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Speed trial and route analysis of m/v Annika Braren with rotor sail

Wind Assisted Ship Propulsion

Interreg North Sea Region WASP

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Speed trial and route analysis of m/v Annika Braren with rotor sail

A speed trial was performed with m/v Annika Braren in September 2021. The purpose of the test was to verify the power saving of the Flettner rotor sail. This report describes the tests conditions, measurements, analysis, and results. The trial test result is extrapolated to annual fuel reduction using voyage analysis and statistical weather distribution.
The work is a part of the Interreg North Sea Region project WASP - Wind Assisted Ship Propulsion.

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Summary and recommendations

A speed trial was performed with m/v Annika Braren in September 2021. The purpose of the trial was to verify the power saving of the Flettner rotor.

The analysis shows that at true wind speed 10 m/s and ship's speed 11.5 knots, the rotor gives a net power saving when the apparent wind angle is larger than 30 degrees and the saving reaches up to 15% at the most favourable wind angle.

The speed trial result is scaled up to give a prediction of the averaged in-service fuel reduction using a ship simulation model correlated to the actual speed trial measurements, a voyage prediction tool and statistical weather distribution.

It is estimated that the power reduction on typical routes is between 2% - 4.5%, corresponding to a fuel saving of 0.4-1.1 kg/nautical mile.

For an average year of operation, the fuel saving potential is estimated to be 0.63 kg/nautical miles, which will give approximately 36 tons fuel saving per year, corresponding to 113 tons CO_2. This assumes that the rotor is fully operable at all times when wind permits, and that the additional thrust is used to reduce engine load and keeping the speed constants to 11.5 knots.

The result is associated with several sources of uncertainty. The mayor one is the wind measurement. It is suggested to study further the drag of the rotor in idling condition, which could not be measured at the sea trial.

It is recommended to log the wind speed on the route, the ship's fuel consumption and operability of the rotor for at least one year to complement this study.

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Symbols and abbreviations

ξ_p	Load variation factor, for power correction according to ITTC (2017)	-
AWS	Apparent wind speed	m/s
AWA	Apparent wind angle	deg
AWS_x	Apparent wind speed in ship longitudinal direction	m/s
AP	Aft perpendicular	
A_T	Transversal wind area	m^2
B	Beam of hull	m
BL	Baseline	
CL	Center line	
Ct	Force coefficient in longitudinal direction (thrust) based on sail projected area	
D	Rotor diameter	m
FP	Fore perpendicular	
FS	Full scale	
GWA	Global wind angle	deg
H	Rotor height	m
IMO	International Maritime Organization	
ITTC	International Towing Tank Conference	
T	Draught	m
T_F	Draught at fore perpendicular	m
TWA	True wind angle	deg
TWS	True wind speed	m/s
V	Volume displacement	M3
V_s	Ship speed	knots
SOG	Speed over ground	knots
COG	Course over ground	deg
STW	Speed through water	knots

1 Introduction

Rörd Braren installed a Flettner rotor from EcoFlettner on m/v Annika Braren in April 2021. On September 25, 2021, a speed trial was performed with the purpose of evaluating the performance of the rotor.

The Trial Team present onboard included Ship Master Capt Mehren and Sofia Werner, SSPA Sweden AB. The trial was planned and conducted by the Trial Team in cooperation.

The speed trial result is scaled up to predicted in-service fuel reduction using a route analysis and statistical weather data. All data processing, analysis and route evaluation is carried out independently by SSPA.

This work is a part of Work Package 5 in the Interreg North Sea Region project WASP. The scope of Work Package 5 is to demonstrate the performance of Wind Propulsion Technologies on five vessels. Annika Braren was the second out of these five to be tested. The first trial, of the ferry Copenhagen, was reported in SSPA report RE40201042-01-00-A and in the proceedings of RINA International Conference on Wind Propulsion (Werner, 2021).

The aim is *not* to compare and rank different wind propulsion technologies. The fuel savings of each installation depend on the ship, speed and route, and therefore the tested cases cannot be compared with each other.

Figure A. Annika Braren (84.98m x 15m) with a 3m x 18m rotor sail from EcoFlettner.

2 Speed trial data

2.1 Conventions and definitions

The following coordinate systems are used in this report:

- Used when referring to locations or distances on the ship:
    - Body-fixed, Cartesian, right-handed system “XYZ” with the origin in intersection of AP, CL and BL.
    - X-axis positive forward
    - Y-axis positive to port
    - Z-axis positive upwards

The following definitions of directions and angles are used in this report.

- Global wind angle (GWA): defined in the geographical system
    - GWA=0° means wind coming from north
- True wind angle (TWA): the angle between the wind direction and the course of the ship
    - TWA=0° means head wind
    - TWA=90° means beam wind (starboard side)

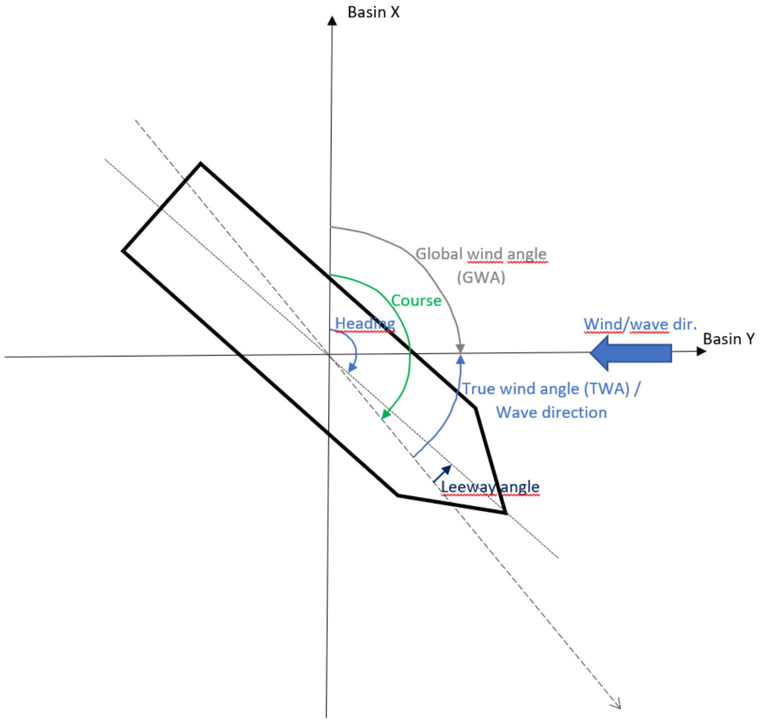


Figure B Definitions of directions and angles

2.2 Ship

The bulk carrier Annika Braren (IMO 9849148) operates mainly in the North Sea region and the Baltic sea. The ship data used for the sea trial analysis is listed in Table 1. The ship has a ducted, controllable pitch propeller. The engine is a 4-stroke direct coupled, and with a shaft generator.

The ship loading condition during trial is given in Table 2.

Table 1. Ship data

Name	Symbol	Magnitude	Comment
Length over all	Loa	84.98 m	
Beam over all	B	15 m	
Load variation factor for power	ξ_p	-0.15	Based on similar ships in SSPA database
Hight of anemometer	h	24 m	from waterline at trial
Transversal wind area	A_T	195 m^2	

Table 2. Ship loading condition during trial

Name	Symbol	Magnitude	Comment
Draft forward	Tf	3.35 m	
Draft aft	Ta	4.25 m	
Displacement	Δ	3541 ton	

2.3 Wind propulsion system

The ship is equipped with one rotor of type “EF 18” from Eco Flettner with dimensions according to Table 3. The rotor is driven by an electric motor and the rotation speed is set automatically.

Table 3 Wind propulsion system particulars

Name	Magnitude	Comment
Span	18 m	
Diameter	3 m	
Endplates	Top and bottom	
Area	54 m^2	projected
Position longitudinal	81.4 m from AP	
Height mid-span	18.63 m	At trial

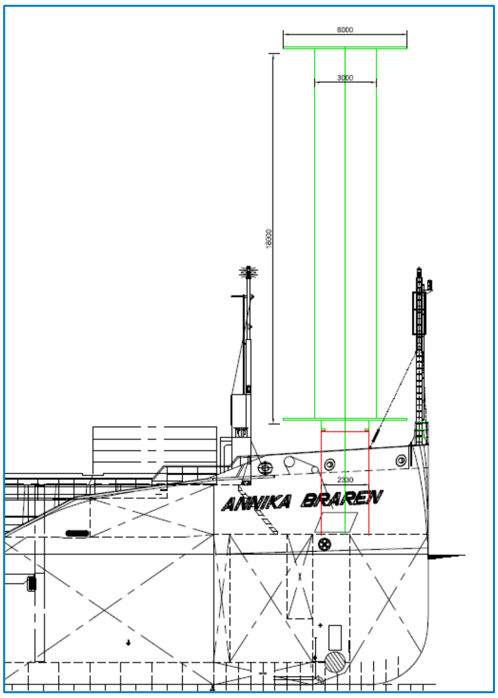


Figure C The rotor at the bow of Annika Braren

2.4 Trial location and environmental conditions

The trial was conducted in the Baltic Sea, north of island Gotland. Environmental conditions registered onboard are given in *Table 4*.

Table 4. Environmental conditions, registered onboard

Name	Magnitude	Comment
Wind	Bf 6. 9-12 m/s from NW	
Waves	0.7-1.5 m from NW	
Swell	None	
Current	unknown	
Water depth	80 m	
Temperature sea water	14°	
Density sea water	1000 kg/m^3	estimated
Temperature air	14°	
Air pressure	1013 mbar	Was not measured
Density air	1.23 kg/m^3	Derived from temperature

2.5 Data acquisition

All recorded data is listed in Appendix 1, Figure 1-52. Data acquisition was performed using the systems given in Table 5. Most of the signals were retrieved from the logging system delivered by Dirks Electronics.

Table 5. Data acquisition sources

Variable	Instrument	Source
Propeller shaft rate		Dirks data log
Shaft generator	Generator PTO	Dirks data log
SOG, COG	GPS	Dirks data log
STW	log	Dirks data log
Fuel oil consumption	Volumetric flow meters, inlet and outlet	Manual reading of averaged value from Eefting displays on the bridge during trial runs
Heading (gyro) Rudder angle		Manual reading of displays on the bridge during trial runs
Relative wind at mast top	Ships Anemometer	Dirks data log
Rotor rpm and power	Rotor engine	Dirks data log

2.5.1 Delivered power

The ship is not equipped with a shaft torque meter. Instead, the delivered power in kW had to be derived from the fuel oil consumption readings using the following relation:

$$P_d = \left(\frac{FOC}{SFOC} - \frac{P_{rotor}}{\eta_{t\_shaftgenerator}}\right)\eta_t\ , \qquad (1)$$

where

FOC is main engine the fuel oil consumption in kg/h,

SFOC is the main engine specific fuel oil consumption, 200 g/kWh according to the Technical File

P_{rotor} is the recorded power consumption of the rotor (kW)

$\eta_{t\_shaftgenerator}$ is the transmission efficiency of the shaft generator, estimated as 0.95

η_t is the propulsion transmission efficiency, 0.97 according to the Technical File

During the trial, the only consumer of the shaft generator was the rotor engine.

The computed delivered power is given in Figure 1, Appendix 1.

2.6 Trial procedure

The trial was conducted according to the principles in ISO 15016/ITTC 7.5-04-01-01.1, with two major deviations: the track and the power settings.

2.6.1 Track

The trial track (Figure D) includes a series of runs with and without the rotor on, at various wind directions. This deviates from the ISO 15016 procedures which prescribes double-runs in reciprocal directions, to allow for current correction. The main reason for selecting this circular track instead of the conventional double runs is that is saves time. (The pros and cons of this choice, and the lack of current correction is further discussed in Chapter 6.)

2.6.2 Power setting

The conventional ISO 15016 procedure prescribes that the power setting (propeller shaft rate and propeller pitch) is kept constant for both runs in a double-run. This process was followed in the previous WASP sea trial for m/v Copenhagen with rotor sail (Werner 2021, SSPA report RE40201042-01). An alternative approach that was discussed in the WASP consortium is to keep the speed constant between two subsequent runs by adjusting the power. In an attempt to compare the feasibility of the two approaches, the present sea trial program included both type of power settings.

2.6.3 Sequence

The trial program covered five wind angles, with three single runs for each wind angle according to the following sequence:

1) Rotor was turned off
2) Steady heading and speed were checked by GPS
3) Measurements conducted for 10 minutes
4) While keeping heading, rpm and pitch constant, rotor was turned on.
5) Steady heading and speed checked with GPS.
6) Measurements conducted for 10 minutes.
7) Ship's propeller pitch reduced to get similar speed as the initial run (with shaft rate constant).
8) When steady speed was reached, measurements conducted for 10 minutes

Additionally, two runs were conducted straight into and following the wind with the rotor turned off. In total 17 single runs were conducted, as listed in Table 6. The complete program took 6 hours.

The rotor rpm was set automatically by the rotors control system.

Constant heading was kept during the runs using the ships autopilot.

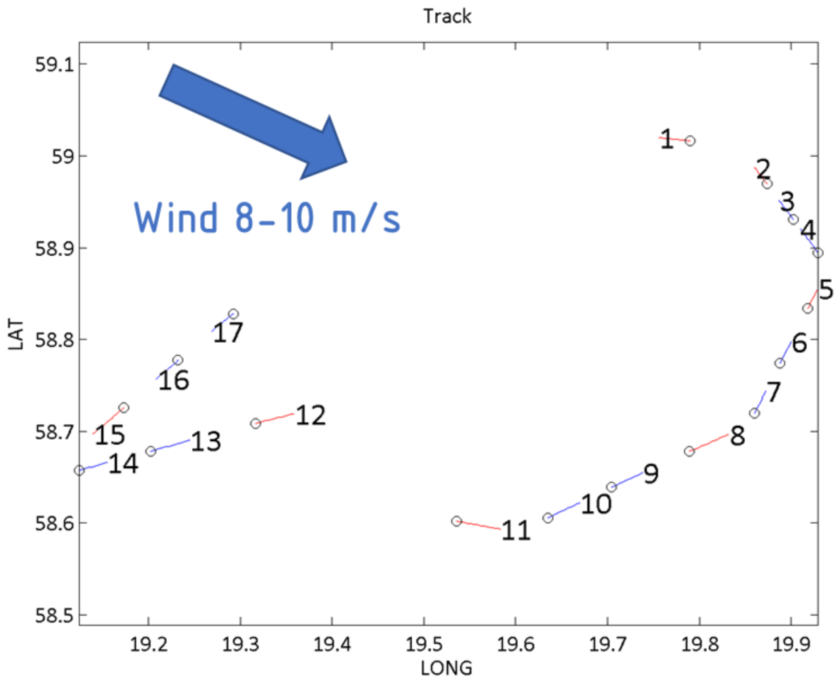


Figure D. Tracks of trial runs. Circles mark the start of each run. Red=without rotor, blue=with rotor

Table 6. Trial program (note that actual wind angle deviated somewhat from the targeted)

Run	Target True wind angle	Rotor	Comment
1	180		For base line
2	140		
3	140	on	
4	140	on	
5	110		
6	110	on	
7	110	on	
8	80		
9	80	on	
10	80	on	
11	0		For base line
12	55		
13	55	on	override auto rpm, otherwise rotor stops
14	55	on	
15	95		
16	95	on	
17	95	on	

3 Trial analysis and results

3.1 Current

In standard speed trial analysis, the ship's speed over ground (SOG) is measured with the GPS and corrected to speed through water (STW) using double runs. The GPS is generally regarded as far more accurate than the speed log. As discussed further below in Section 6.1, this procedure is not possible to follow in the present trial, due to the presence of wind propulsion. Instead, the speed is measured with the ship's log. There is therefore no need to correct for current.

3.2 Wind

The true wind during the trial shown in Figure E and Figure F is derived from the apparent wind measured with the ship's anemometer and the ship's speed. The wind was not completely constant during the trial. This could potentially disturb the trial evaluation process, when runs with and without rotor are compared. Figure G and Figure H show the derived true wind during the triplets of runs that are compared. To minimise this disturbance, the ship's wind resistance is subtracted from each individual run, according to the ISO 15016 procedure.

According to ISO 15016, the measured wind should be averages between two runs in opposite directions, to reduce the disturbance of the ship's superstructure on the anemometer. In this trial, the runs were however not conducted as reciprocal double-runs and therefore this procedure cannot be followed.

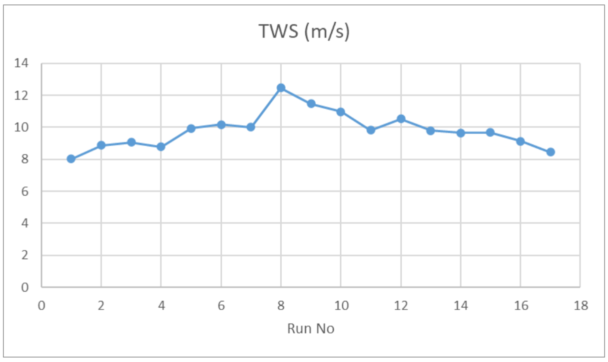


Figure E. True wind speed, at height of anemometer

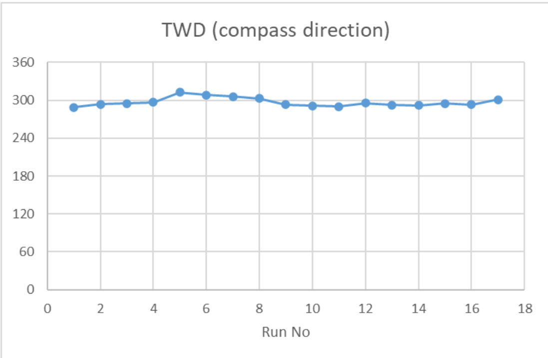


Figure F. Global wind direction, at height of anemometer

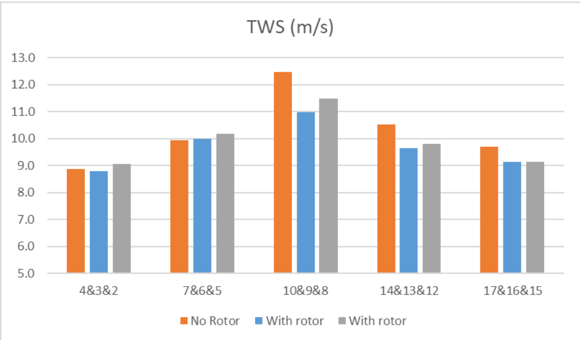


Figure G. True wind speed during speed runs

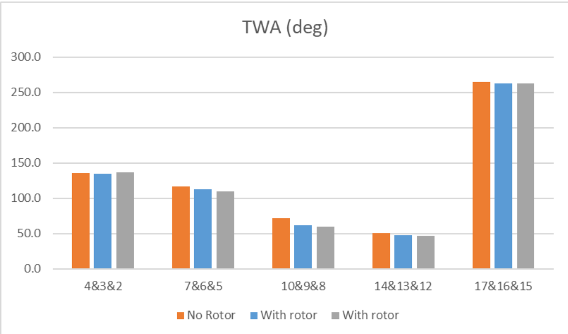


Figure H. True wind angle during speed runs

3.3 Water temperature, displacement and superstructure resistance

The measured power for each single run is corrected for the wind resistance of the superstructure based on ISO/ITTC standard procedure. The wind resistance coefficient is the "Handy size bulk carrier" from the ITTC procedures (ITTC 2021).

Correction for water temperature and a correction of displacement to baseline displacement are done according to the procedures.

3.4 Idling rotor drag

Since the purpose is to derive the effect of the rotor compared to the ship without any rotor, the resistance of the idling rotor during the trial was subtracted from the runs when the rotor was not used. The rotor resistance is estimated as:

$$R_{rotor} = C_d \frac{1}{2} \rho_{air} \cdot H \cdot D \cdot AWS_x{}^2 \tag{2}$$

The resistance coefficient of the idling rotor, C_d, is estimated to be 0.5 (Kramer, 2016). AWS_x is the apparent wind speed in the ships longitudinal direction at the hight of the rotor.

Figure 53c-d in the Appendix list the resistance components that are subtracted from the measurements, including the idling rotor drag. The rotor drag can appear to be large in comparison to the superstructure resistance, but then it should be noticed that the superstructure drag does not include the wind speed from the ships forward motion, as per ISO standard, whereas this component is included in the rotor drag.

3.5 Power correction

The correction of propulsive efficiency due to the added resistance corrections and idling rotor resistance is derived using the Direct Power Method according to the ISO standard using the assumed load variation factor stated in Table 1. (See the ISO 15016 standard for a detailed description of the Direct Power Method.)

The corrected power is listed in Appendix 1, Figure 53d.

3.6 Baseline

Figure I shows the speed power curve from the ship's towing tank test (MARIN Report No 27920-3), together with the speed trial runs with the rotor turned off and the power corrected according to ISO 15016. (Run 1 and 11 is evaluate as conventional double runs with wind averaging, the others as single runs.) The model test curve has been shifted in the vertical direction along with the ISO procedures. The shape of the shifted model test curve is used in the rotor evaluation of the performance in the next section.

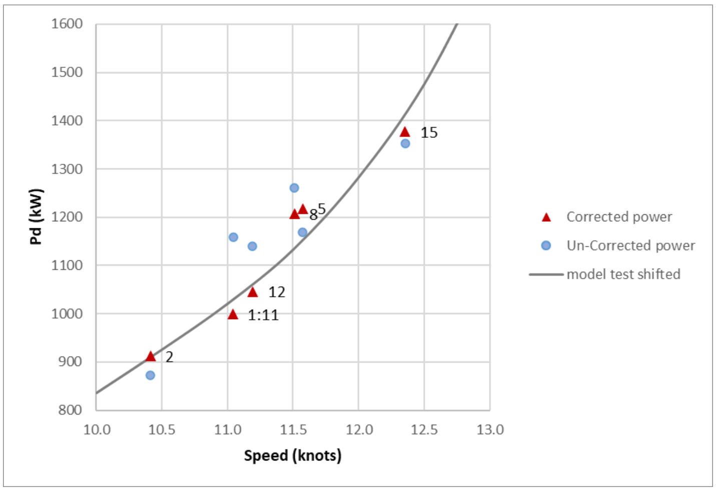


Figure I. Runs without rotor, corrected according to ISO 15016.

3.7 Rotor evaluation

The principle of the rotor evaluation is to compare single runs *with and without* rotor at the *same wind angle*. Section 6.2 discusses this approach further. Figure J and Table 7 gives a comparison of the speed and corrected power between the runs with and without rotor. Recall that three runs were performed for each wind direction. Each sequence started with a run without rotor (red circles in Figure J). For the second run, the rotor was turned on. It is seen in Figure J that this made the speed to increase. As a consequence of the increased speed, the power is decreased somewhat, due to higher propeller efficiency when off-loading. During the last run in each sequence, it was attempted to get back to the no-rotor speed by adjusting the propeller pitch. It is however rather difficult to control the speed of a ship to a high degree of accuracy. The natural variation in wind and waves makes the ship's speed to vary. The speed measurements displayed in the bridge is scattered. It is not until the recorded speed has been averaged over longer time that the new speed figure can be obtained. Therefore, it is a guess work to find the suitable power setting for the last run to match the right speed.

The results in Figure J and Table 7 gives the direct result of the trial, but it is hard to interpret. In Chapter 4, the result is normalised to give representative power savings for a given speed.

Table 7 Speed and corrected power from speed trial.

	With and without rotor runs - when power was constant between the runs		With and without rotor runs - when speed was constant between the runs	
AWA	Δ STW	Δ Pd	Δ STW	Δ Pd
deg	knots	%	knots	%
99	0.16	-7.8%	0.33	-7.7%
75	-0.13	-17.8%	0.50	-3.9%
40	-0.17	-17.7%	0.36	-5.1%
30	0.07	-1.1%	0.30	2.0%
307	-0.23	-15.1%	0.30	-1.2%

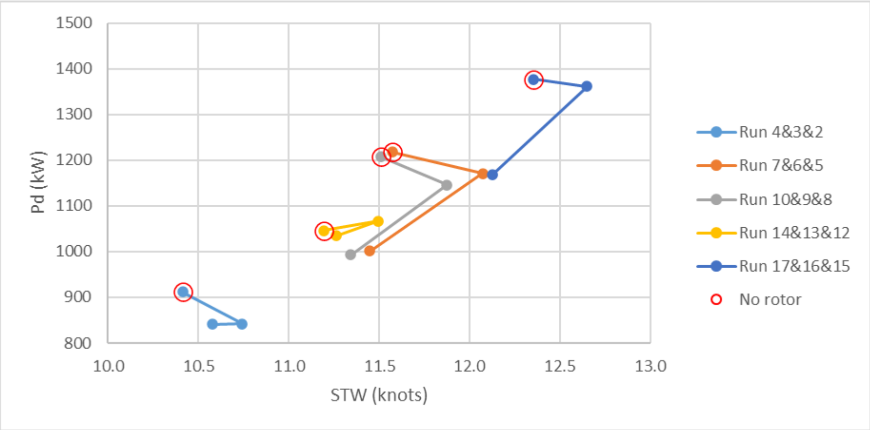


Figure J Speed and corrected power from trial

4 Rotor performance analysis

The result of the trial presented in the previous chapter showed that the rotor is able to both increased the speed as well as reduce the propulsion power. In this chapter, the trial result is normalised such that a power reduction for a given ship speed can be presented. Two alternative normalisation methods are used, and the differences are discussed in Chapter 6.

4.1 Normalisation Method 1

To derive the power difference at a nominal speed V_{ref}, the corrected trial power is interpolated to V_{ref}, using the shape of the ship's baseline curve. (The base line curve was derived in Section 3.6). This is done by fitting a 3rd order polynomial to the baseline curve and shift it vertically, as Figure K indicates.

The derived power difference is corrected to a nominal wind speed using:

$$\Delta P_{TWS_{ref}} = \Delta P \cdot \frac{TWS_{ref}^{\;2}}{TWS^2} \cdot \frac{\rho_{a\,ref}}{\rho_{a\,trial}} \tag{4}$$

where TWS_{ref} is the reference wind speed and TWS is the true wind speed during the sea trial, at the same height. The wind variation over height is computed according to ISO 15016 using exponent 1/7. $\rho_{a\,ref} = 1.24\ \mathrm{kg/m3}$.

The resulting power savings are given in Table 8.

Normalisation Method 1 includes several simplifications, which will be discussed further in Chapter 6.

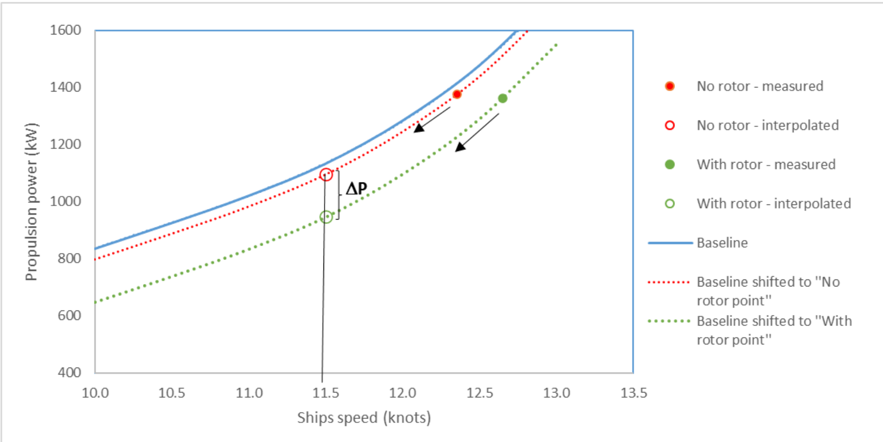


Figure K. Example of how speed trial result is extrapolated to nominal speed using the shape of the Baseline curve.

Table 8. Method 1: Power reduction derived from speed trial and normalized to reference ship's speed 11.5 knots. "Gross" means without considering power consumption from rotor.

