL2013-DeadDrift-04

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The Halifax Class frigates are currently undergoing a midlife modernization as part of the FELEX program. An existing data set for standardization and manoeuvring/controllability for the HALIFAX Class frigates is from a trial in 1991 on HMCS HALIFAX when the ships were newly built. The ships now operate at a deeper displacement and have undergone a number of appendage changes. In order to update manoeuvring data for the post-refit ships a sea trial was conducted on HMCS CALGARY in September 2013. This report presents a summary description of this standardization and manoeuvring/controllability sea trial. Instrumentation, conditions, and data processing are discussed. The analysis and results from the trial are given in separate reports.

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Canadian Patrol Frigate (CPF); Halifax Class; Halifax Class Modernization (HCM); Frigate Life Extension (FELEX); sea trial; manoeuvring; controllability