	Trial wind condition				Ship's speed 10 knots	
Run	**AWS**	**AWA**	**TWS**	**TWA**	**ΔPd Gross** trial wind condition	**ΔPd Gross** TWS=10m/s
	m/s	**deg**	**m/s**	**deg**	**kW**	**kW**
3	6.5	98	9.1	135	131	205
6	9.7	76	10.2	112	202	250
9	15.3	41	11.5	62	166	162
13	14.5	30	9.8	47	51	68
16	10.6	59	9.1	263	150	231
4	6.1	99	8.8	137	101	168
7	9.7	75	10.0	110	186	239
10	14.8	40	11.0	60	174	186
14	14.3	30	9.6	47	27	37
17	10.6	53	8.4	271	120	217

4.2 Normalisation Method 2

In Method 1, the translation of a speed increase to a power decrease is done by shifting the power curves. This does not fully account for the changed propulsive efficiency when the propeller is unloaded due to the wind propulsion. A second simplification in Method 1 is that the changed apparent wind due to a changed ship speed is not accounted for. In order to include these effects, a second normalisation method is introduced. It makes use of a 1DOF speed-power prediction program, which can model the relation between speed, power and the change in propeller efficiency due to changed speed or propeller load. The propeller characteristics of Wageningen C 4.40 is used to model the propeller. The process follows the present steps:

1. Ensure that the output of the speed-power prediction program is equal to the Baseline curve (the ship's calm water speed-power curve at the actual loading condition, without rotor)
2. Use the speed-power program to find the additional force in the longitudinal direction that matches the change in speed AND corrected power between two runs *with* and *without* rotor. That force was the rotor thrust, *T* in the run with rotor.
3. The thrust coefficient is derived by

$$C_t = \frac{T}{\frac{1}{2}\rho_a \cdot H \cdot D \cdot AWS^2} \quad (5)$$

   with AWS measured at the trial and translated to mid-hight of the rotor and using 1/7 power law.
4. Ct is regressed against AWA using polynomial curve fitting (Figure L).

5. For the nominal condition (ship's speed 11.5 knots, TWS_{10m}=10m/s, air temperature 15 deg), the apparent wind is computed for a range of wind directions, and the rotor thrust T is computed using the C_t-polynomial.
6. The speed power prediction program is executed both with and without the rotor thrust (entered as a reduction of resistance) and at the nominal speed. The difference in the resulting power is denoted Gross Power Saving. This represents the hydrodynamic power saving.
7. The rotor power consumption, as measured during the trial, is subtracted from the Gross Power Saving to give the Net Power Saving. It is assumed that this number include transmission efficiency.

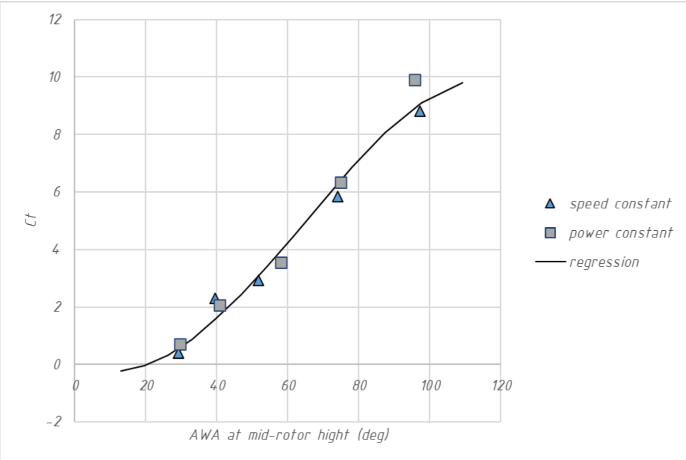


Figure L. Thrust force coefficient derived indirectly from sea trial

4.3 Results

The resulting gross saving (power saving without considering the rotor power consumption) from Method 1 and Method 2 are compared in Figure M. The conclusions on methodology is further discussed in Section 6.3.

The derived net power saving at the nominal condition is given in Figure N. At true wind speed 10 m/s and ship's speed 11.5 knots, the rotor gives a net power saving for apparent wind angles larger than 30 degrees, and reaches up to 15% saving at the most favourable angle.

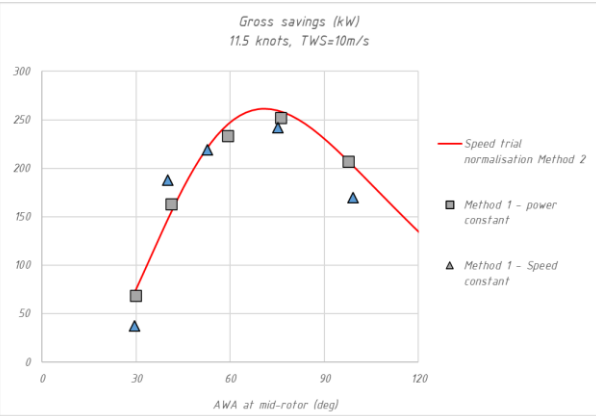


Figure M. Power savings derived with normalization method 1 and 2 at nominal conditions. Reference wind speed 10m/s at 10m above sea.

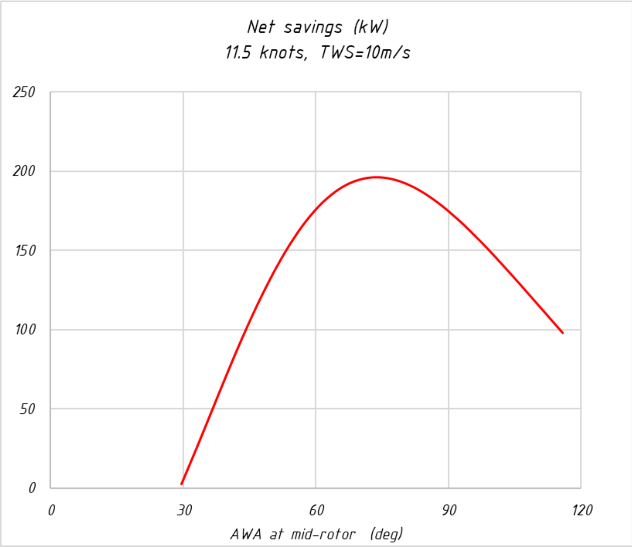


Figure N Power savings derived with normalization method 2 at nominal conditions. Reference wind speed 10m/s at 10m above sea.

5 In-service fuel saving

The following sections describe the methodology applied to estimate the power saving due to the rotor for the given routes.

In short, the procedure is outlined as follows:

- Calibrate digital models of the ship, propeller and rotor against sea trial.
- Predict the required power to reach the intended speed for a matrix of environmental conditions, using an in-house Velocity Power Prediction (VPP) program. The VPP model is presented in section 5.1.
- Assembly statistics of the environmental conditions that the vessel will encounter along the route over time.
- Perform route simulations using Monte Carlo technique over combinations of environmental conditions along the route to estimate statistical properties of route energy requirement.

5.1 Power prediction

5.1.1 Ship and propeller models

For each unique environmental condition encountered by the vessel it is necessary to predict the power requirement to reach the intended speed. A quasi-static force equilibrium is found at the intended speed, at which the propulsive and rudder forces are in equilibrium with hydrodynamic and aerodynamic forces. This equilibrium equation is set up in 4 DOF (Degrees of Freedom) including surge, sway, roll and yaw as follows:

$$[Fx, Fy, Mx, Mz] = f(n, \delta, \varphi, \psi)$$

Where $[Fx, Fy, Mx, Mz]$ are total force and moment residuals on the vessel in surge, sway, roll, and yaw respectively, n is the propeller rpm, δ is the rudder angle, φ is the heel angle and ψ is the leeway angle. The problem is a multi-dimensional root-finding problem and is solved iteratively, ultimately finding the required input parameters to generate a zero vector as output.

The function f consists of a set of force calculation routines, each one responsible for calculating a subset of the total force acting on the vessel given the current input parameters. The following force calculation routines has been used in this report:

- **Calm water resistance**

The speed-power curve in the actual service condition was first derived by shifting the model test curve for ballast draught (MARIN 2016) to fit the sea trial measurements without rotor (Figure I). The design draught model test curve was adjusted to maintain the same power to displacement ratio between ballast and design draught as in the model test. Finally, resistance curves were derived using the propulsive efficiency η_D from the model test.

- **Added resistance in waves**

Spectral superposition of R_{AW} (found from model tests in regular waves from SSPA database) and wave spectrum (ITTC) to find mean added resistance in an irregular sea state.

- **Manoeuvring and rudder forces**

Manoeuvring forces based on bis system model in Norrbin (1970). The forces on the hull and rudder due to drift and rudder angles are introduced in the ship simulation tool in terms of manoeuvring coefficients. The manoeuvring coefficients used is extracted from SSPAs database of manoeuvring model tests.

- **Propulsive forces**

The propulsive factors are taken from the model test report (MARIN 2016). The propeller is modelled as a Wagening C 4.40 with constant pitch 1.0. This simplification is assumed not to have any impact on the result, since the propeller model only needs to predict the slope of the propeller efficiency correctly. The chosen propeller model is supposed to represent the actual propeller well in this respect.

The propulsive set-up is verified by comparing the predicted power and shaft rate with the sea trial baseline runs.

- **Superstructure aerodynamic forces**
  The wind resistance coefficient is the “Handy size bulk carrier” from the ITTC procedures (ITTC 2021).

- **Wind propulsor model**

A quasi-static force model of a generic rotor sail is used for the route simulations in this report

- Apparent wind is calculated, including effects from the Atmospheric Boundary Layer (ABL) in accordance with ITTC recommended profile (ITTC 1984).
- Wind propulsor force coefficients are derived as detailed in Section 5.1.2.
- Force contribution in vessel coordinate system is calculated based on apparent wind, aerodynamic coefficients and geometry.

5.1.2 Rotor model

The rotor model is derived with the following process:

The starting point is lift and drag curves for a rotor of the actual aspect ratio derived using full scale CFD simulations (Li, 2011). In these CFD simulations, the rotor is standing on a symmetry plane, i.e without any ship hull. The presence of the ship hull influences the rotor performance in varying degree depending on wind direction. Therefore, the ideal rotor model needs to be calibrated to the measured speed trial results. This is done by multiplying the force coefficient C_x of the ideal rotor with a correction factor c, which is a function of apparent wind direction.

The correction function is derived as a polynomial curve fit which coefficients are found by minimizing the difference between the tuned rotor thrust force and the thrust force from the regression of the speed trial results (see section 4.2).

The same correction is applied to the side force, assuming that the ideal rotor Cl/Cd is preserved. This is an assumption, but since side forces is not measured at the speed trial, it is the best possible assumption. However, the magnitude of the side force has only a marginal effect on the power gain for the current case.

The rotational speed of the rotor is set based on interpolation in tabular values with respect to apparent wind speed and direction. The tables are derived by data processing of the ships logs since the rotor was installed.

The power required to operate the rotor is a function of rotor rotational speed, also derived from the logs.

The rotor model is turned off according to table of rotational speed versus apparent wind retrieved form the ship's logs. In head wind, the idling rotor gives an added resistance according to equation (2).

5.1.3 Power saving

The speed power predictions are executed both with and without the rotor thrust at the nominal speed. The difference in the resulting power is denoted Gross Power Saving. This represents the hydrodynamic power saving. Including the power consumption from spinning the rotor gives the net power saving.

5.2 Route analysis method

The route simulation tool uses a Monte Carlo technique over combinations of environmental conditions along the route to estimate statistical properties of route energy requirement. The method is described in by Olsson et.al (Olsson 2020).

The methodology entails the following limitations and assumptions:

- No route optimisation with respect to weather or current.
- The rotor will be in use whenever wind condition allows, according to the rpm-wind table mentioned above.
- When rotor is used, main engine power will be reduced to keep the prescribed ship speed.
- The main engine is assumed to always deliver enough power and torque to reach the intended speed, i.e. no involuntary speed reductions.
- Voluntary speed reductions are not accounted for.

The routes are divided into legs, as shown in Figure O. Appendix 1. For each leg on the route, a discrete joint weather distribution (True wind speeds and True wind angles) is derived from wind statistics obtained from the ERA5 reanalysis dataset available in the Copernicus Climate Data Store (https://cds.climate.copernicus.eu). Each leg is treated independently, and leg-wise distributions are assumed to be uncorrelated.

5.2.1 Operational conditions for route simulation

The route analysis is carried out for the following conditions:

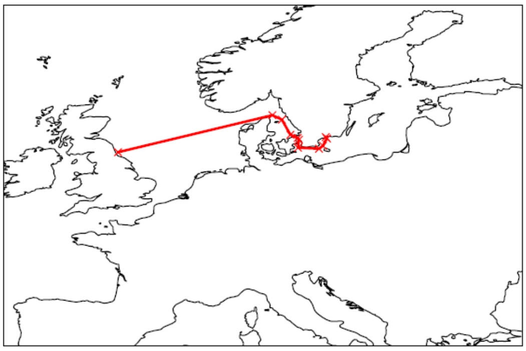
- Ship's speed 11.5 knots
- Laden draught: Tf/Ta=6.35m/6.35m
- Ballast draught: Tf/Ta= 3.3m/4.3m
- Density air 1.24 kg/m^3
- SFOC=200 g/kWh independent on engine load

Five routes are analysed. Route 5 is a generic setting based on the EEDI weather matrix (IMO 2021). The routes are selected based on ship's the expected voyages the coming years, following the same trade pattern as other vessels in the ship owner's fleet. The distribution between these routes over a year is given in percentage in the table, weighted against their length. The weights are estimated by grouping similar voyages, for example voyages between the Netherland or western Germany to Sweden are counted as Karlshamn-Vlissingen and so on. Voyages that did not fit with any of the routes 1-5 were categorized as EEDI-route.

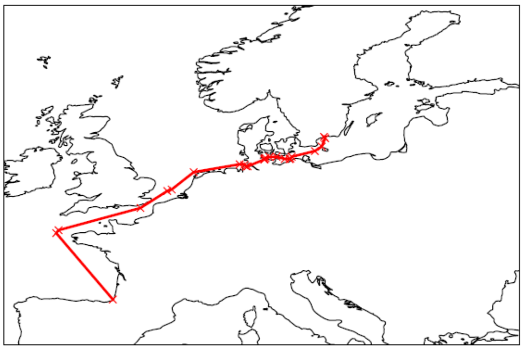
The wind statistics for the routes are presented in Figure P and Figure Q, and in more detail in the Appendix.

Table 9. Routes for analysis

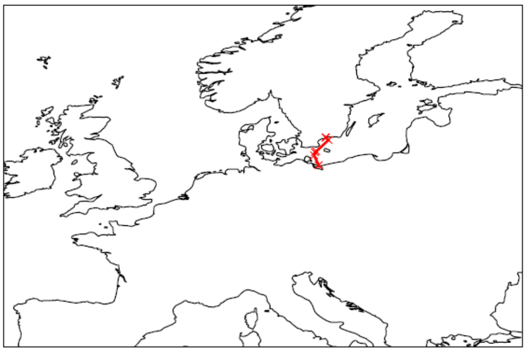
	Share	Outbound	Inbound
Route 1	14%		
Laden		Karlshamn	Sunderland via Skagen
Ballast		return	
Route 2	18%		
Laden		Karlshamn	Pasajes via Kiel
Ballast		return	
Route 3	2%		
Laden		Karlshamn	Swinoujscie
Ballast		return	
Route 4	57%		
Laden		Karlshamn	Vlissingen
Ballast		return	
Route 5	9%	EEDI weather	



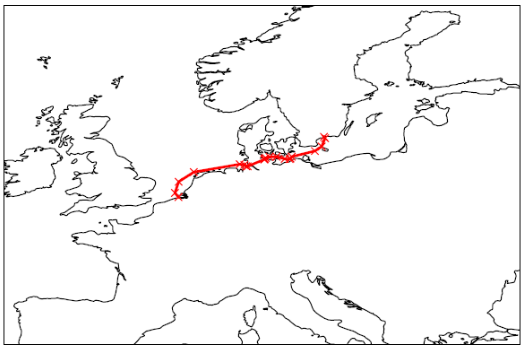
Karlshamn Sunderland via Skagen



Karlshamn Pasajes via Kiel



Karlshamn Swinoujscie



Karlshamn Vlissingen via Kiel

Figure O. Routes

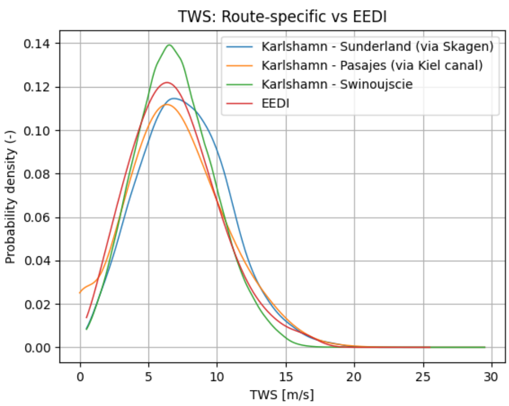


Figure P The probability of true wind speed on the routes from external weather source.

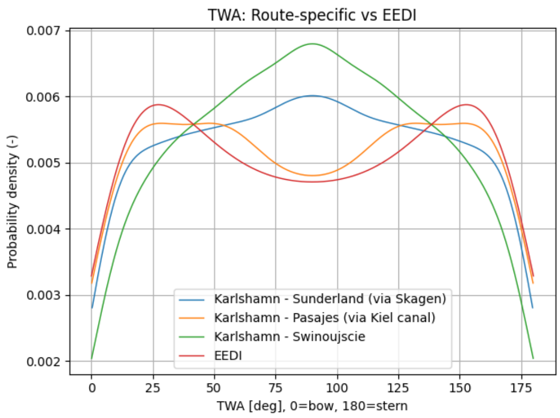


Figure Q The probability of true wind angle relative to ship heading, from external weather source.

5.3 Results

5.3.1 Power saving at all wind conditions

The power prediction model can now be used to derive the power saving at all wind conditions, as presented in Figure R.

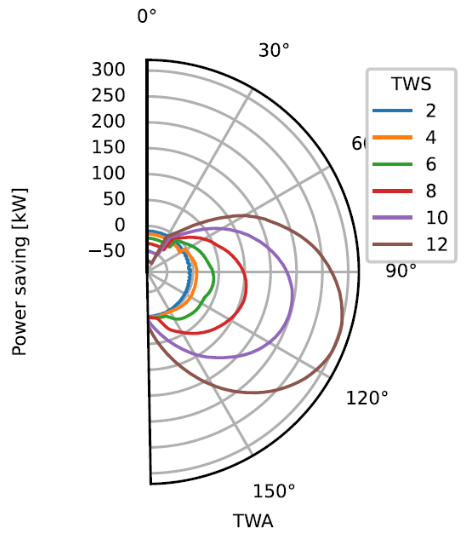


Figure R. Net power saving at ship's speed 11.5 knots. Polars based on performance prediction calibrated against sea trial. (TWS in m/s)

5.3.2 Power saving on the route

The average power and fuel savings are given in Table 10 and Figure S. This represents the average value of letting the ship sail the route 100 000 times in randomly chosen weather conditions based on weather statistics from the full year of 2019. Some days the weather will be favourable with large power savings, some days it will be adverse. The probability distribution curves are shown in Appendix 1.

Largest power saving in is achieved on route Sunderland to Karlshamn. On this route the prevailing winds are from stern quarter, where the rotor works best.

The route Karlshamn – Pasajes has a large portion of head wind, which is not favourable for the rotor performance. The power saving is therefore smaller for this route (It is assumed that the rotor is not used during the Kiel canal passage.)

On the route Karlshamn – Swinoujscie, the dominating winds gives wind from the beam, which is advantageous for the rotor performance. However, the wind speeds are generally lower in this sea area compared to for example in the North Sea.

Table 10 Average power and fuel saving predicted for routes

Route			power saving (%)	power saving (kW)	energy saving (MWh/trip)	fuel saving (ton/trip)	fuel saving (kg/nm)
1	Karlshamn	Sunderland via Skagen	2.5	48	3.0	0.60	0.83
	Sunderland	Karlshamn via Skagen	4.6	64	4.0	0.80	1.11
2	Karlshamn	Pasajes via Kiel	1.9	35	3.9	0.78	0.59
	Pasajes	Karlshamn via Kiel	2.9	40	4.6	0.92	0.70
3	Karlshamn	Swinoujscie	2.4	43	0.5	0.10	0.70
	Swinoujscie	Karlshamn	3.9	52	0.65	0.13	0.91
4	Karlshamn	Vlissingen	1.2	20	1.0	0.20	0.35
	Vlissingen	Karlshamn	3.5	43	2.2	0.44	0.76
5	EEDI weather	Design	2.2	33			0.58
	EEDI weather	Ballast	2.5	30			0.52

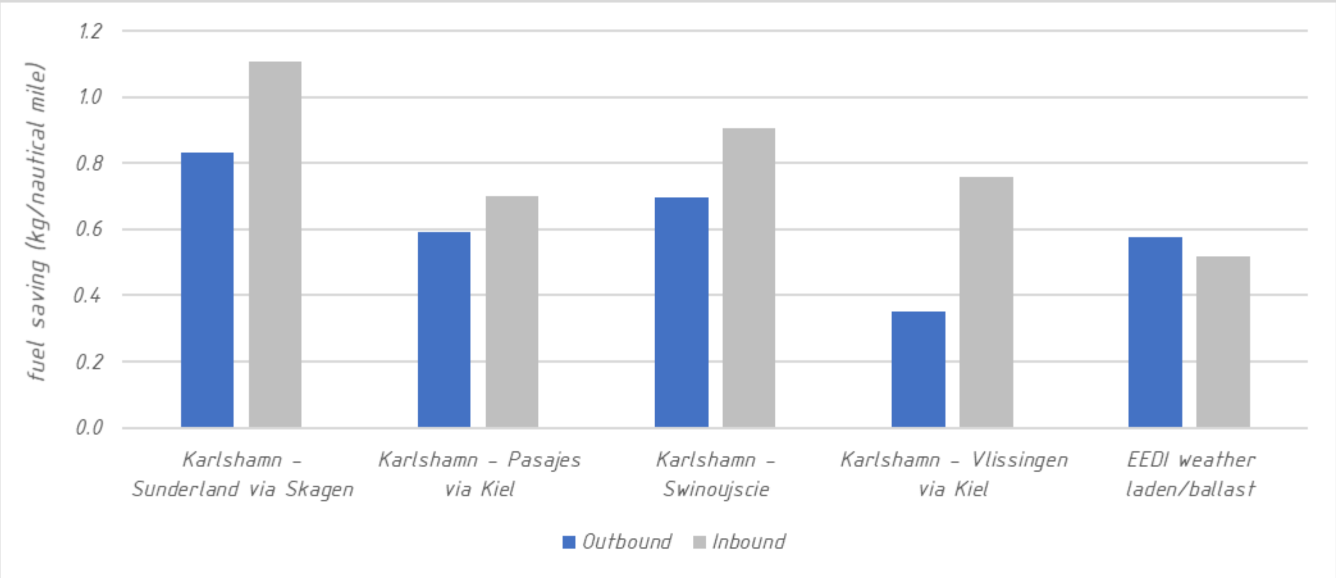


Figure 5 Average fuel saving per route

5.4 Yearly average saving

Based on the distribution of the voyages given in Table 10, the average fuel saving is 0.63 kg/nautical miles. With a total sailing distance of 57000 per year (2021) this means 36 tons fuel saving per year, corresponding to 113 tons CO2.

6 Discussion on evaluation methodology

6.1 The lack of double runs

According to sea trial standard ISO 15016, a sea trial should be carried out as double runs as in Figure T. This makes it possible to correct the measured speed over ground (SOG) for current, to derive an accurate measure of speed through water (STW). The reason for this procedure is that speed logs, which gives STW, are usually less accurate than the GPS, which gives the SOG.

The present trial deviated from the normal procedure and used the STW from the speed log directly. The motivation for this is that the purpose of the trial is to derive *relative* performance, i.e. with and without rotor. It is assumed that the speed log readings can give accurate enough *differences* between the runs with and without rotor.

By avoiding double runs, the trial program can be completed in less time, which is the main benefit.

A disadvantage is that the so called "wind averaging" procedure in the ISO standard cannot be used with double runs are omitted. The wind averaging method is useful to compensate for influence of the superstructure on the anemometer. This increases uncertainty of this trial.

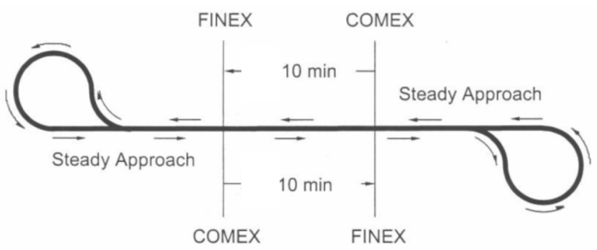


Figure T. Trial trajectory of one double run (ITTC 2017)

6.2 Rotor evaluation based on single runs

The testing principle employed in this project is that single runs *with and without* rotor at the *same wind conditions* are compared. The following list discusses the issues that could disturb the comparison:

- Difference in wind condition for runs that are compared. Figure G and Figure H in section 3.2 show the wind conditions of the runs with and without rotor that are compared. The largest difference within a triplet is 1.5 m/s (for run 10-9). This means that the ship's windage drag was larger for the run without rotor than the one with rotor. However, the superstructure resistance is compensated for by a correction of the power (see section 3.3). The air resistance coefficient is taken from the ITTC library and is not ship specific, which could introduce an error in the comparison. The possible error from this approximation is conservatively estimated to 10% of the air resistance. However, as can be seen in Appendix 1 Figure 53, the wind resistance correction is 7.5% of the total resistance for this run. This means that the possible error on the power difference is around 0.75%.
- The added resistance due to waves could potentially differ between the runs, since the speed is changed. The wave resistance was not estimated specifically in this trial, but according to experience is of the magnitude as the wind resistance in head waves. At larger wave directions, like in this trial, it is less. Assuming conservatively that the wave resistance is 10% of the total resistance, and the speed difference between runs is 0.5 knots. Assume further conservatively that wave resistance is proportional to speed squared. This then gives an error in the comparison between the runs of less than 1% on the power.

6.3 Normalization methods

The normalization Method 1, described in section 4.1, simplifies the following aspects that Method 2 accounts for:

1) The propulsive efficiency is not necessarily the same when moving along the power curve as when changing the net longitudinal force for a given speed (as when adding a rotor).
2) Correcting to a nominal ship speed and true wind speed also means that the apparent wind speed and angle is different.

Method 2 requires that the ship's resistance curve, propulsive factors and propeller characteristics are known or assumed. Based on the model test and tuning against the actual trial, good estimates can be done. A sensitivity check showed that the influence of these assumptions on the end result is small.

A comparison between the two normalisation methods is presented in Figure M on page 20 and in Figure U. It shows that the two methods correspond fairly well. The scatter is probably related to the poor precision uncertainty of the measurements.

Method 1 is simple and transparent and does not require any speed-power prediction program as Method 2 does. Therefore, it can be a useful method in praxis but should be limited to cases with small contribution of wind propulsion and when the sea trial wind speed is close to the nominal. Further research should be done on the limitation of Method 1 and Method 2 for more powerful wind propulsion installations.

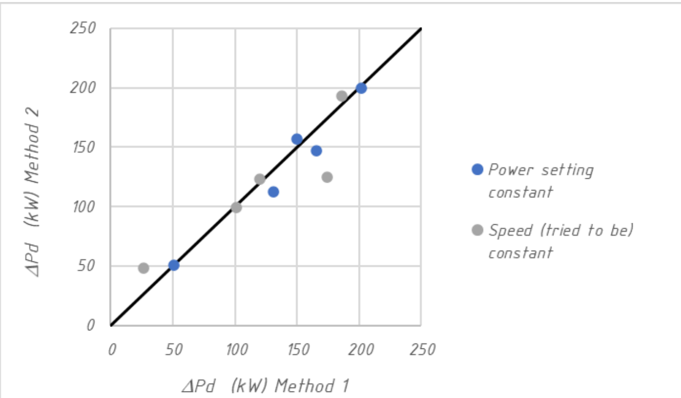


Figure U Normalization methods 1 and 2

6.4 Constant speed or constant power

The conventional ISO 15016 procedure prescribes that the power setting (propeller shaft rate and propeller pitch) is kept constant for both runs in a double-run. An alternative approach is to keep the speed constant between two subsequent runs by adjusting the power. The benefit would be to limit the need for correction in either Method 1 or Method 2.

In an attempt to compare the feasibility of the two approaches, the present sea trial program included both type of power settings.

The first observation is that it is, as expected, difficult to achieve a given speed in practice on the vessel. The ship's speed reading is constantly varying, and it is not until the end of a trial run that one can derive the averaged value. The ship's large inertia makes the response to a changed engine load setting very slow and therefore it is not possible to fine tune the speed by hand.

The second observation is that the result as presented in Figure M on page 20 and in Figure U does not show any benefit of either method in terms of scatter or difference between Method 1 and Method 2. Somewhat larger difference between Method 1 and Method 2 can be seen for the runs where constant speed was attempted, but it could just as well relate to measurement uncertainty.

There is an advantage of keeping the power setting constant when analysing with Method 2: even if the true propeller pitch setting is not measured accurately, at least it is known that it was the *same* setting in the two runs. This reduces some uncertainty.

Another advantage is that it is faster to conduct the trial with constant power, since the adjustment and trying to find the right speed takes some time.

Finally, the advantage of keeping the power constant is that it follows the ISO standard.

The conclusion is that constant power is recommended for WASP sea trials.

6.5 Speed trial uncertainty assessment

The bias uncertainty of a speed trial is stated in the ISO standard to be 2%. In the present work, the purpose is to derive a power *difference*, and then the bias error can be assumed to cancel out. The exception is the wind. A bias error of the anemometer will strike differently on the run with rotor compared to the run without rotor.

The precision error of speed trials in general is estimated by Werner (2020) and Insel (2008) to be around 7-8%. However, most of is this uncertainty relates to the fact that there are different sister ships tested, and trials conducted at different occasions.

Here follows an estimate of the uncertainty of the derived power difference, following ITTC 7.5-02-01-01 (Type A). <u>The authors do not claim it to be a complete uncertainty assessment, but rather an indication of the magnitude of the larger error sources.</u>

Variable	Comment, source of uncertainty	Uncertainty of variable (Type A)	Uncertainty of power saving
Heading	Standard deviation of time signal	1 deg	insignificant
STW	Standard deviation of time signal	0.1 kts	40 kW
FOC	Standard deviation of time signal	10%	115 kW
AWA	Standard deviation of time signal Disturbance of hull	5 deg	Secondary effects: hull air resistance, regression of thrust function in Method 2
AWS	Standard deviation of time signal Disturbance of hull Atmospheric boundary layer difference from 1/7 power law	0.5 m/s	20 kW (on the normalisation to given wind speed)
	Assumptions in the normalisation method. Assessed by varying the input.		small

The largest source of uncertainty is the standard deviation of the log and the fuel consumption readings. Fuel consumption measurements are less accurate that shaft torque meters, especially volumetric gauges. This could be the reason why the present trial result is more scattered than what has been seen for other WASP sea trials.

The anemometer also affects the evaluation uncertainty. One part is related to fluctuation of the natural wind and therefore, high frequency logging is preferred. The other part is the disturbance of the hull, which is more problematic as it is very difficult to assess. It is hard to measure the “true” apparent wind hitting the rotor sail, as all possible locations to place an anemometer is disturbed by the hull or the rotor.

The uncertainty analysis leads to the 95% uncertainty interval indicated in Figure V.

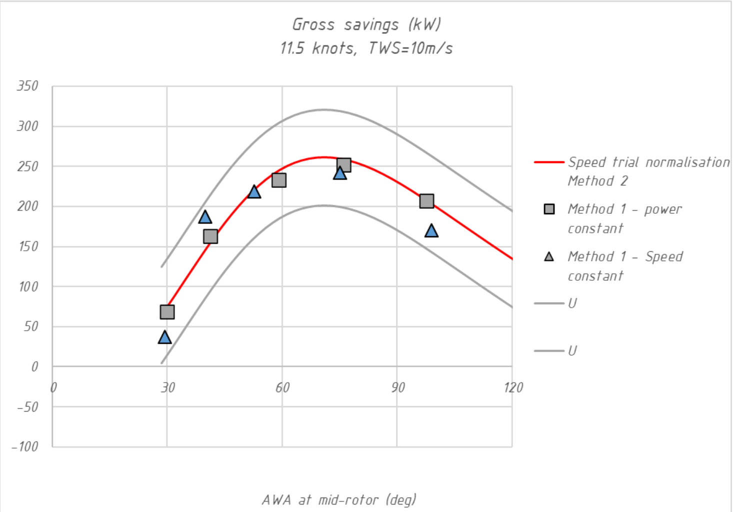


Figure V. Speed trial evaluation with estimated 95% uncertainty interval

6.6 Ship model uncertainty

Simulation models always include assumptions and simplification and cannot mimic the behaviour of complex ship system exactly. This introduces errors in the simulation results.

For the complete generalised model, the manoeuvring coefficients are estimated based on experience and the ducted CPP have been modelled as a conventional propeller, since there was no model test of CFD analysis done to extract the manoeuvring coefficient for the actual vessel. This is believed to have insignificant effect on the fuel saving results as the drift was found to be small even for the high wind speeds at the speed trial.

The process of calibrating the simulation model to the trial tests is believed to result in an accurate ship model for apparent wind angles between 30 and 100 degrees from the bow. The resistance that the rotor is assumed to generate in head wind is based on an empirical assumption of resistance of a cylinder. The uncertainty associated with this assumption, in particular the influence of the hull, should be investigated further using numerical tools.

6.6.1 Quality of correlation of the virtual ship model

Figure W compares the power saving predictions from the virtual ship model against the power savings derived from the sea trial using Method 1. There are a few outliers, which probably refers to the large uncertainty of the measurements. This diagram indicates the uncertainty that the present analysis can provide.

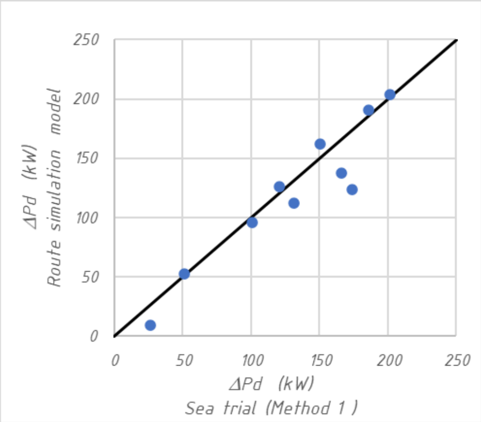


Figure W The power prediction model used for the routing analysis against the power saving from the trial, Method 1

6.7 Route simulation uncertainty

The weather statistics probably contributes to high uncertainty in the route simulation. The weather provider does not state any uncertainty levels for the data, though.

The largest uncertainty relates to the actual operation of the vessel and rotor. The annual power saving derived with the route analysis assumes that the rotor is used all the time when the wind conditions allows, i.e. no down-time due to maintenance etc. It is also assumed that the speed is kept constant, i.e. that the crew chose to adjust the engine power to keep the fixed speed when the rotor is in operation, rather than running at a fixed power and “save” time to port. If the latter happens, no fuel saving will be made.

After a longer period of operation, this report may be updated based on weather statistics and other operational data.

7 Conclusions

7.1 Result

A speed trial was performed on m/v Annika Braren in September 2021 with the purpose of verifying the power saving of the rotor.

The analysis shows that at true wind speed 10 m/s and ship's speed 11.5 knots, the rotor gives a net power saving when the apparent wind angle is larger than 30 degrees. The saving reaches up to 15% at the most favourable wind angle at 10 m/s.

The speed trial result is scaled up to give a prediction of the averaged in-service fuel reduction using a ship simulation model correlated to the actual speed trial measurements, a voyage prediction tool and statistical weather distribution.

It is estimated that the power reduction on typical routes is between 2% - 4.5%, corresponding to a fuel saving of 0.4-1.1 kg/nautical mile. For an average year of operation, the fuel saving potential is estimated to be 0.63 kg/nautical miles, which will give approximately 36 tons fuel saving per year, corresponding to 113 tons CO_2. This assumes that the rotor is fully operable at all times when wind permits, and that the additional thrust is used to reduce engine load and keeping the speed constants to 11.5 knots.

The mayor uncertainties of the trial result include the speed and fuel consumption measurements, and the wind measurement. The disturbance of hull to the wind measurement onboard the vessel may disturb the relation between the trial result, which is based on the on-board measurements, and the route analysis that scale up the result to yearly fuel savings, which is based on the natural undisturbed wind on the ocean. The drag if the rotor in when idling, for example in head wind condition or low wind speed, is based on a simplified empirical relation. Further calculations or measurements are required. The largest uncertainty is probably the way the wind assistance technology will be handled and operated in reality. If the device will be in-active due to maintenance, failure, safety or other issues, then the power saving will off course be less. The same applies if crew choose to use the additional thrust from the wind to increase the ship's speed instead of reducing the power. Utilising weather routing adapted to wind propulsion can on the other hand increase the saving.

7.2 Methodology

The standard ISO/ITTC speed trial procedures were followed to as large extent as possible. In contrast to normal procedures, the speed was measured using the ship's log and therefore no current correction was needed. The effect of the rotor was extracted by comparing single runs with and without rotor for the same wind condition.

In accordance with the ISO/ITTC standards, the power was kept fixed between the runs with and without rotor. Additionally, it was attempted to keep the speed constant between runs with and without rotor. However, this did not prove to be superior in any sense. It is recommended for future sea trials to keep the power setting fixed.

Two methods to normalise the speed trial results are proposed. The first method uses the shape of the ship's speed power curve to extrapolate to nominal condition. This method involves several simplifications including the effect on propulsive efficiency due to changed propeller load. The second method is more complex and makes use of a ship simulation model. The difference between the results of the two methods are well within the estimated uncertainty margin.

The proposed trial methodology is shown to be a feasible way to perform full scale verification for commercial vessels with wind assistance. With this approach a trustworthy result can be derived at a feasible cost, within a limited time frame, and using transparent, commercially available tools and established procedures.

7.3 Recommendations

It is recommended to log the wind speed on the route, the ship's fuel consumption and operability of the rotor for at least one year to complement this study.

Further research should be done on the limitation of Method 1 and Method 2 for more powerful wind propulsion installations.

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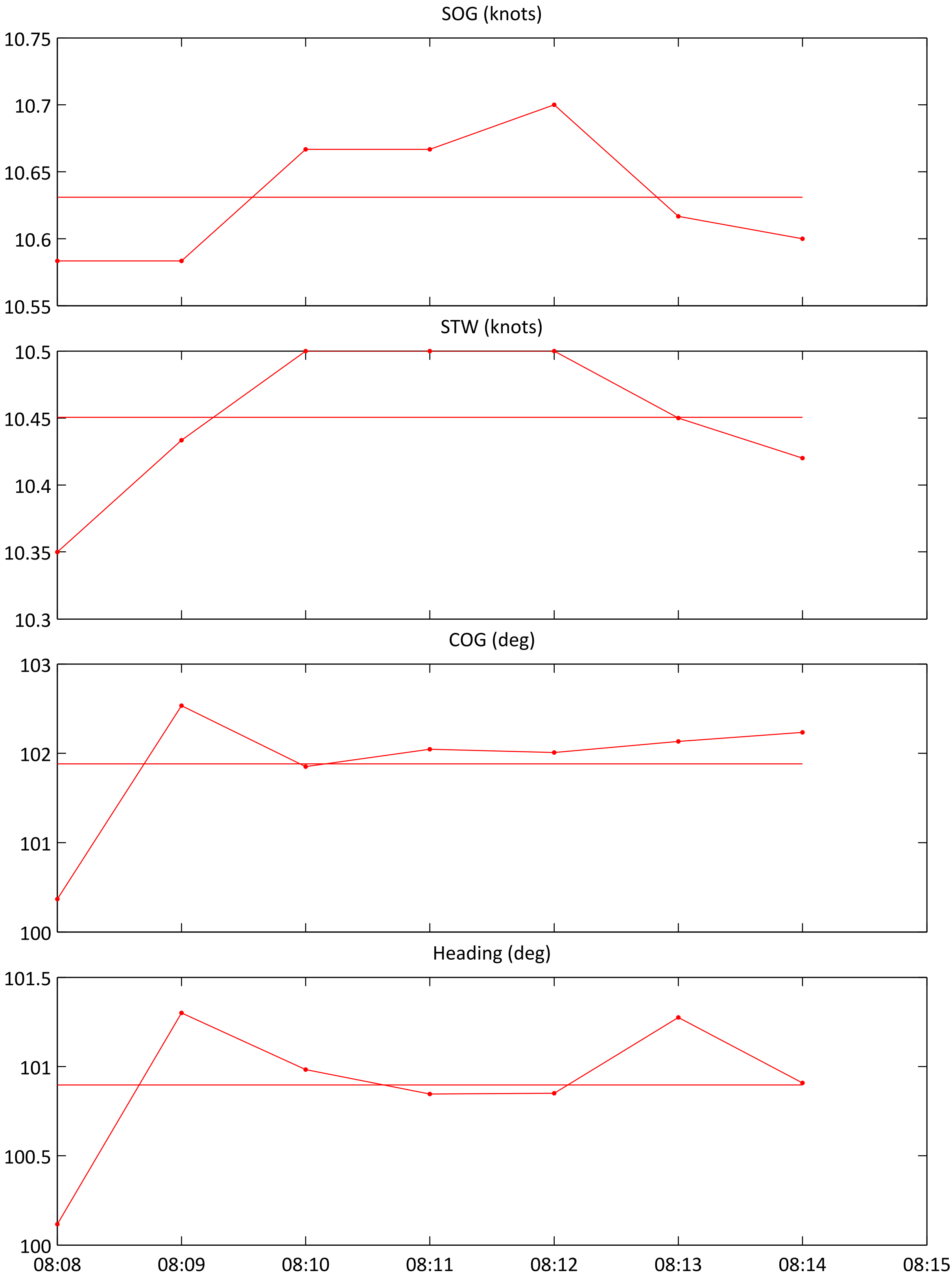
Appendix: 1

Figure: 1a

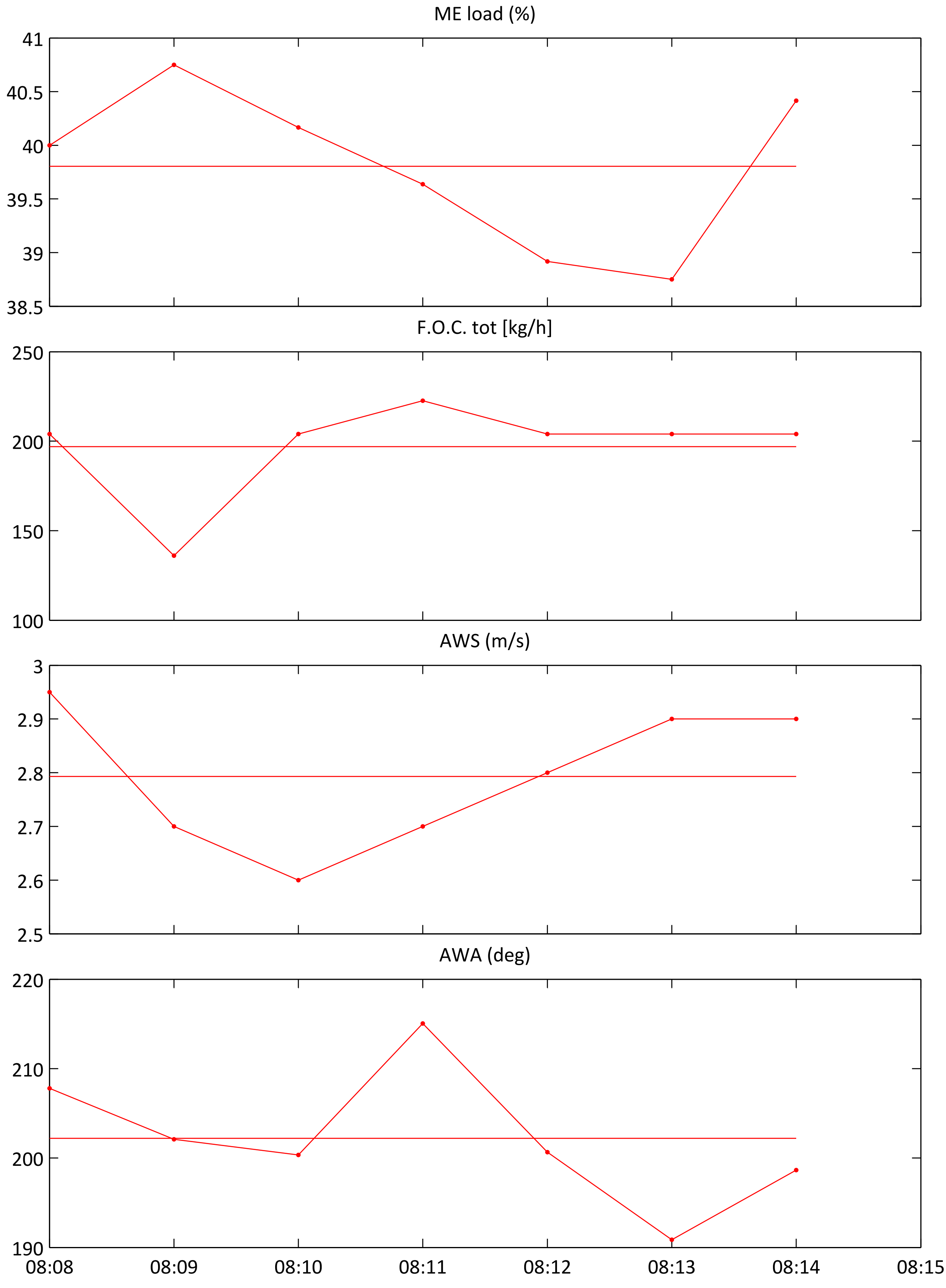
Run	Time start	Target True wind angle	Rotor	Heading (deg)	COG (deg)	STW (knots)	SOG (knots)	ME FOC (kg/h)	ME load (%)	pitch %	ME rpm
1	6:06	180	off	101	102	10.45	10.63	197	40	73	144
2	6:28	140		158	156	10.41	10.50	180	45	75	146
3	6:44	140	on	160	159	10.74	10.80	172	46	75	146
4	6:55	140	on	160	159	10.58	10.64	172	42	74	146
5	7:15	110		196	195	11.57	11.67	241	14	88	146
6	7:35	110	on	196	195	12.07	12.42	244	3	88	146
7	7:52	110	on	196	195	11.45	11.75	210	56	82	144
8	8:09	80		231	230	11.51	11.71	260	4	89	144
9	8:28	80	on	231	228	11.87	12.21	262	7	89	144
10	8:41	80	on	231	227	11.34	11.76	230	45	86	144
11	9:00	0		290	289	11.64	11.73	281	11	91	144
12	10:19	55		245	244	11.19	11.57	235	18	87	144
13	10:40	55	on	245	243	11.49	11.92	246	2	87	144
14	10:56	55	on	245	242	11.26	11.60	239	56	85	144
15	11:24	95		30	31	12.35	12.02	279	11	92	144
16	11:44	95	on	30	31	12.65	12.12	287	14	92	144
17	12:02	95	on	30	32	12.13	11.69	251	5	87	144

			at anemometer							
Run	***TWS (m/s)***	***TWA (relative ship)* (deg)**	**TWD (relative N) (deg)**	**AWA (deg)**	**AWS (m/s)**	**Rotor power (kW)**	**Rotor RPM**	**Rudder deg**	**wave H (m)**	**Computed Pd (kW)**
1	8.0	188	288	202	2.8	0.0	0.0			955
2	8.9	136	294	99	6.3	0.0	0.0	2	0.7	873
3	9.1	135	295	98	6.5	32.5	185.9	2		801
4	8.8	137	297	99	6.1	32.6	201.1	3		801
5	9.9	117	312	80	9.0	0.0	0.0	2	1.5	1169
6	10.2	112	308	76	9.7	62.3	259.4	2		1120
7	10.0	110	306	75	9.7	61.5	259.4	1		956
8	12.5	71	303	50	15.4	0.0	0.0	2		1261
9	11.5	62	293	41	15.3	60.8	259.2	1		1209
10	11.0	60	291	40	14.8	60.3	259.4			1054
11	9.8	0	290	0	15.8	0.0	0.0	0		1363
12	10.5	51	296	33	14.9	0.0	0.0	2		1140
13	9.8	47	292	30	14.5	61.4	259.5	2		1130
14	9.6	47	292	30	14.3	61.0	259.4	1		1097
15	9.7	265	295	300	11.1	0.0	0.0			1353
16	9.1	263	293	301	10.6	61.4	259.4	2		1329
17	8.4	271	301	307	10.6	60.8	259.4	2		1155

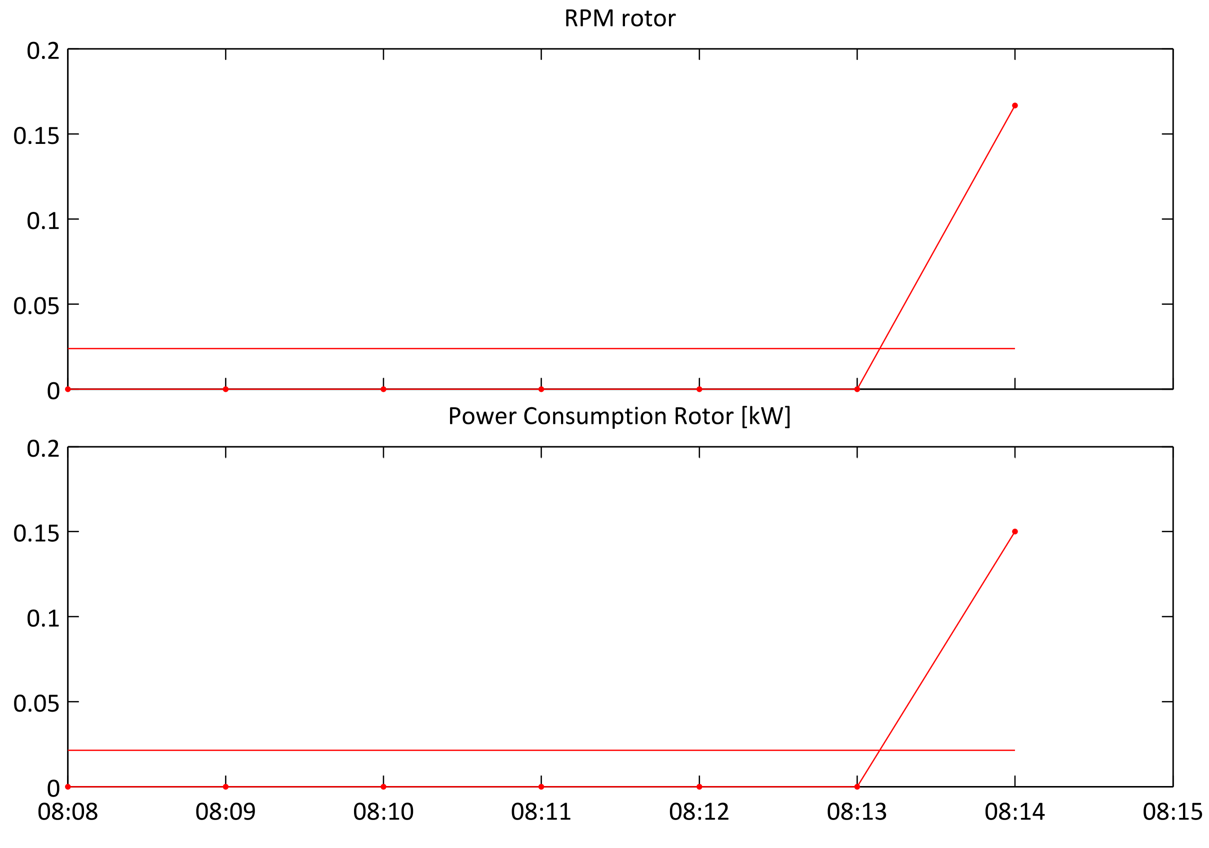
Run 1 Figure: 2



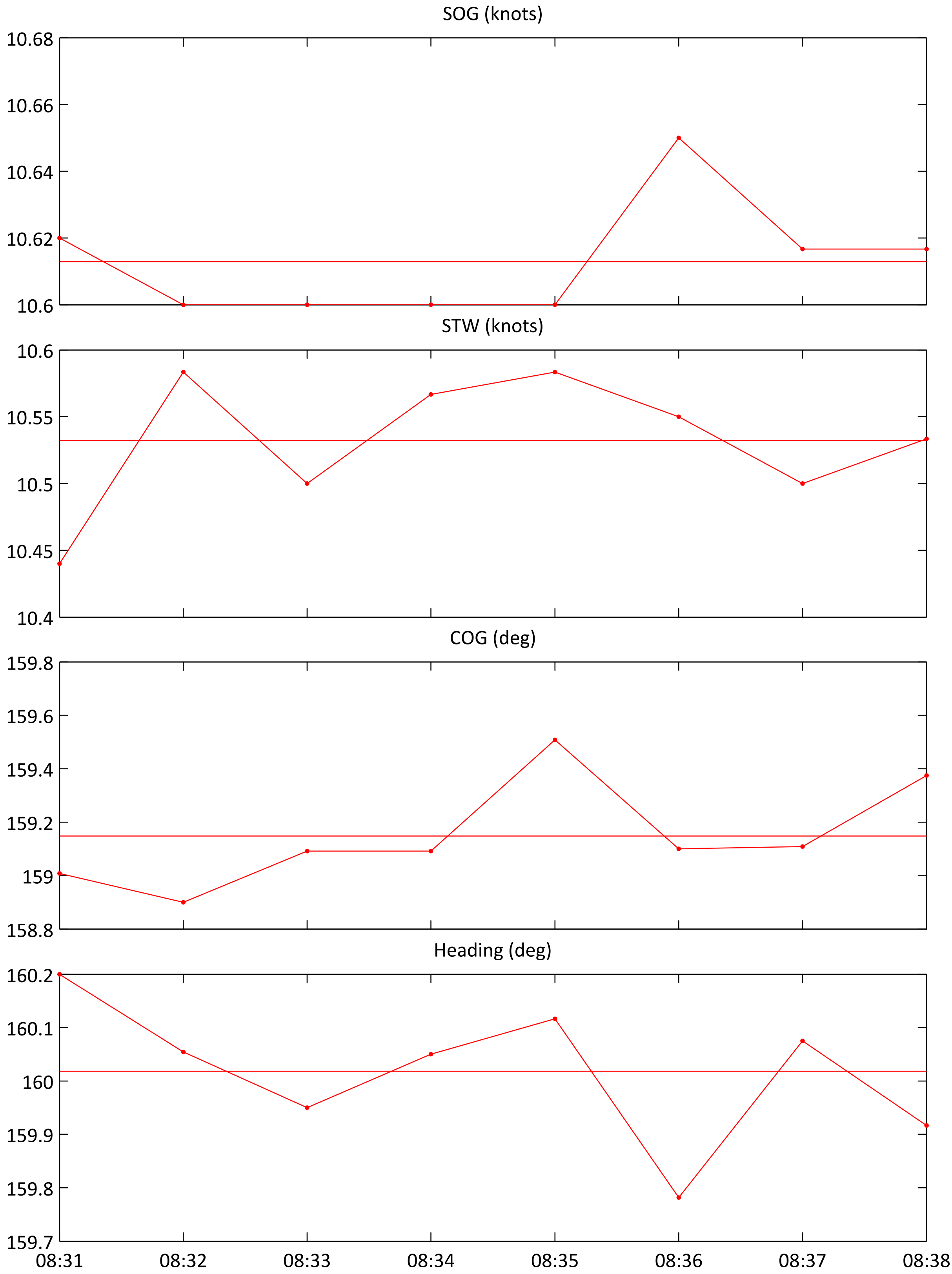
Run 1 Figure: 3



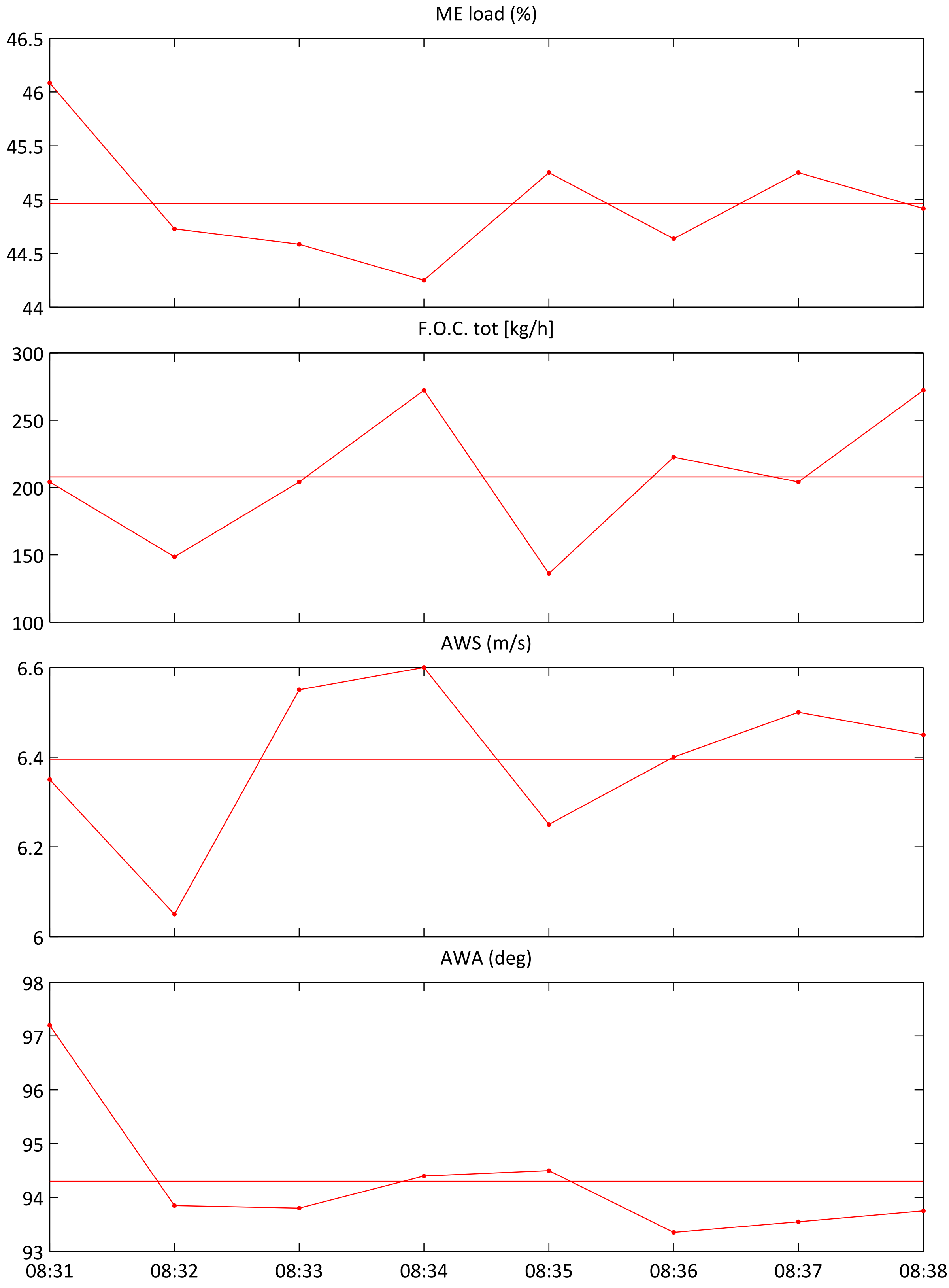
Run 1 Figure: 4



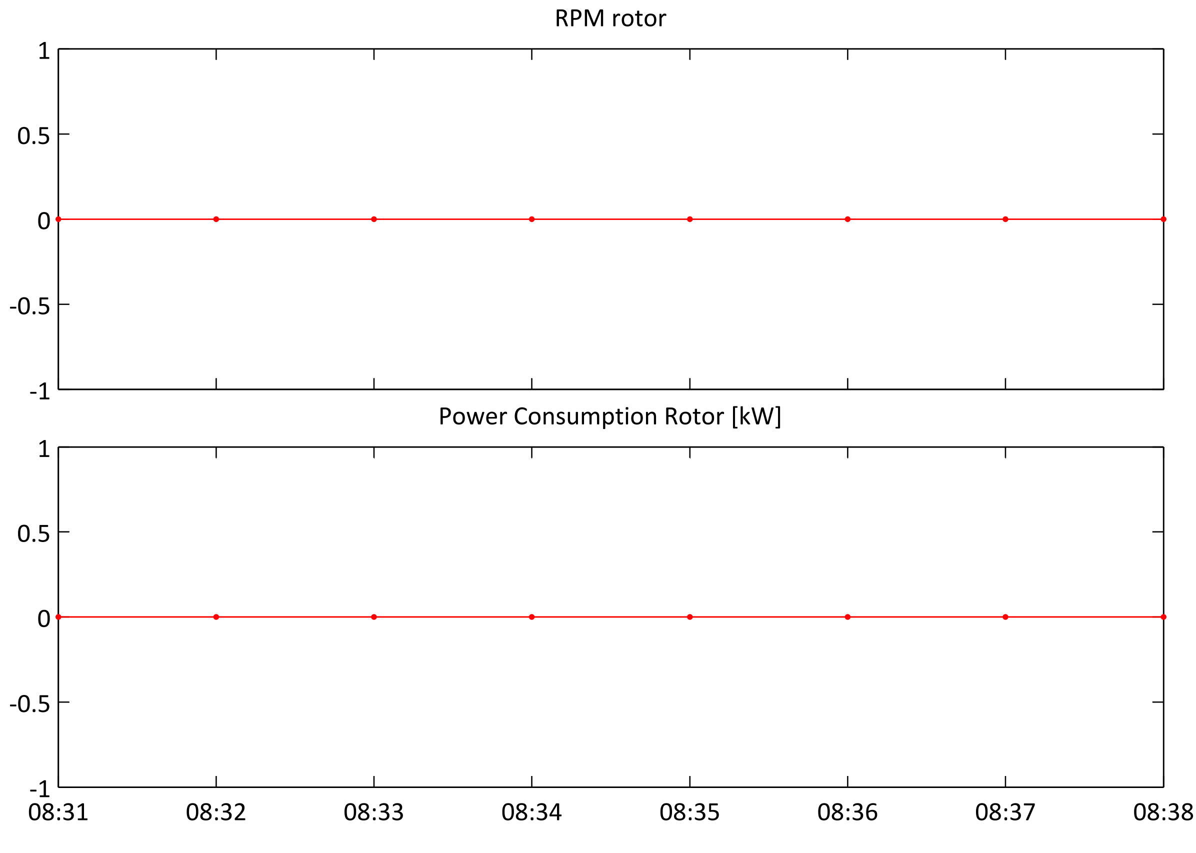
Run 2 Figure: 5



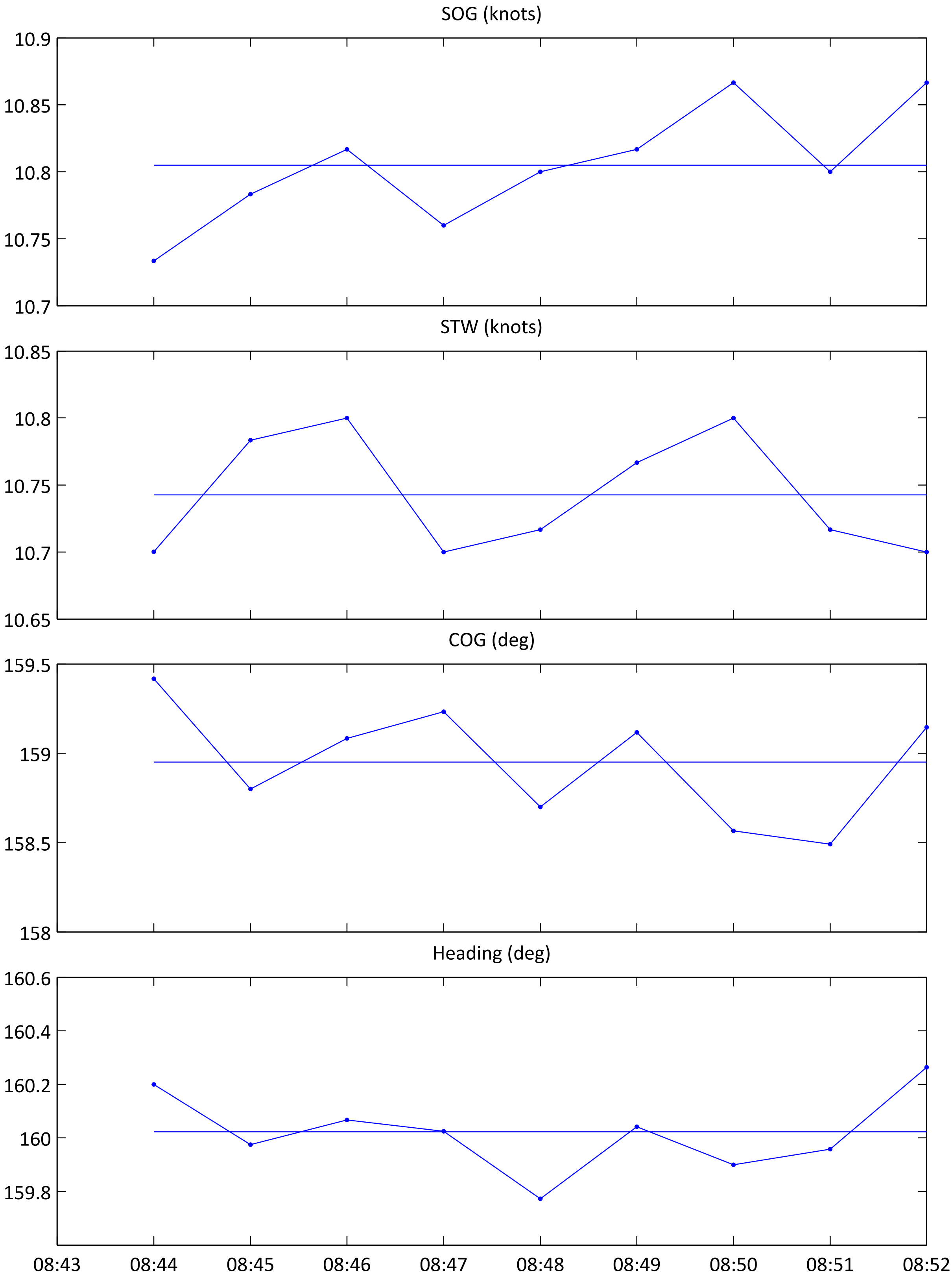
Run 2 Figure: 6



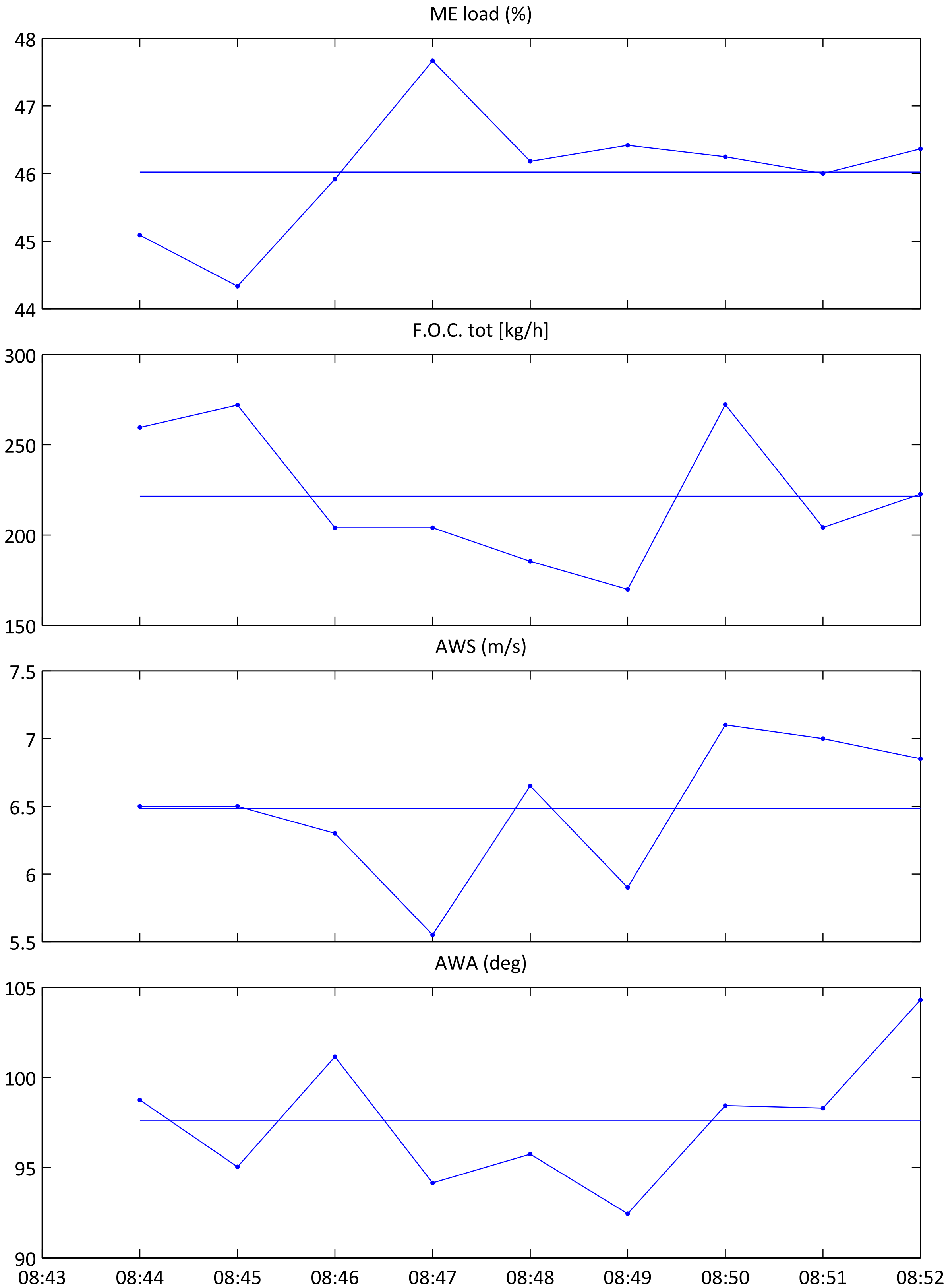
Run 2 Figure: 7



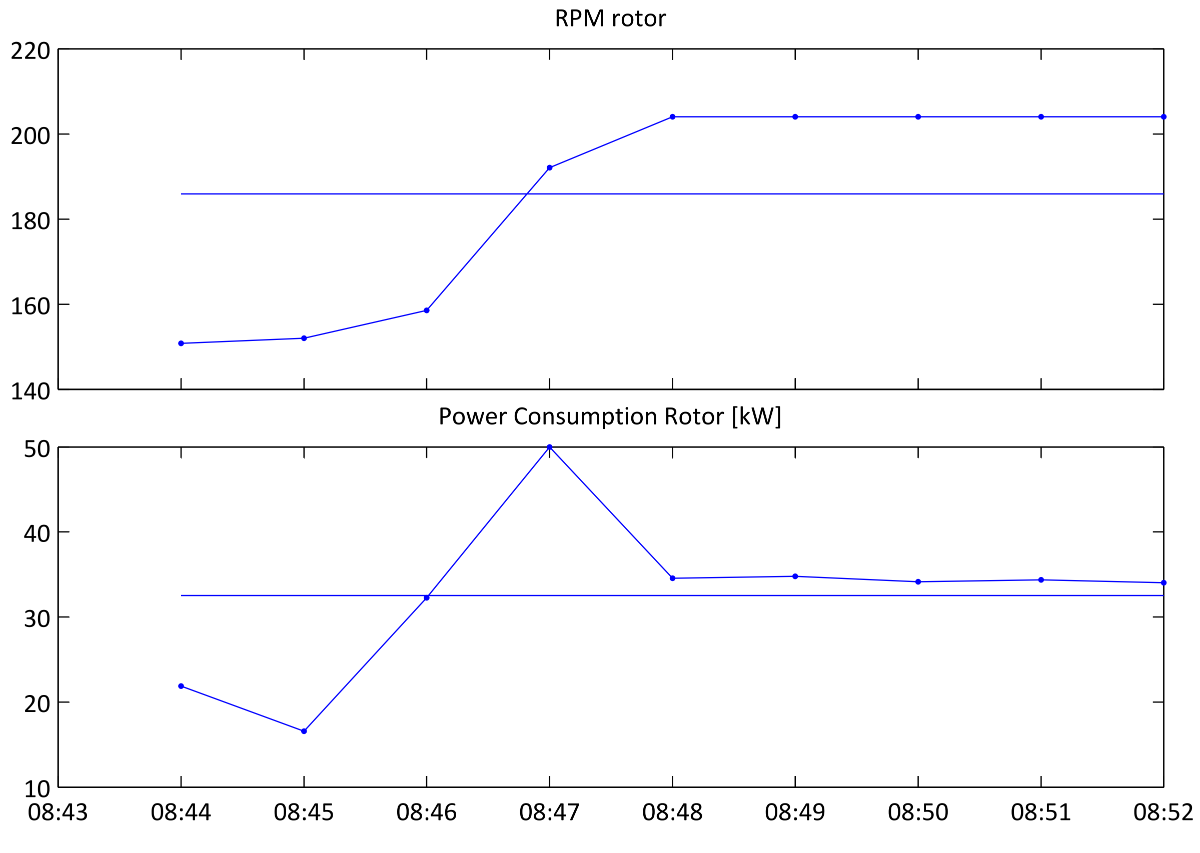
Run 3 Figure: 8



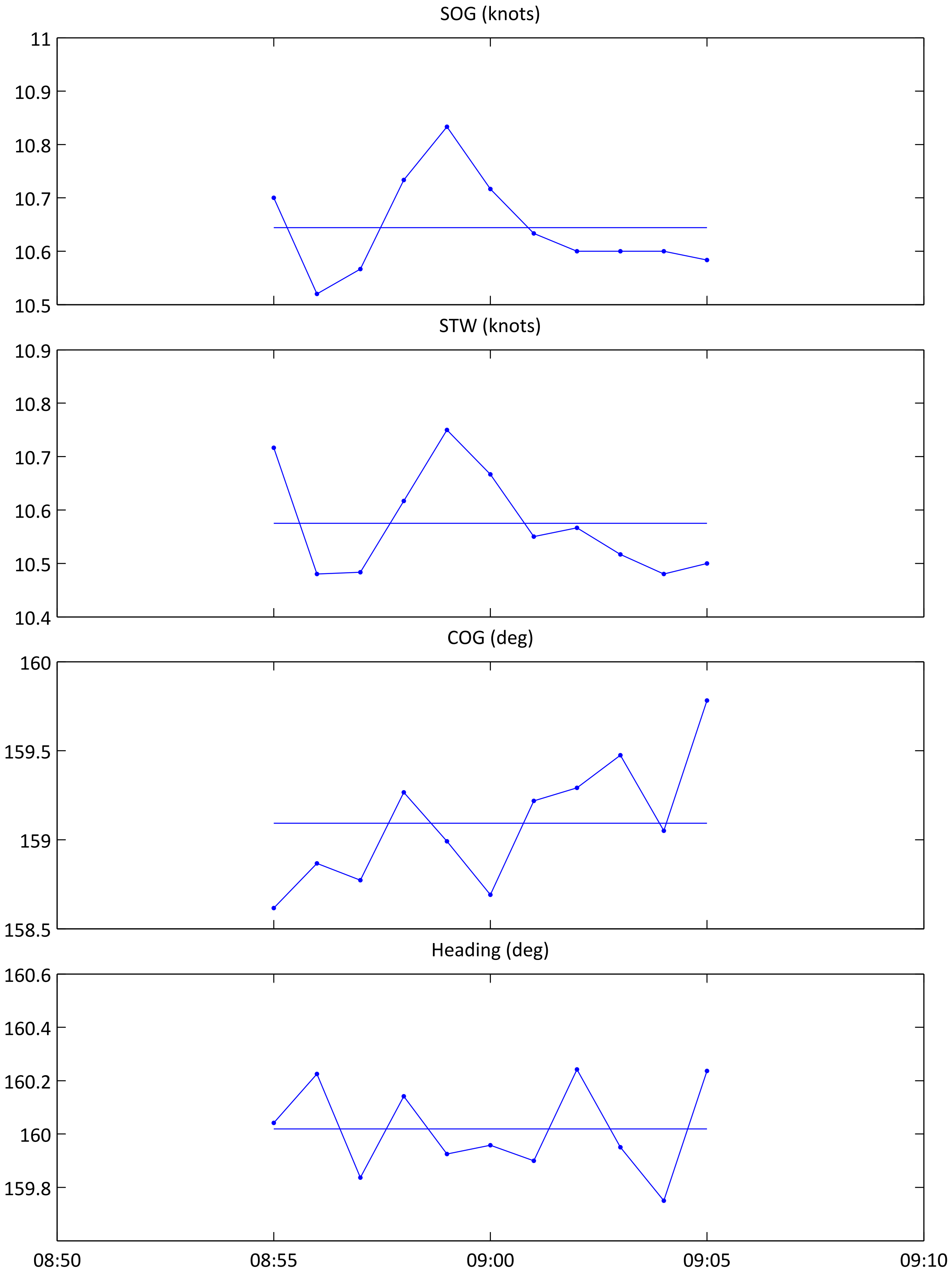
Run 3 Figure: 9



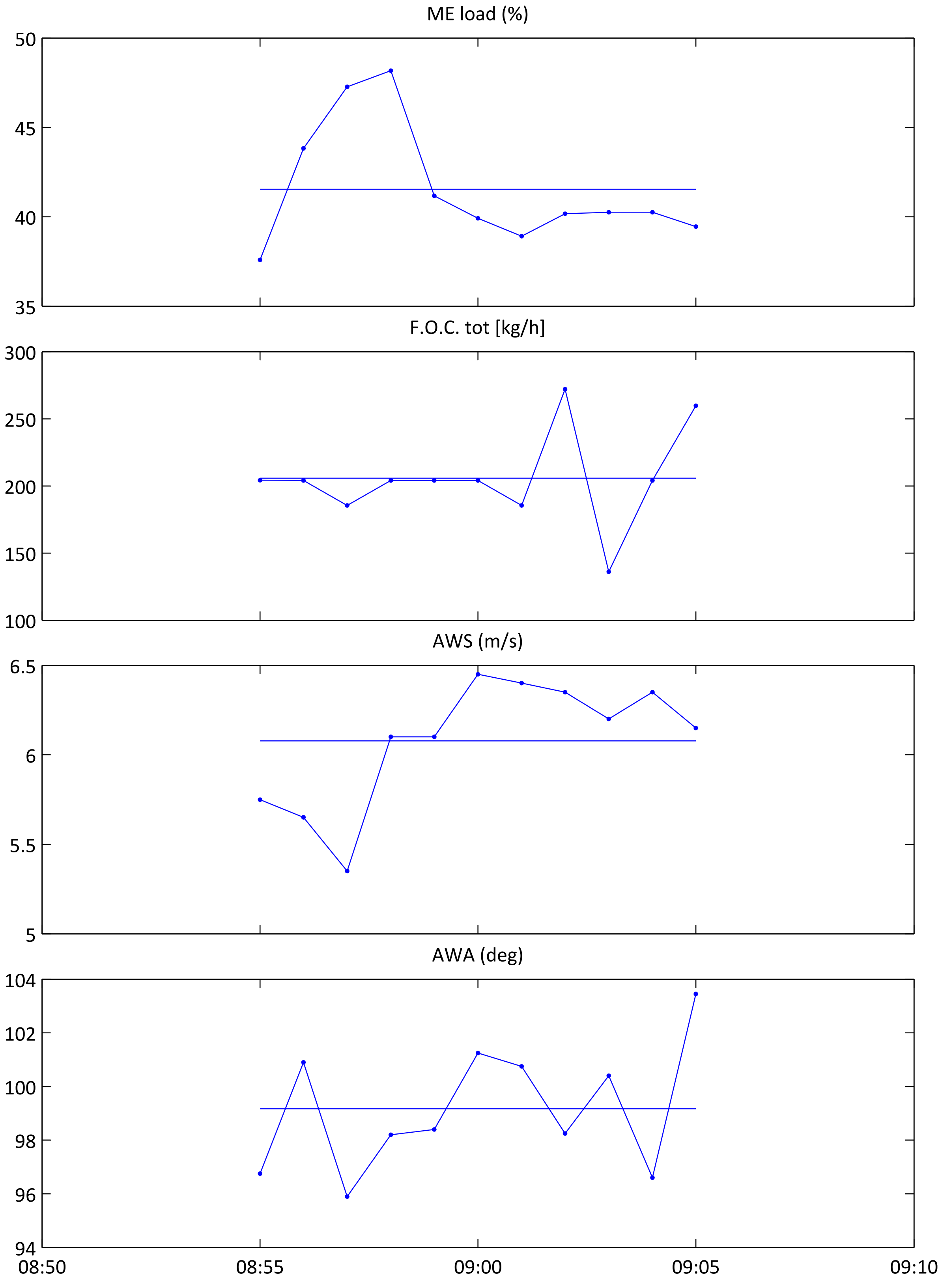
Run 3 Figure: 10



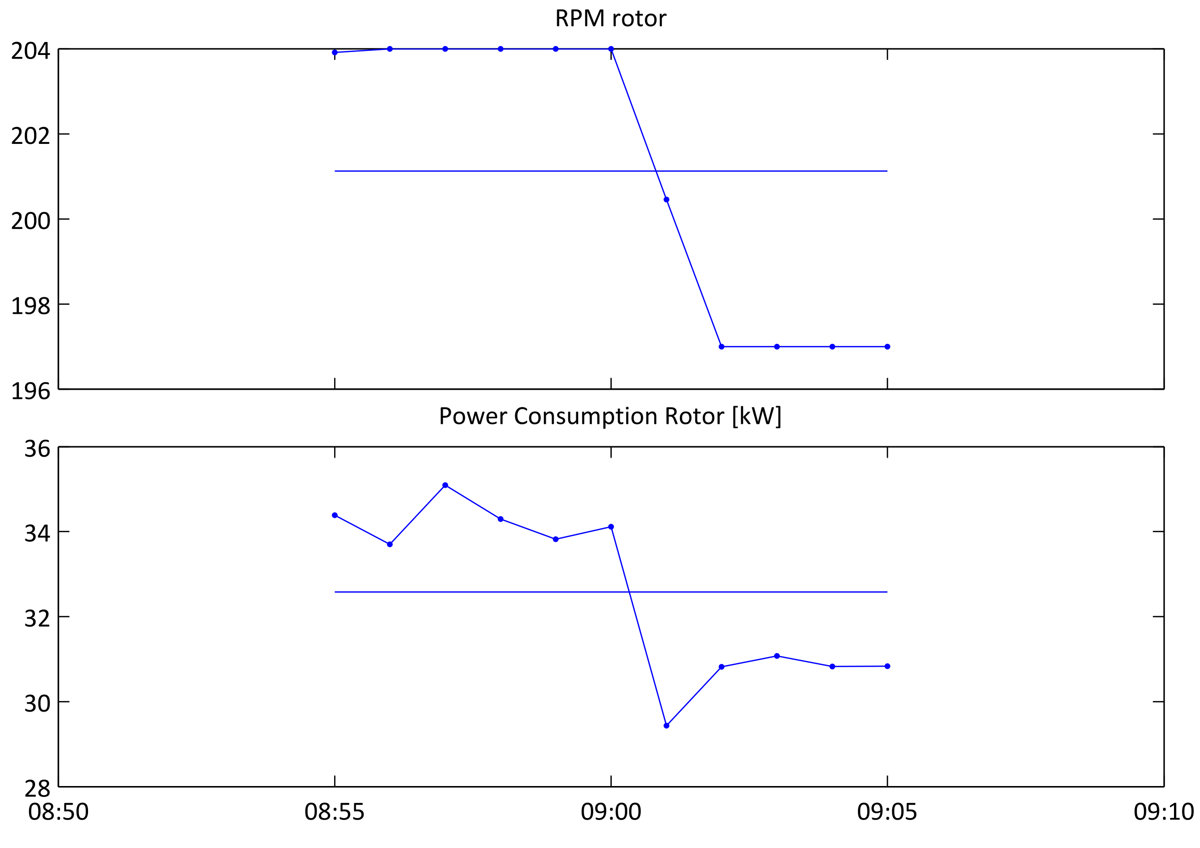
Run 4 Figure: 11



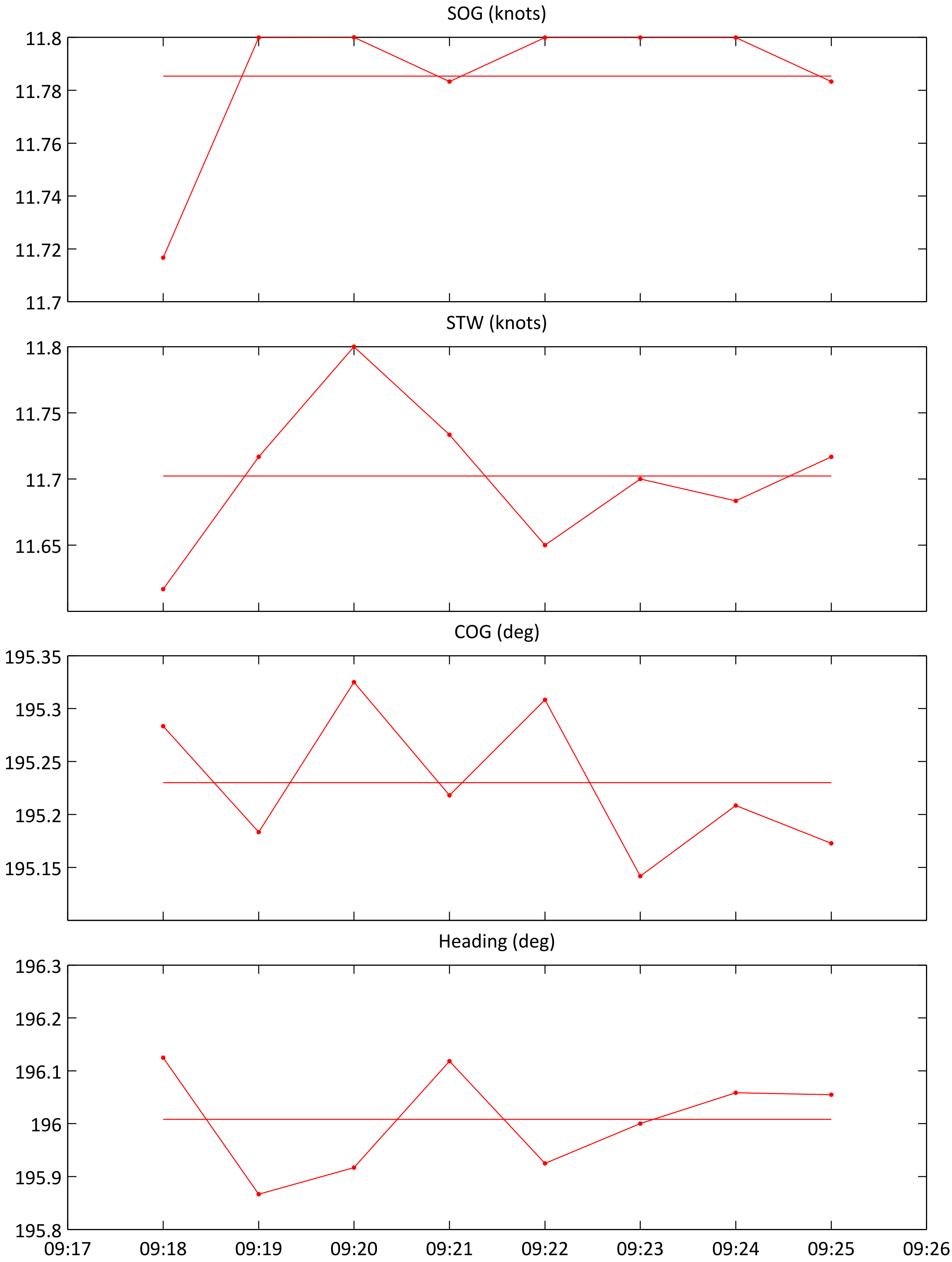
Run 4 Figure: 12



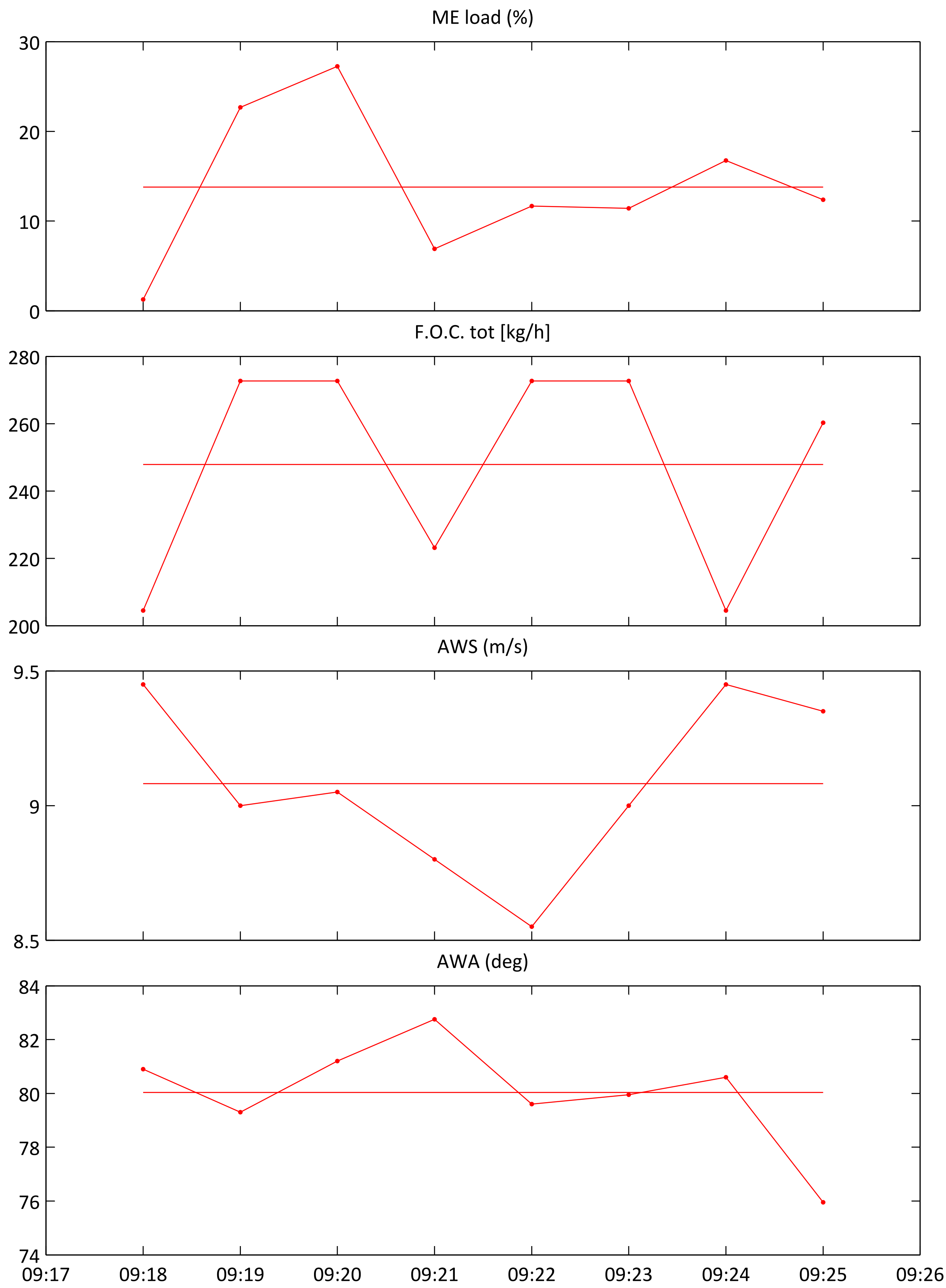
Run 4 Figure: 13



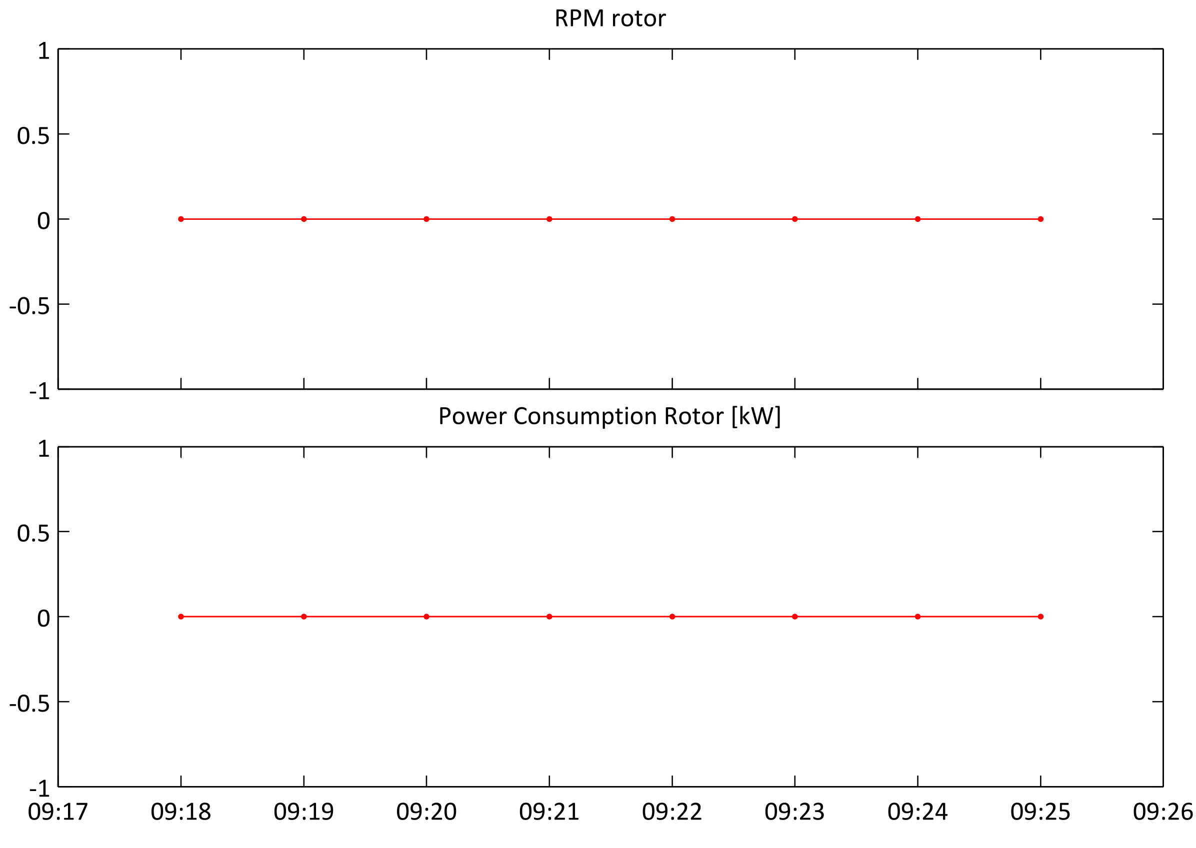
Run 5 Figure: 14



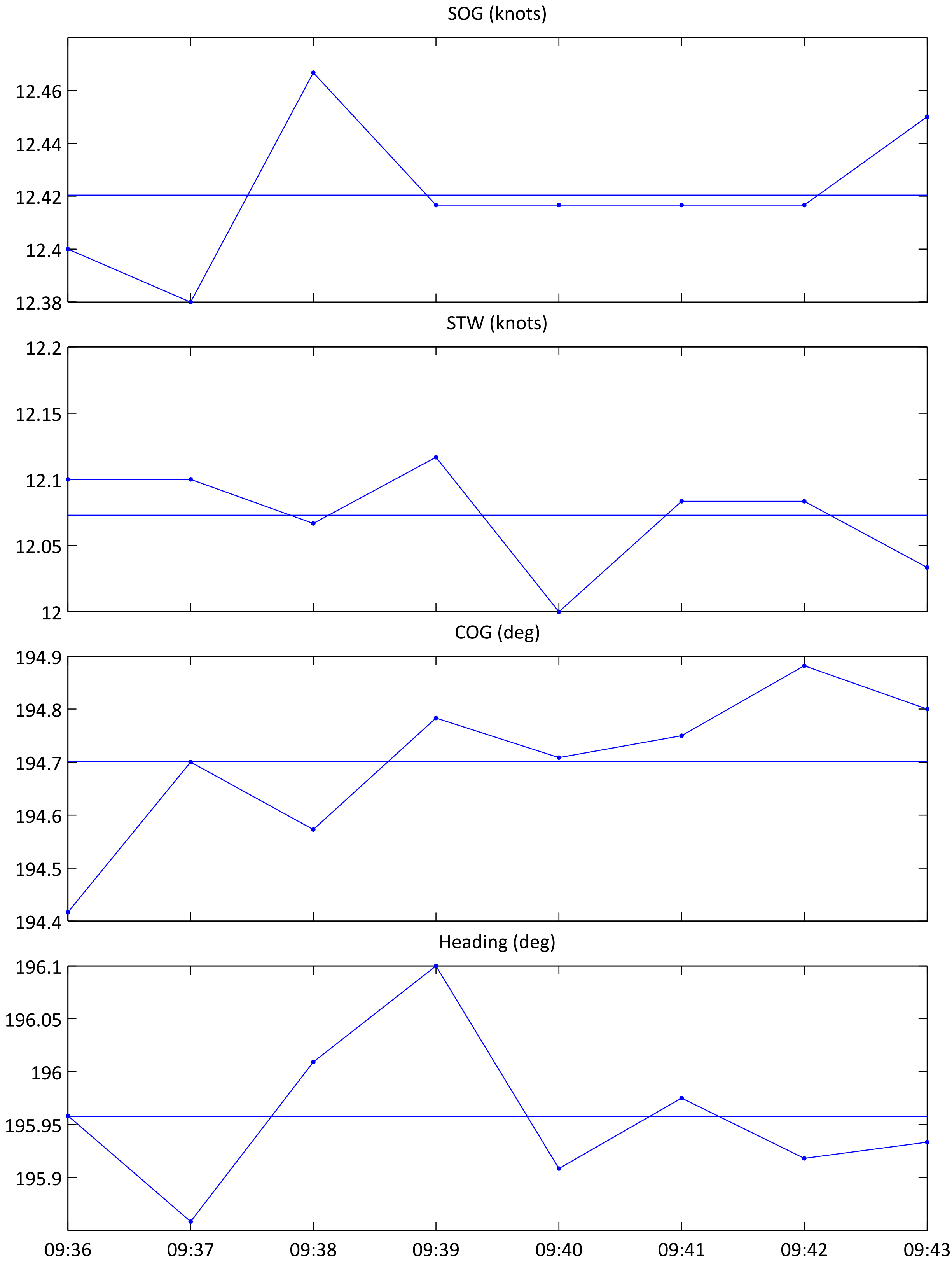
Run 5 Figure: 15



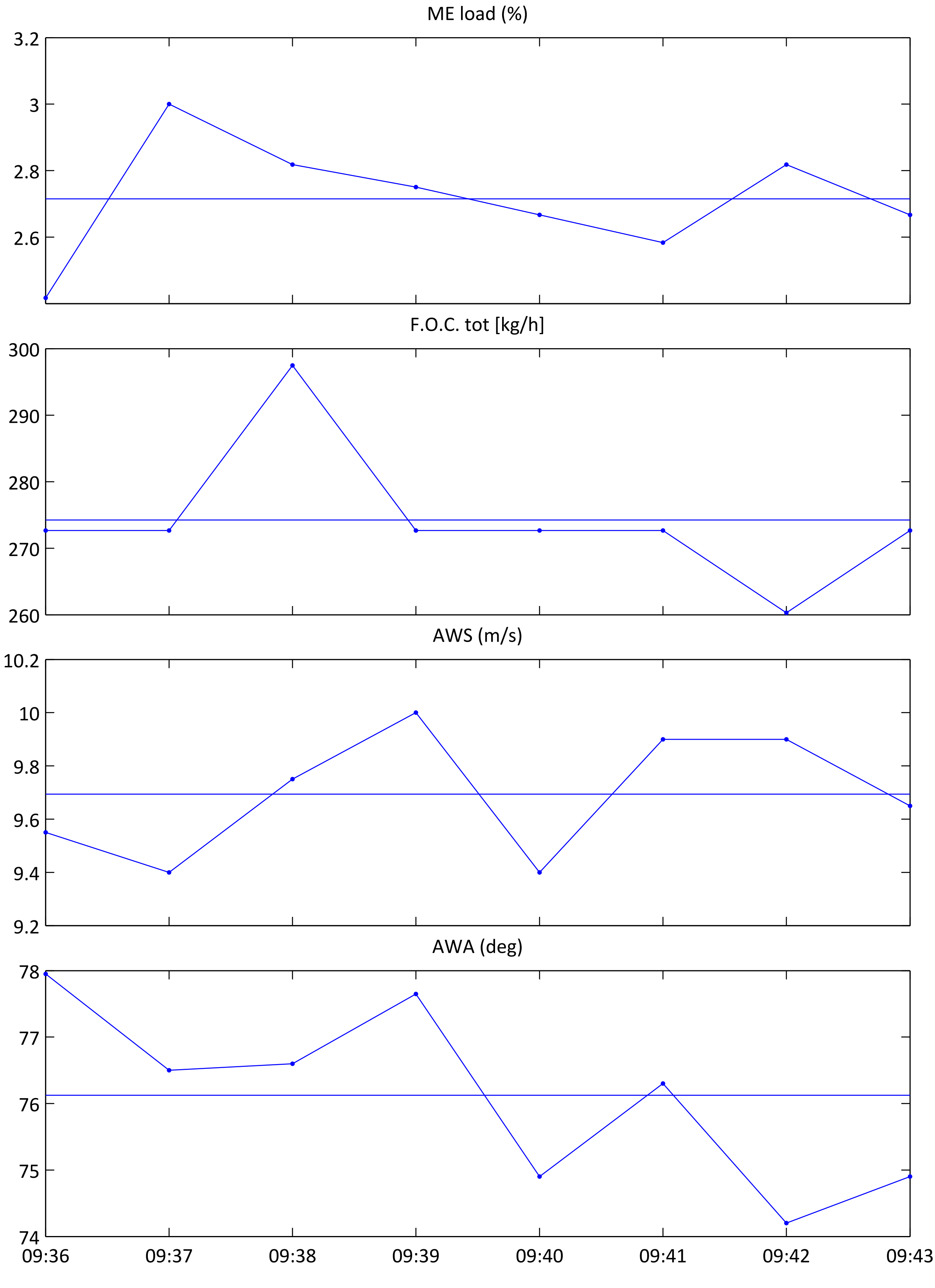
Run 5 Figure: 16

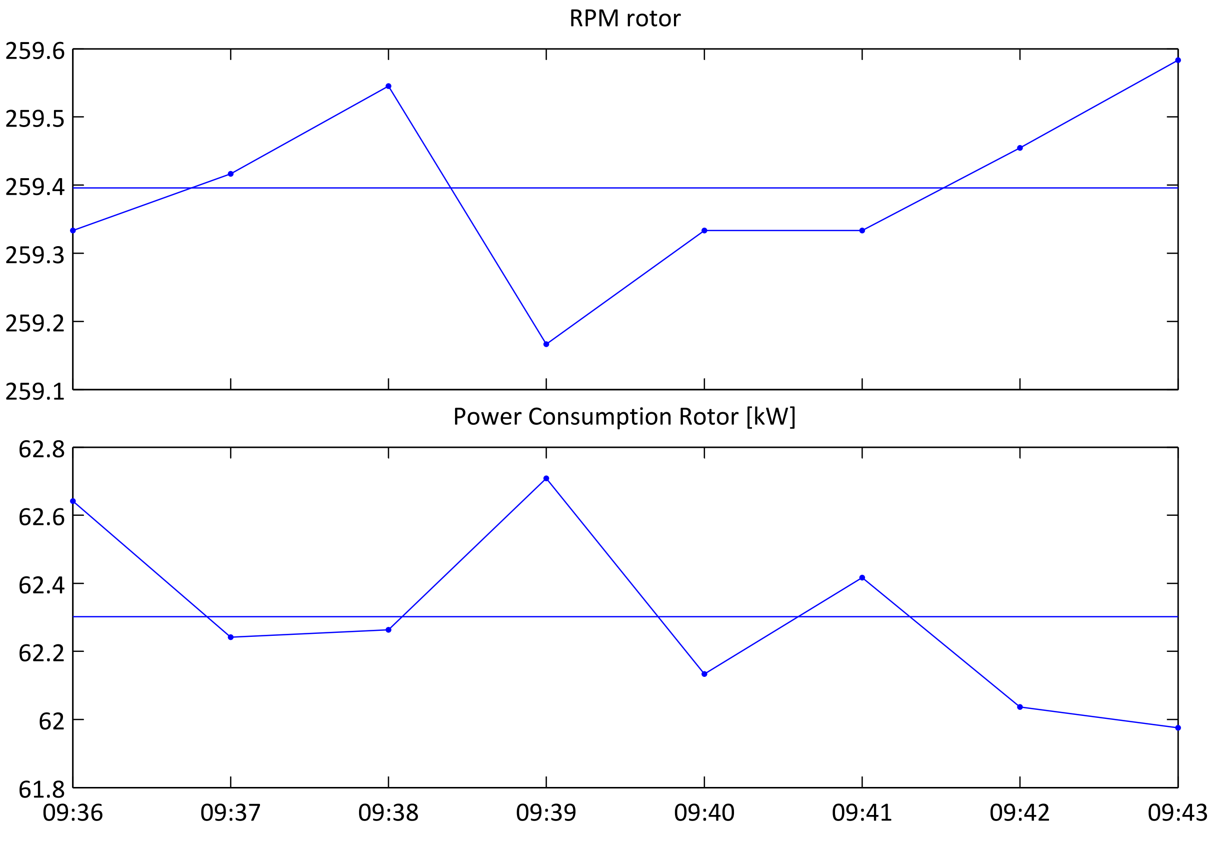


Run 6 Figure: 17

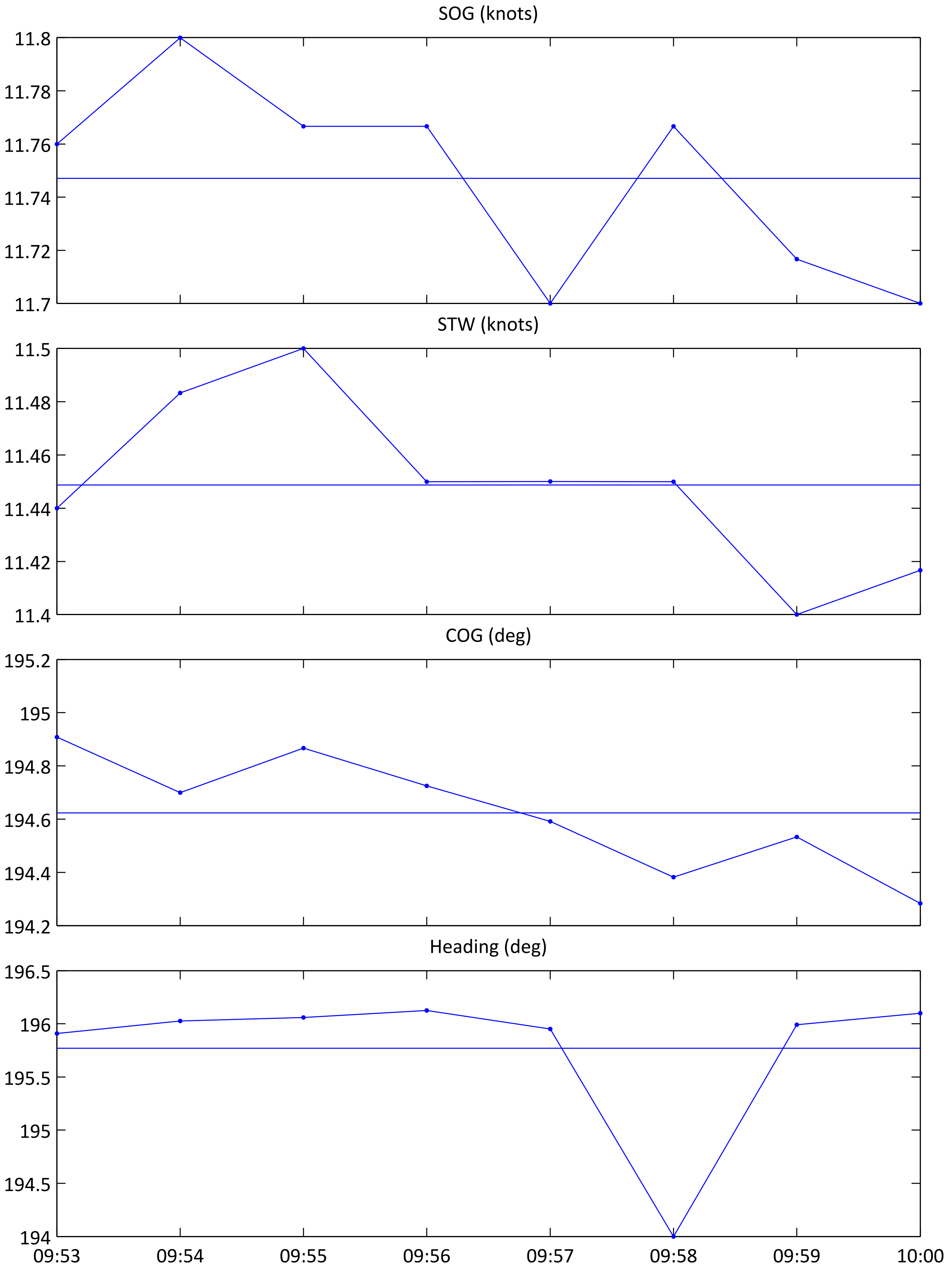


Run 6 Figure: 18

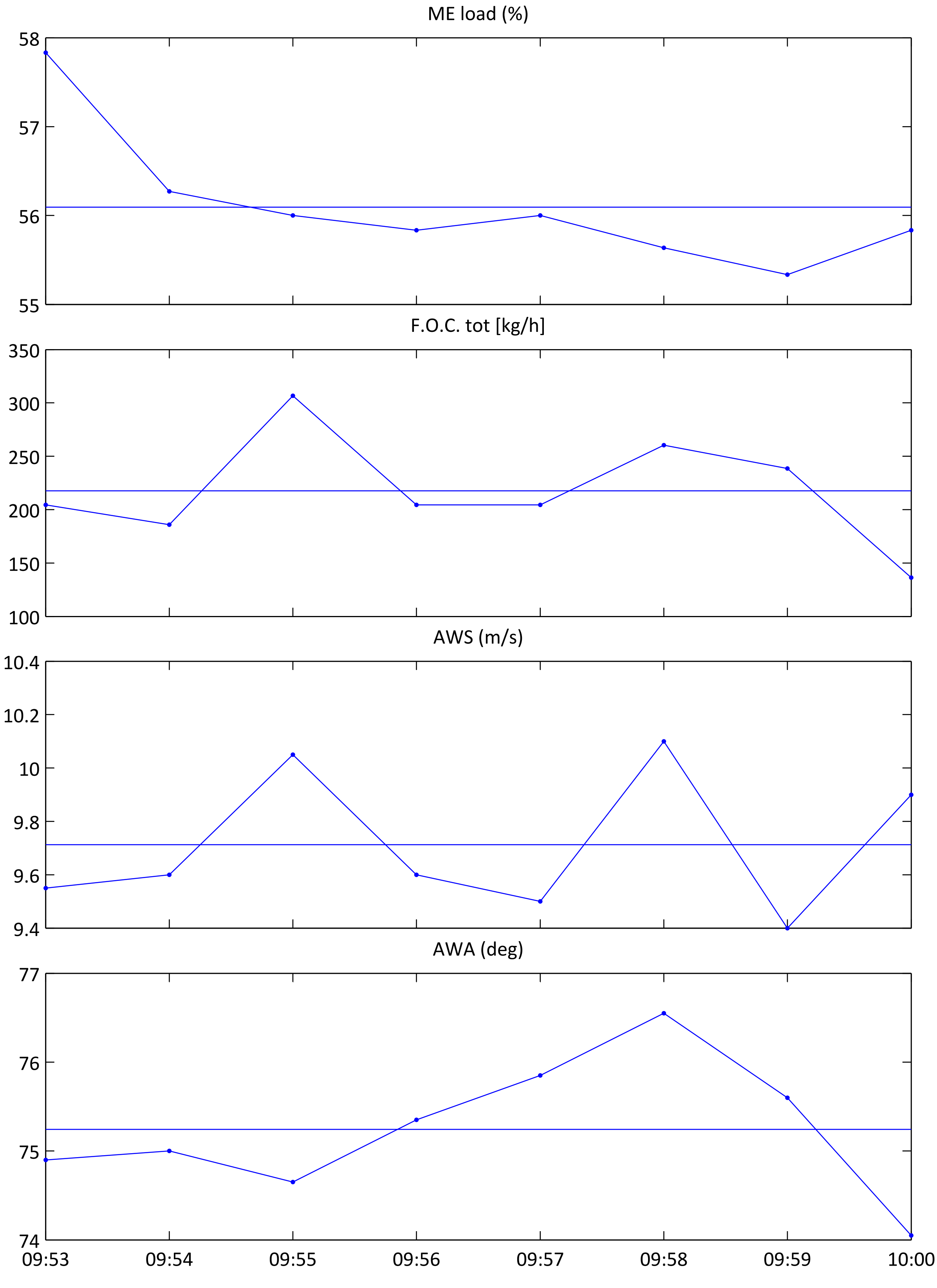



RPM rotor
259.6
259.5
259.4
259.3
259.2
259.1
Power Consumption Rotor [kW]
62.8
62.6
62.4
62.2
62
61.8
09:36
09:37
09:38
09:39
09:40
09:41
09:42
09:43

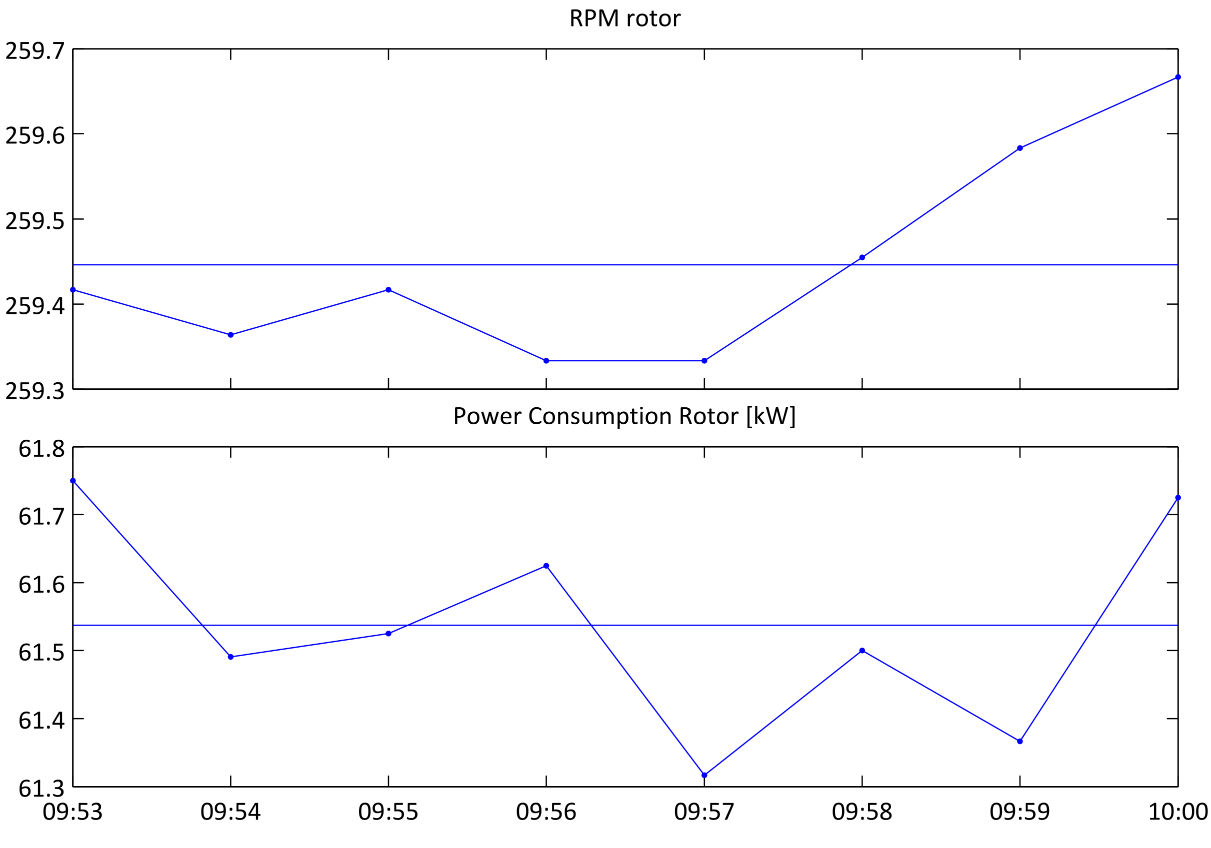
Run 7 Figure: 20



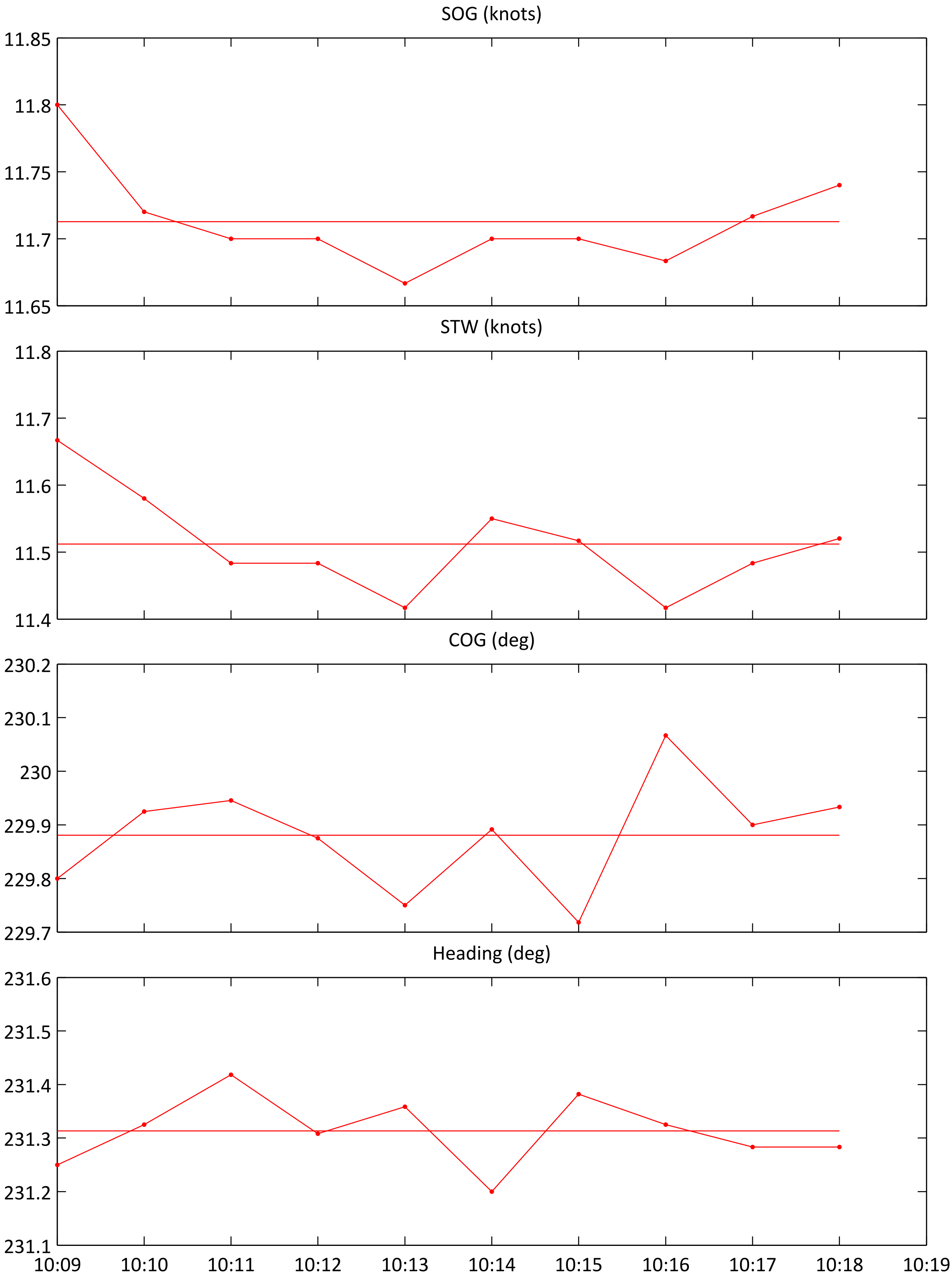
Run 7 Figure: 21



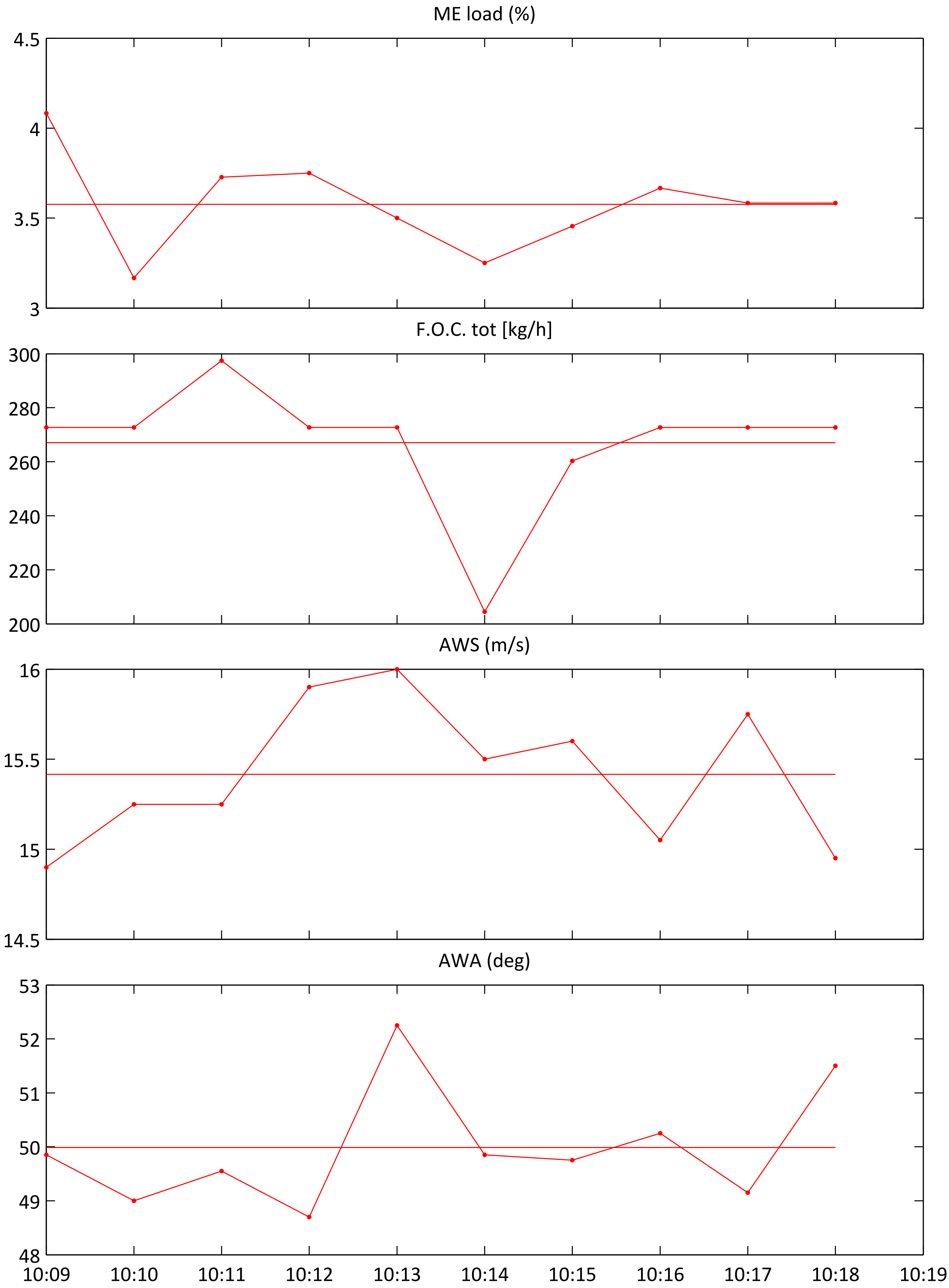
Run 7 Figure: 22



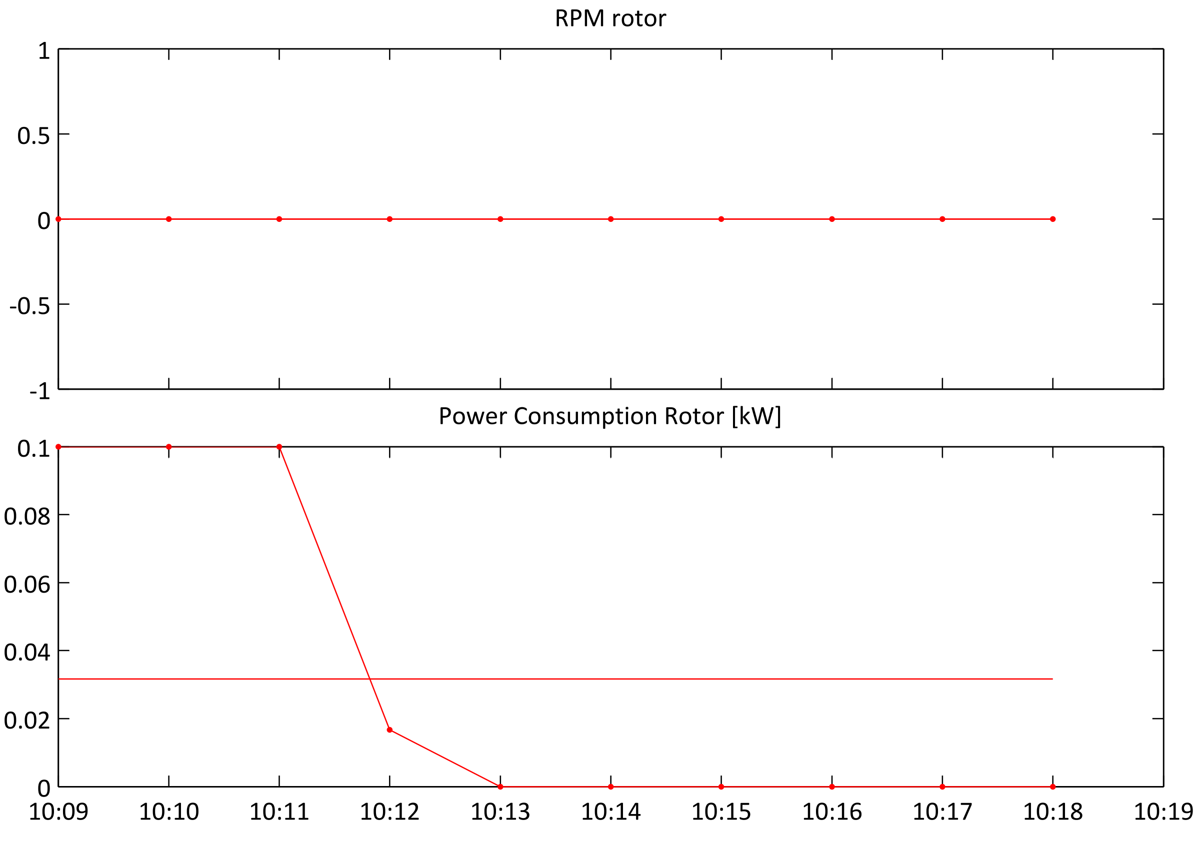
Run 8 Figure: 23



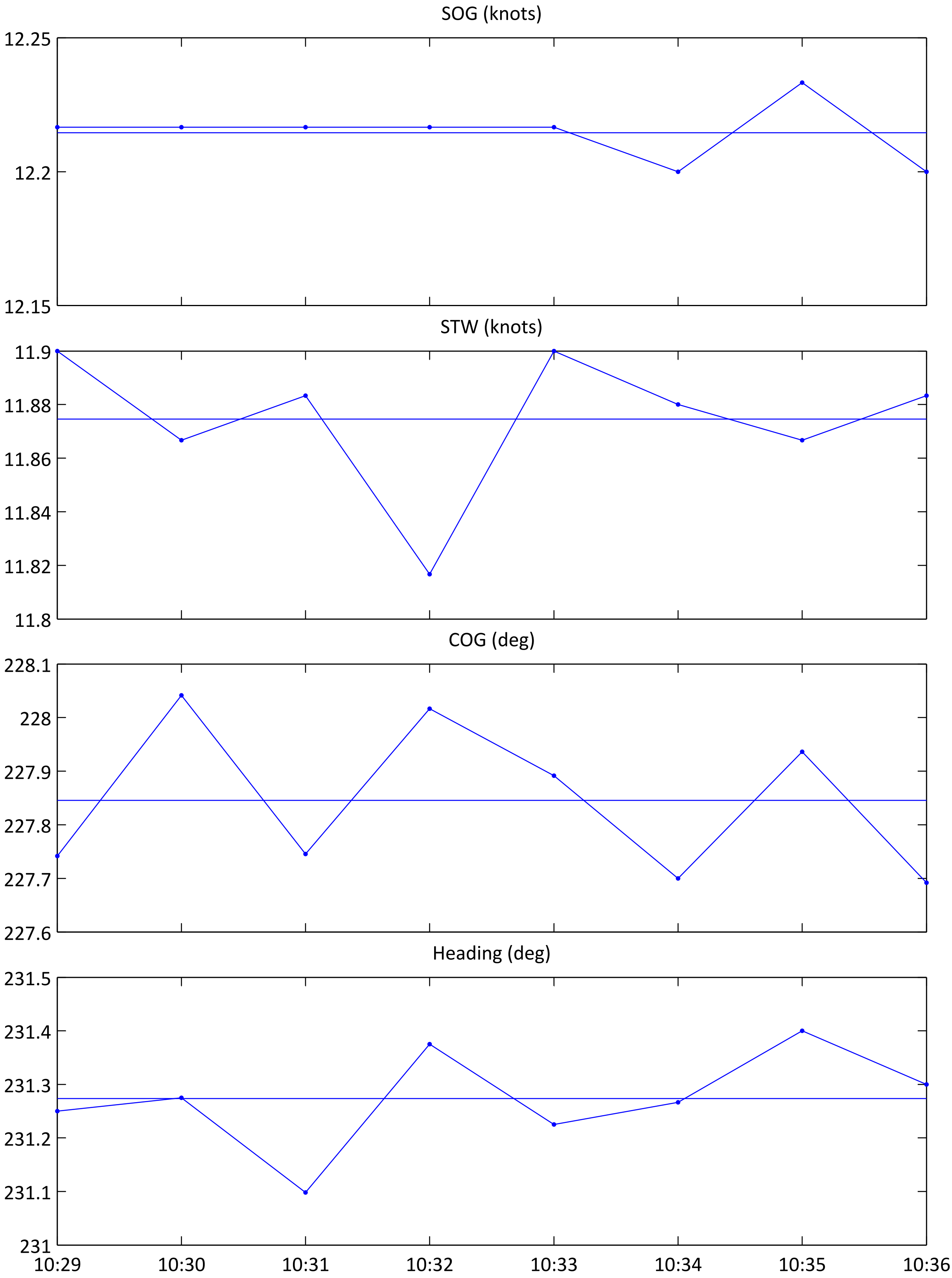
Run 8 Figure: 24



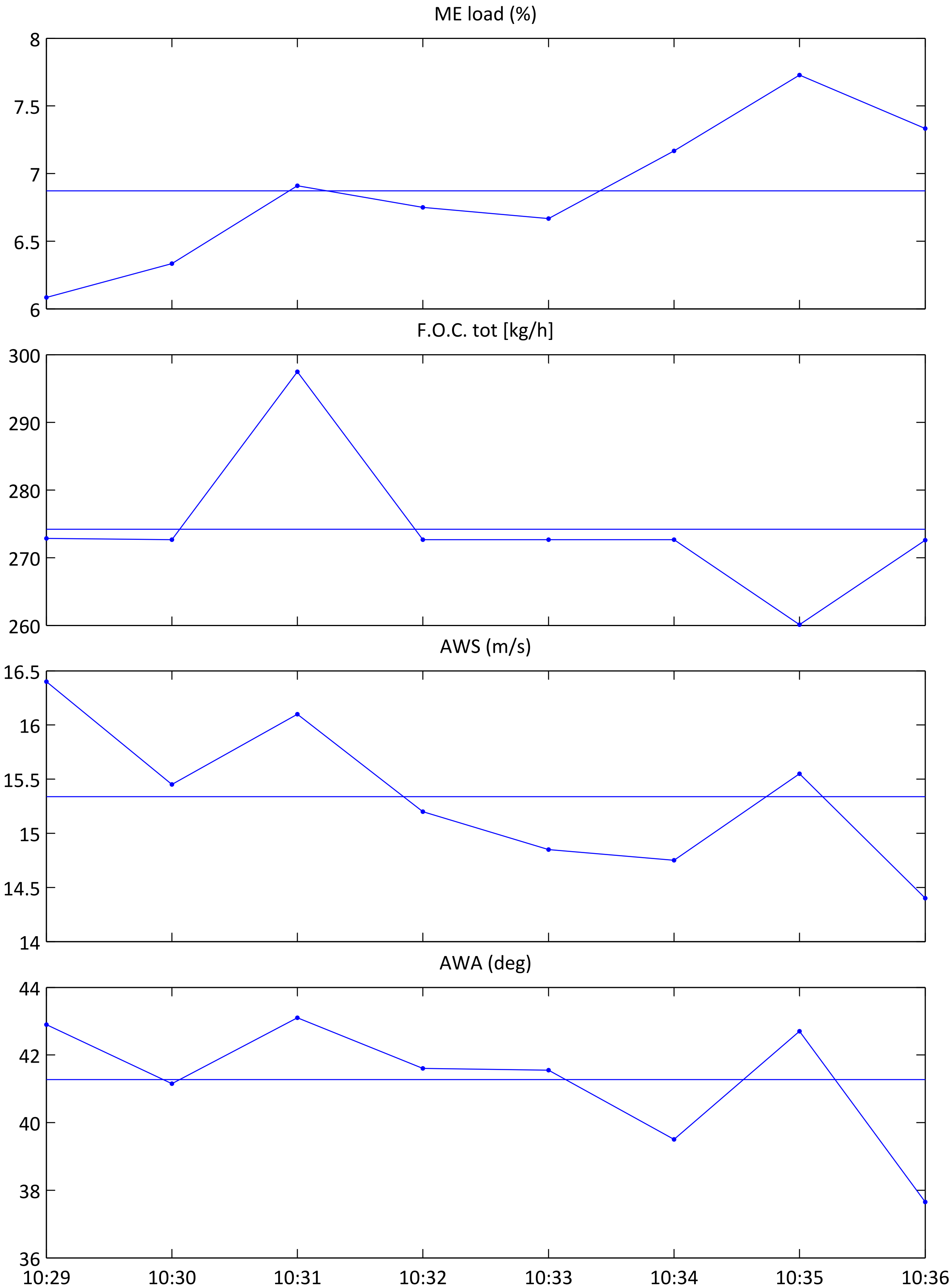
Run 8 Figure: 25



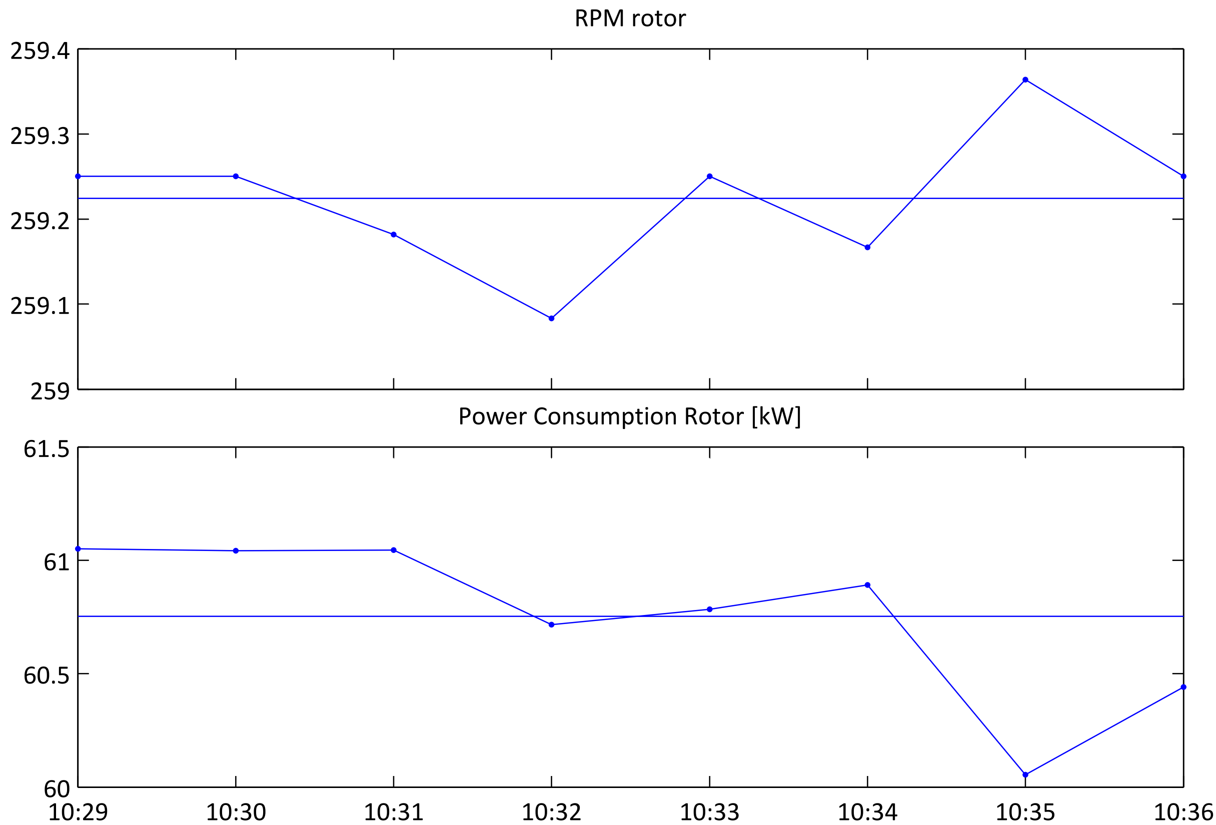
Run 9 Figure: 26



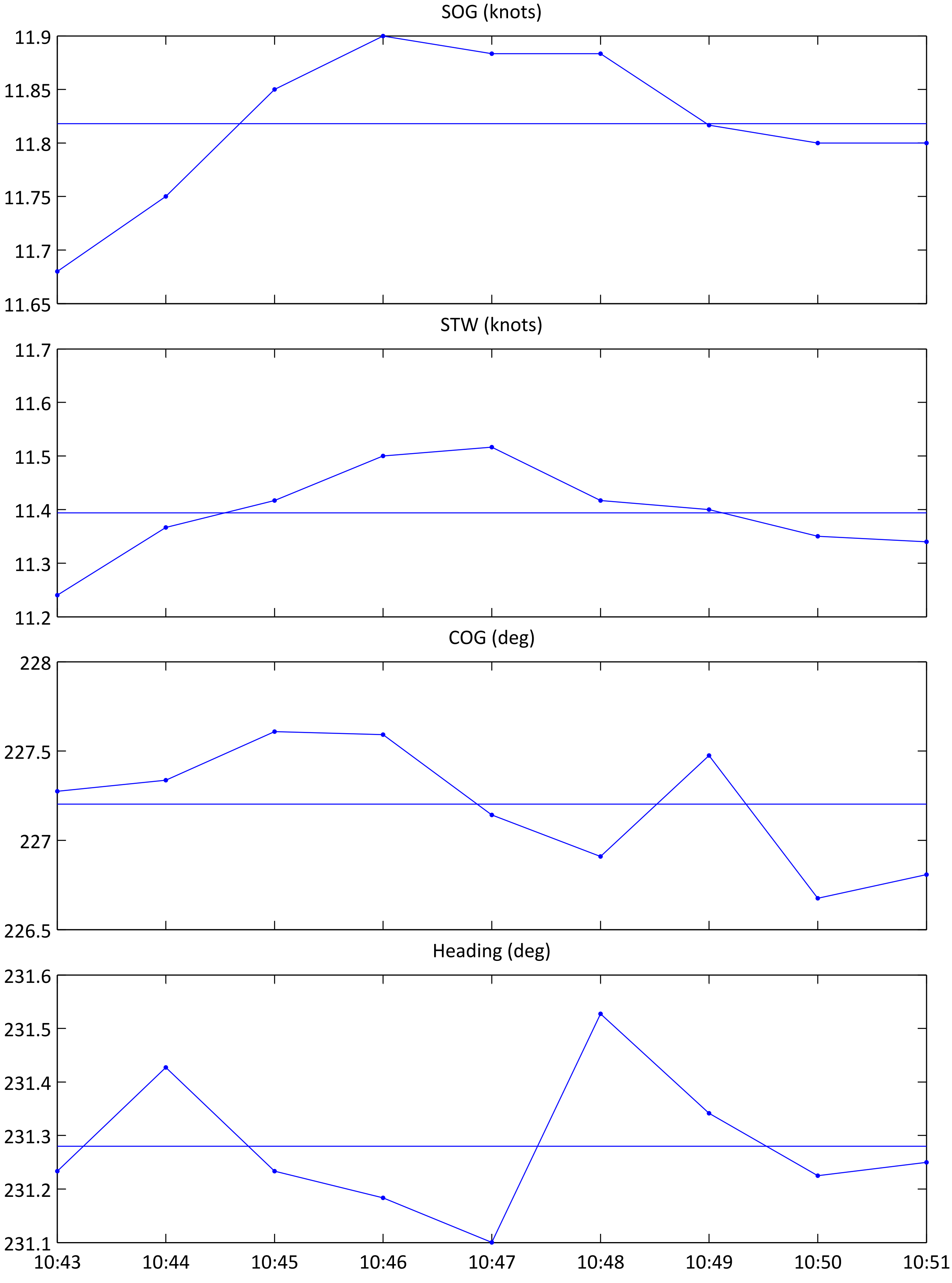
Run 9 Figure: 27



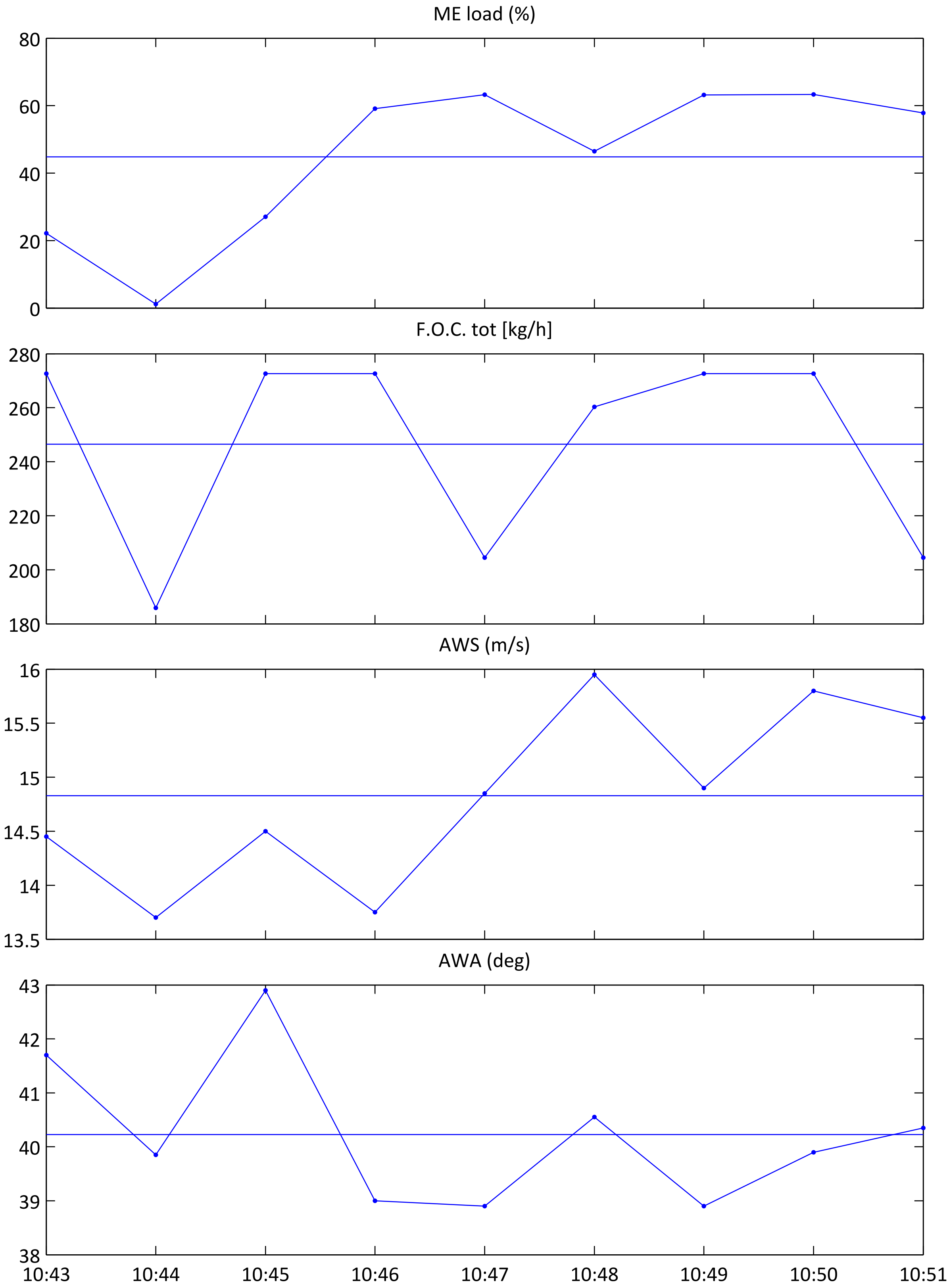
Run 9 Figure: 28



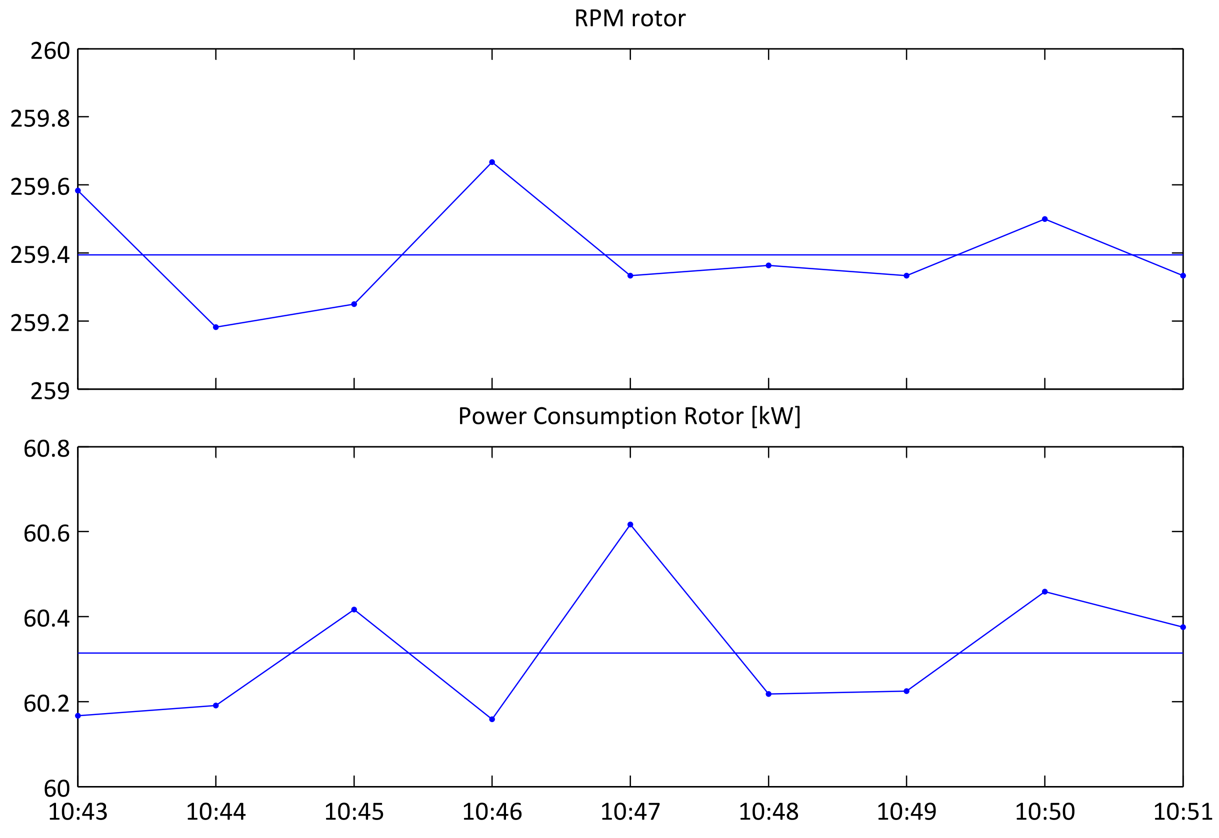
Run 10 Figure: 29



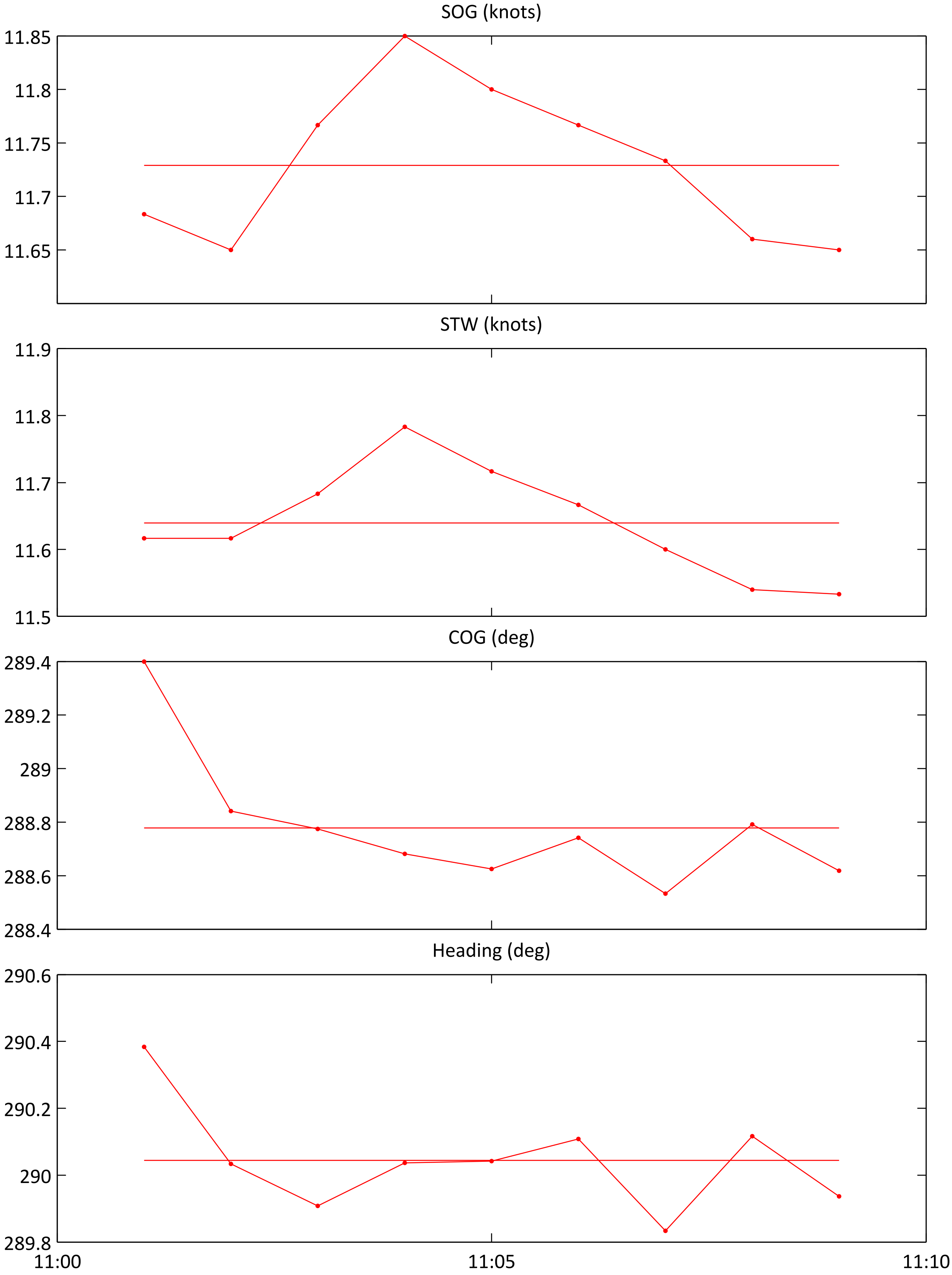
Run 10 Figure: 30



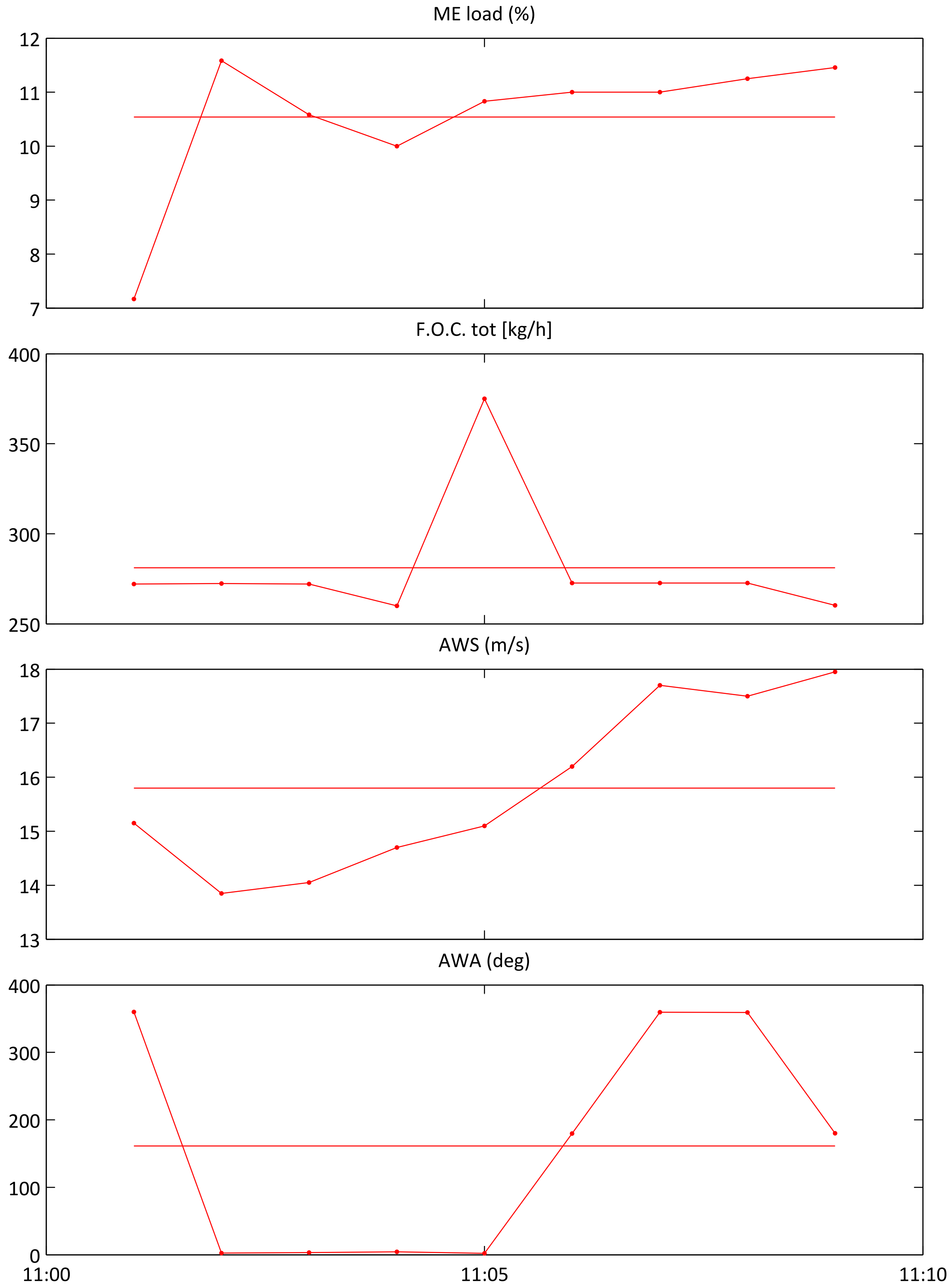
Run 10 Figure: 31



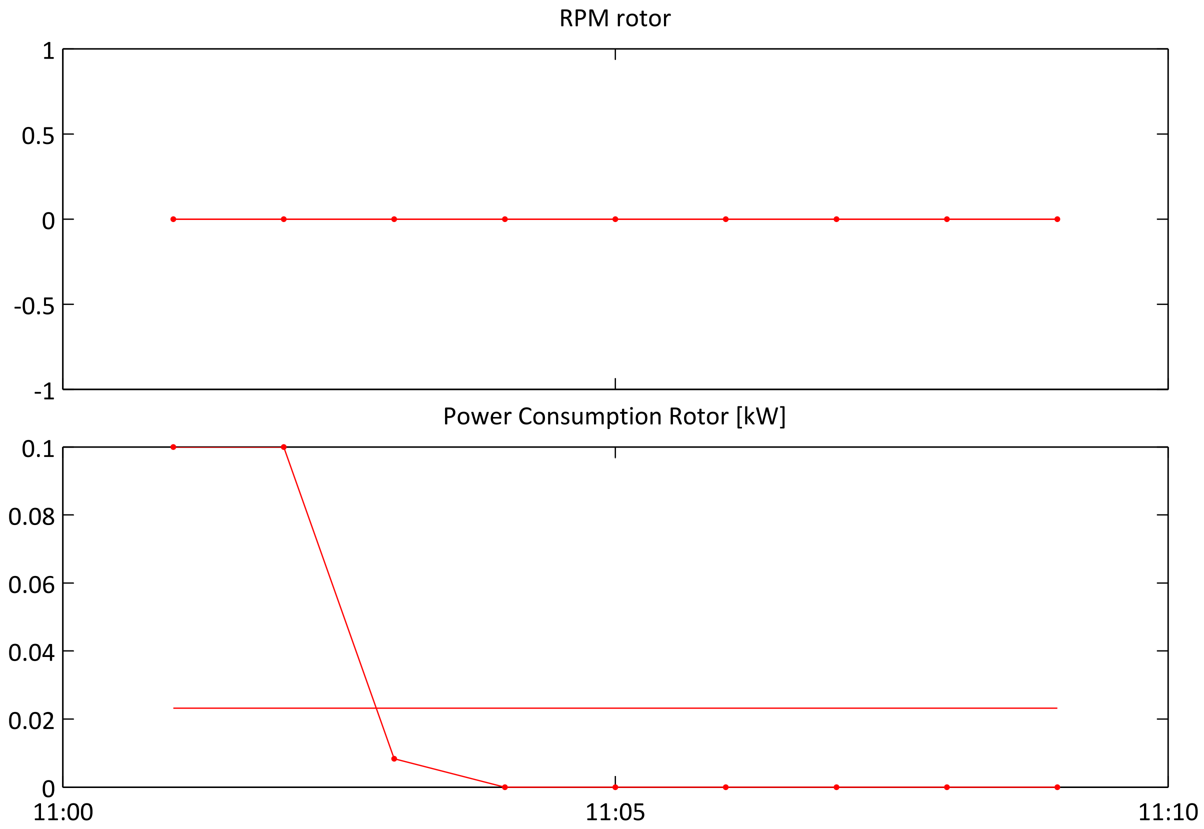
Run 11 Figure: 32



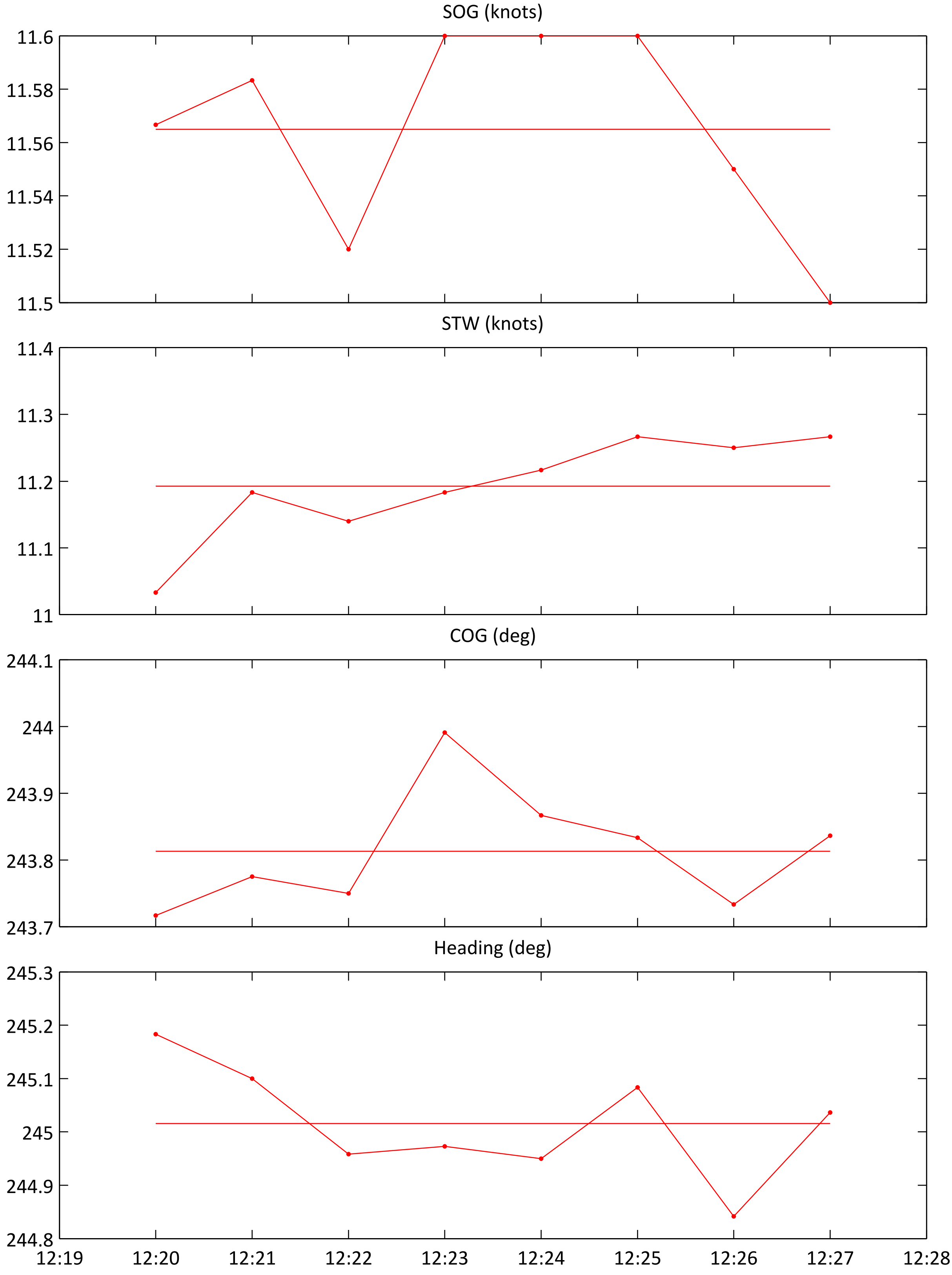
Run 11 Figure: 33



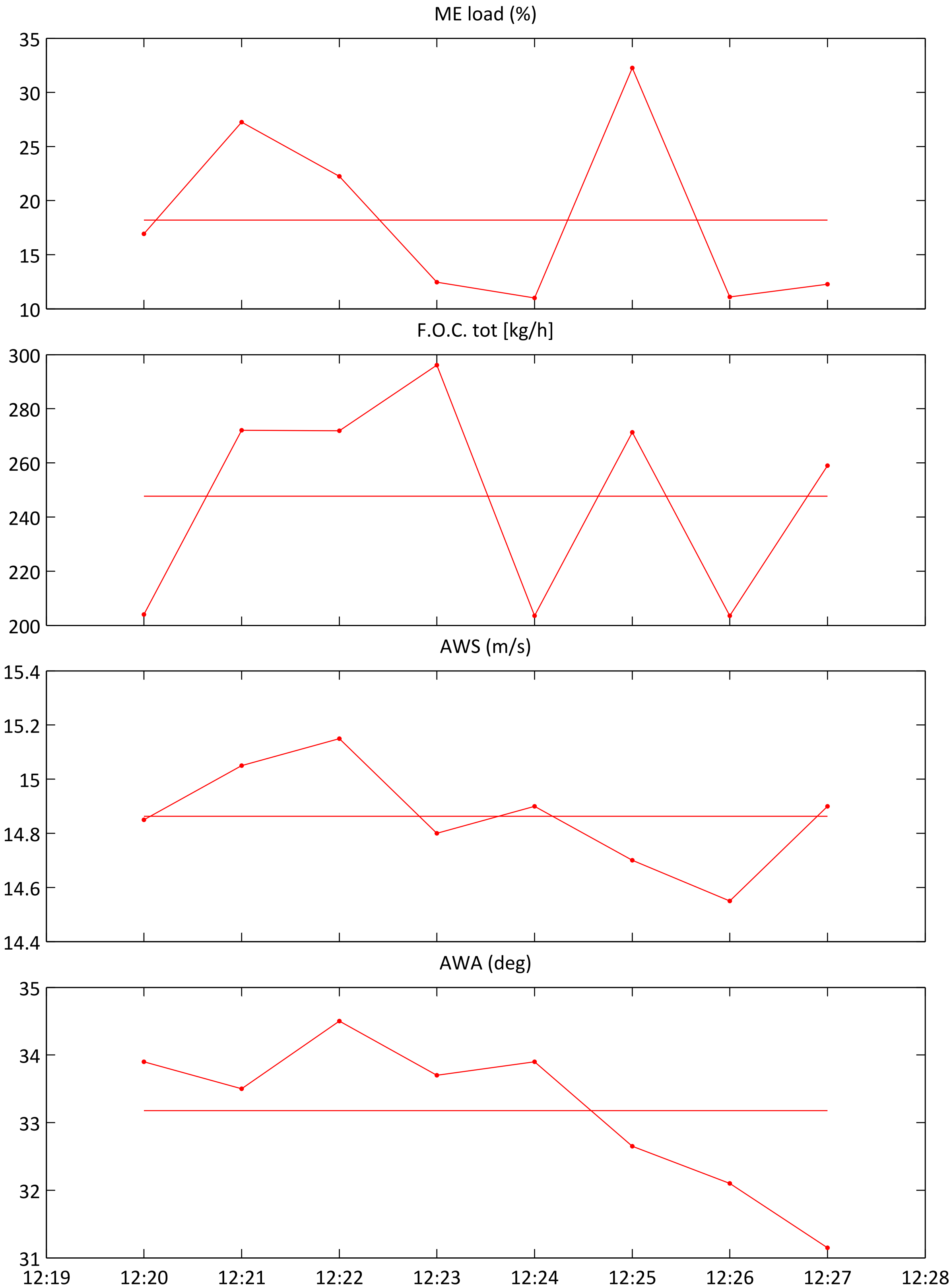
Run 11 Figure: 34



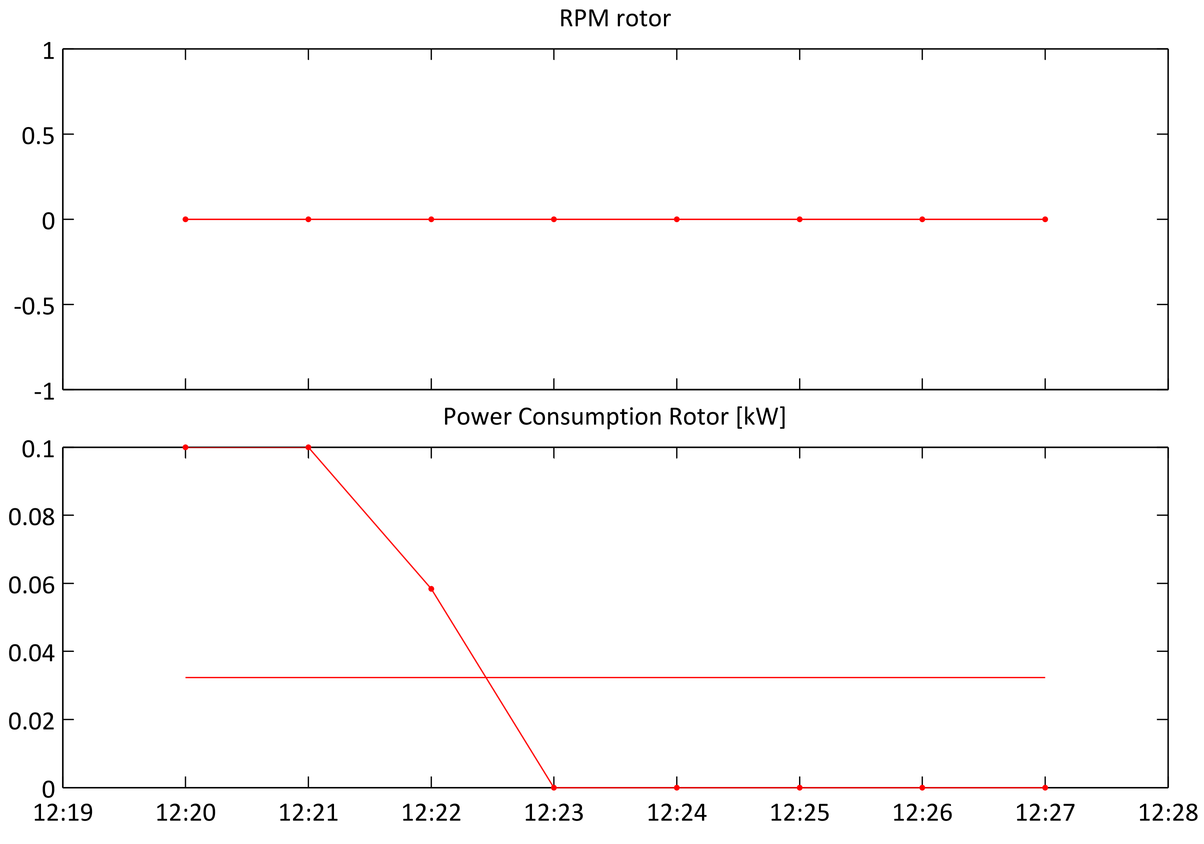
Run 12 Figure: 35



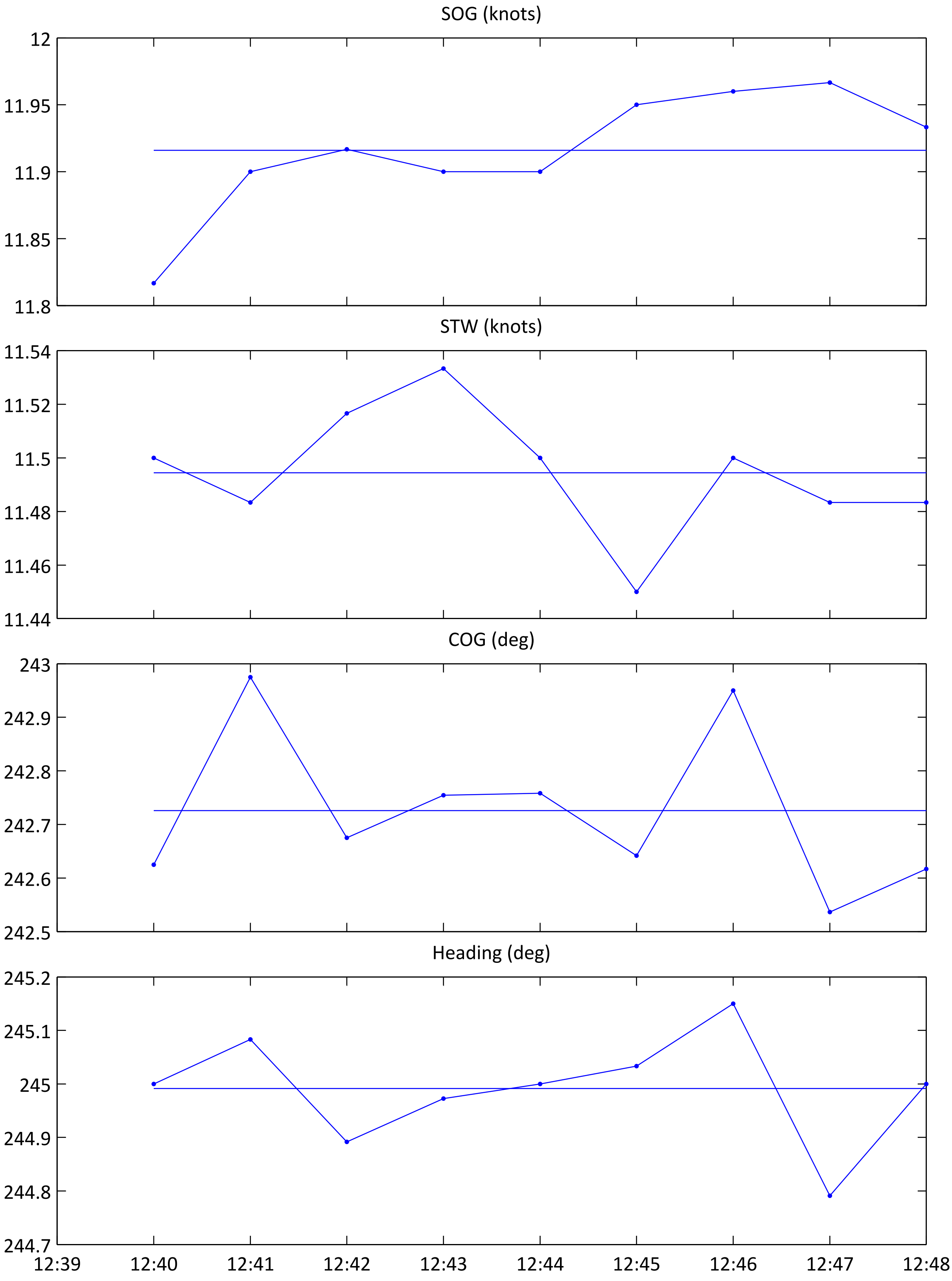
Run 12 Figure: 36



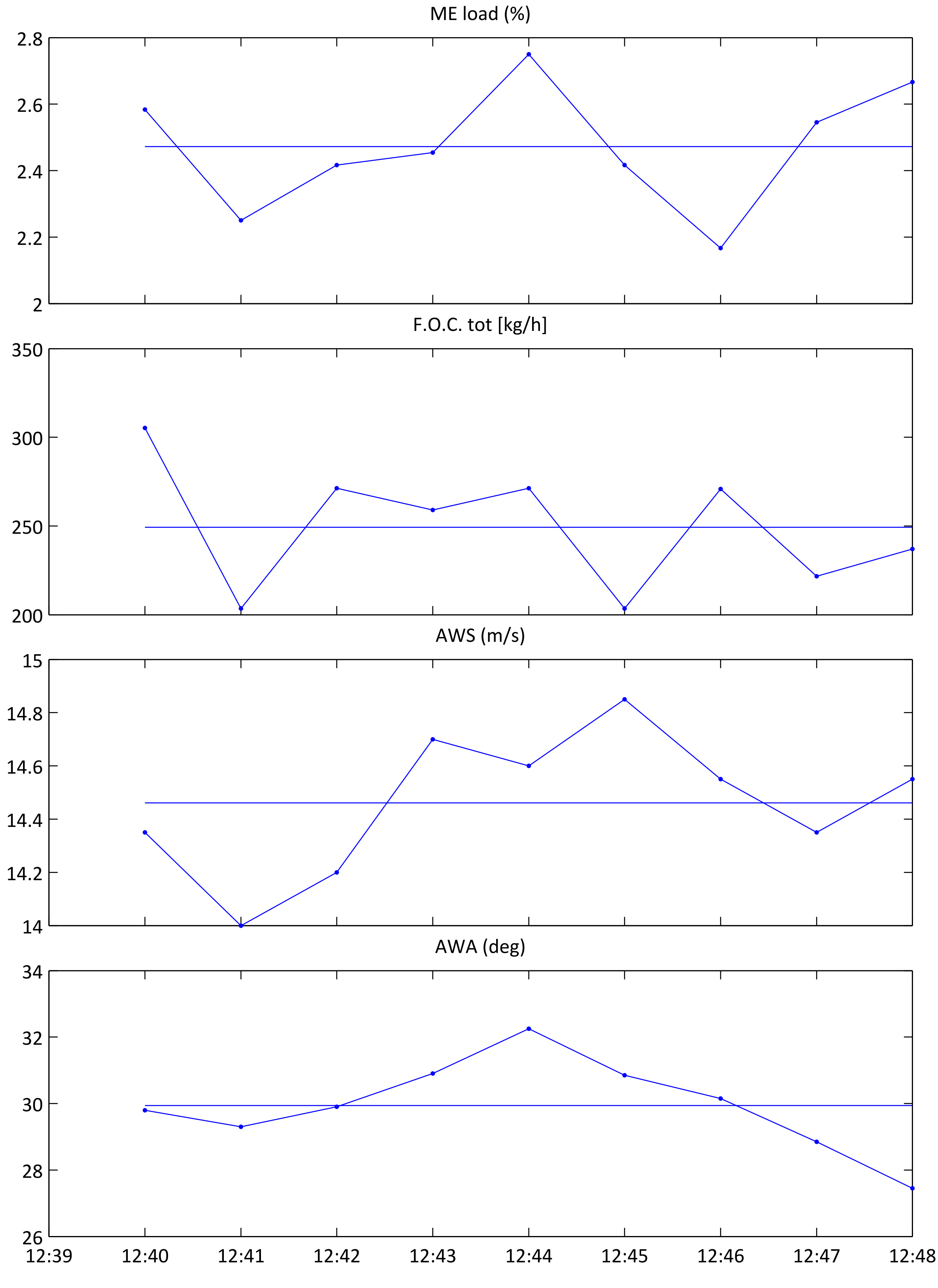
Run 12 Figure: 37



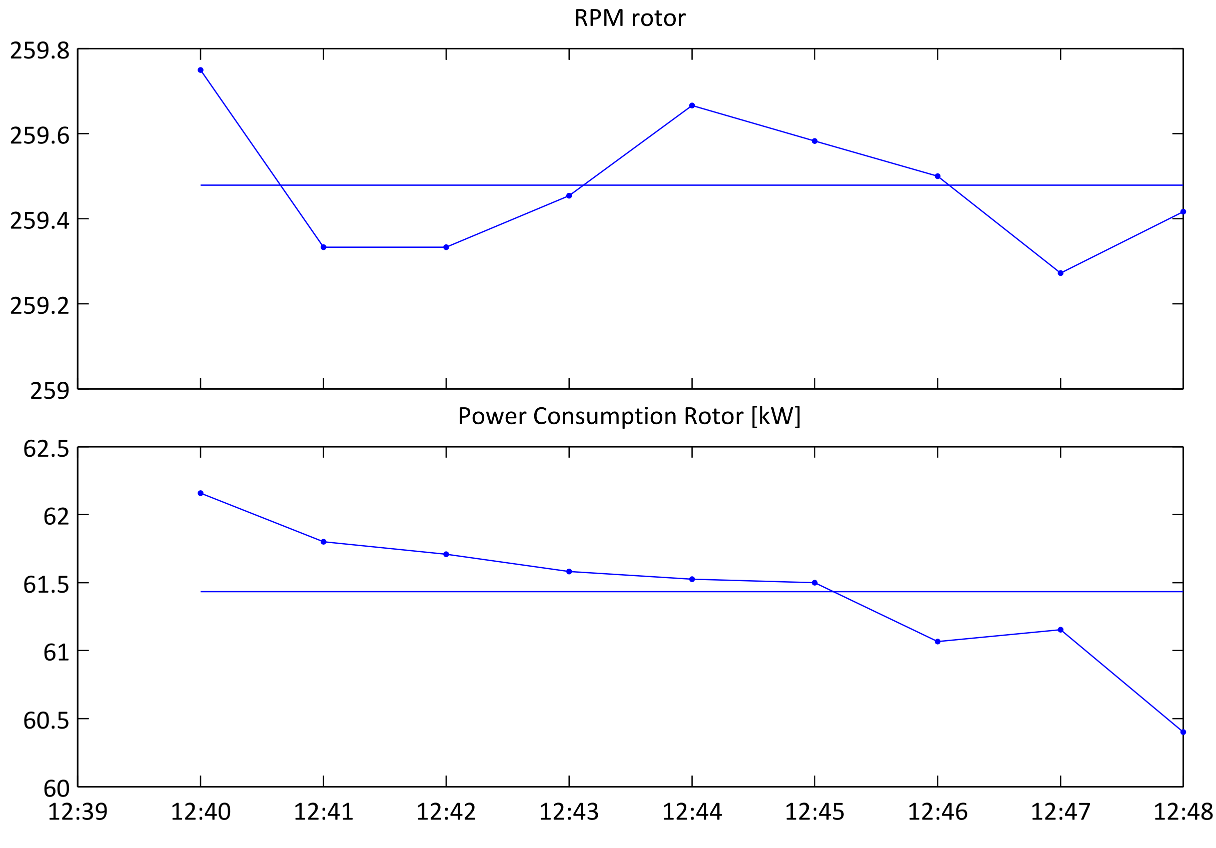
Run 13 Figure: 38



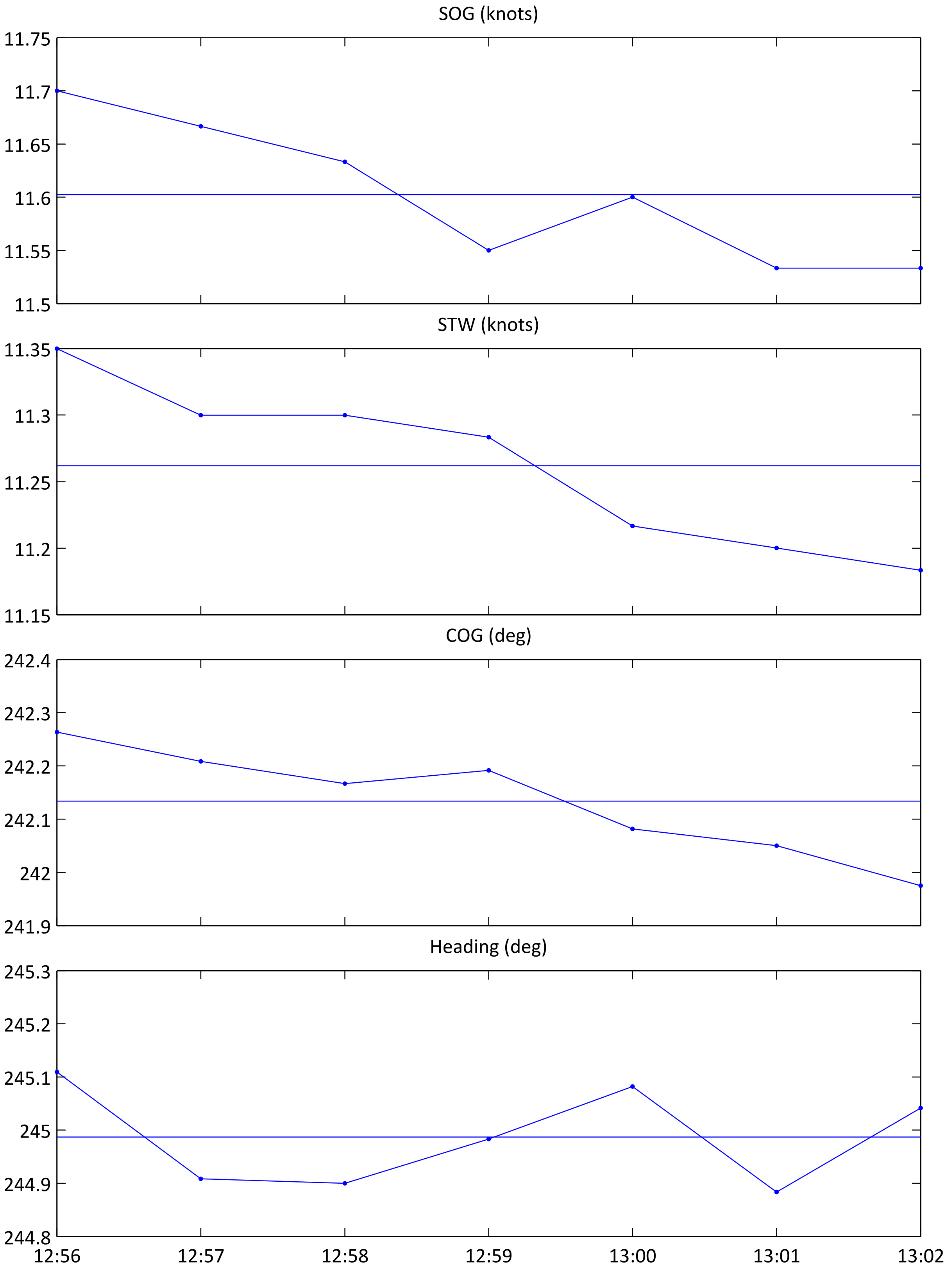
Run 13 Figure: 39



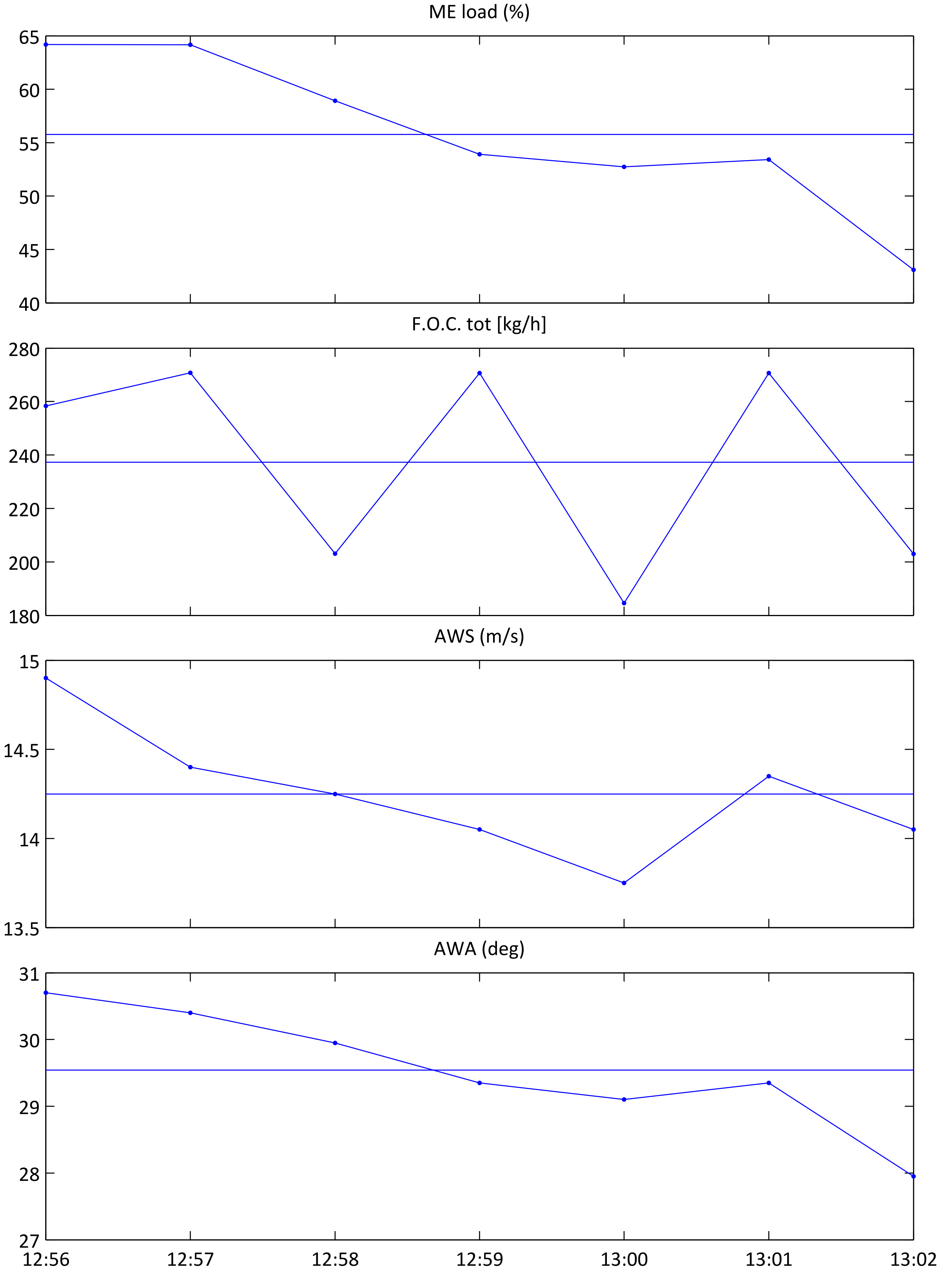
Run 13 Figure: 40



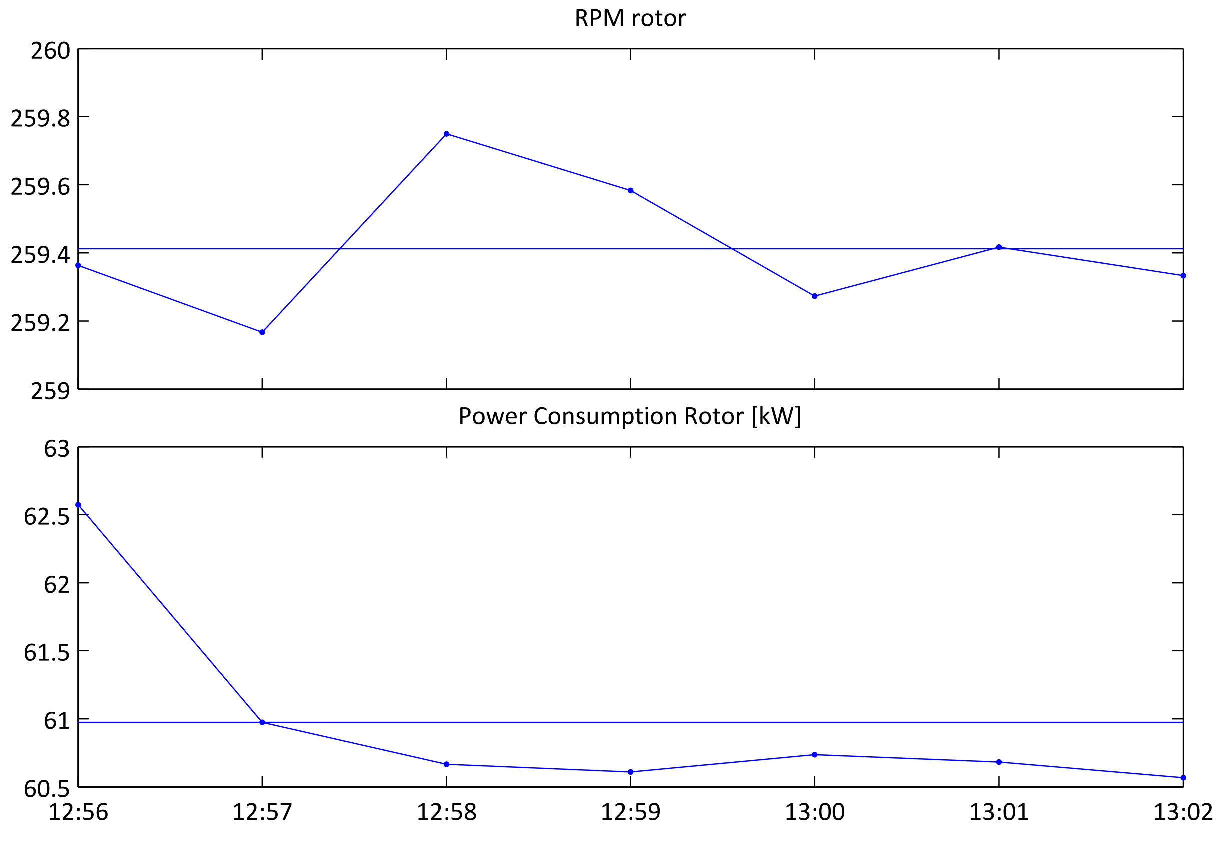
Run 14 Figure: 41



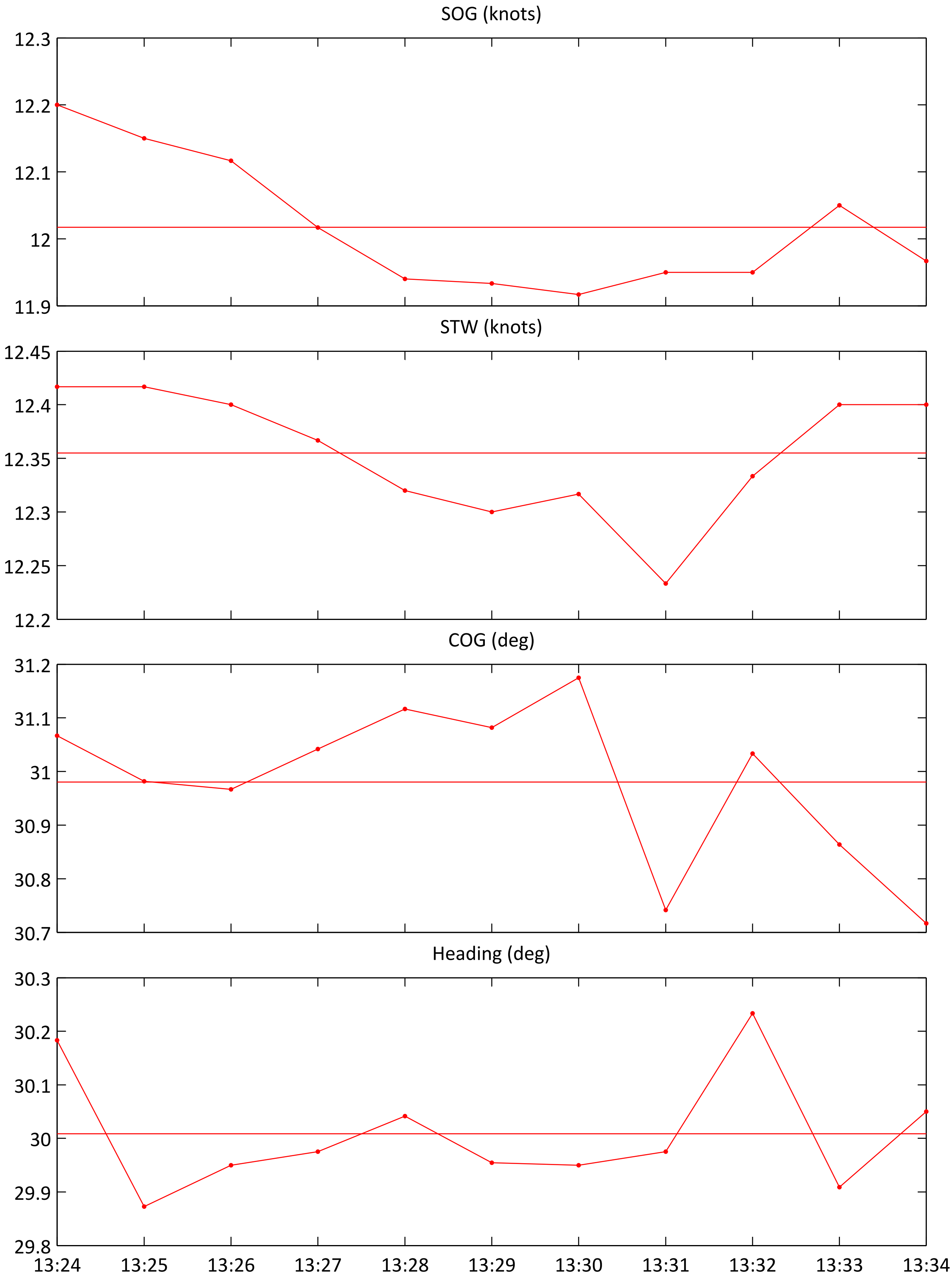
Run 14 Figure: 42



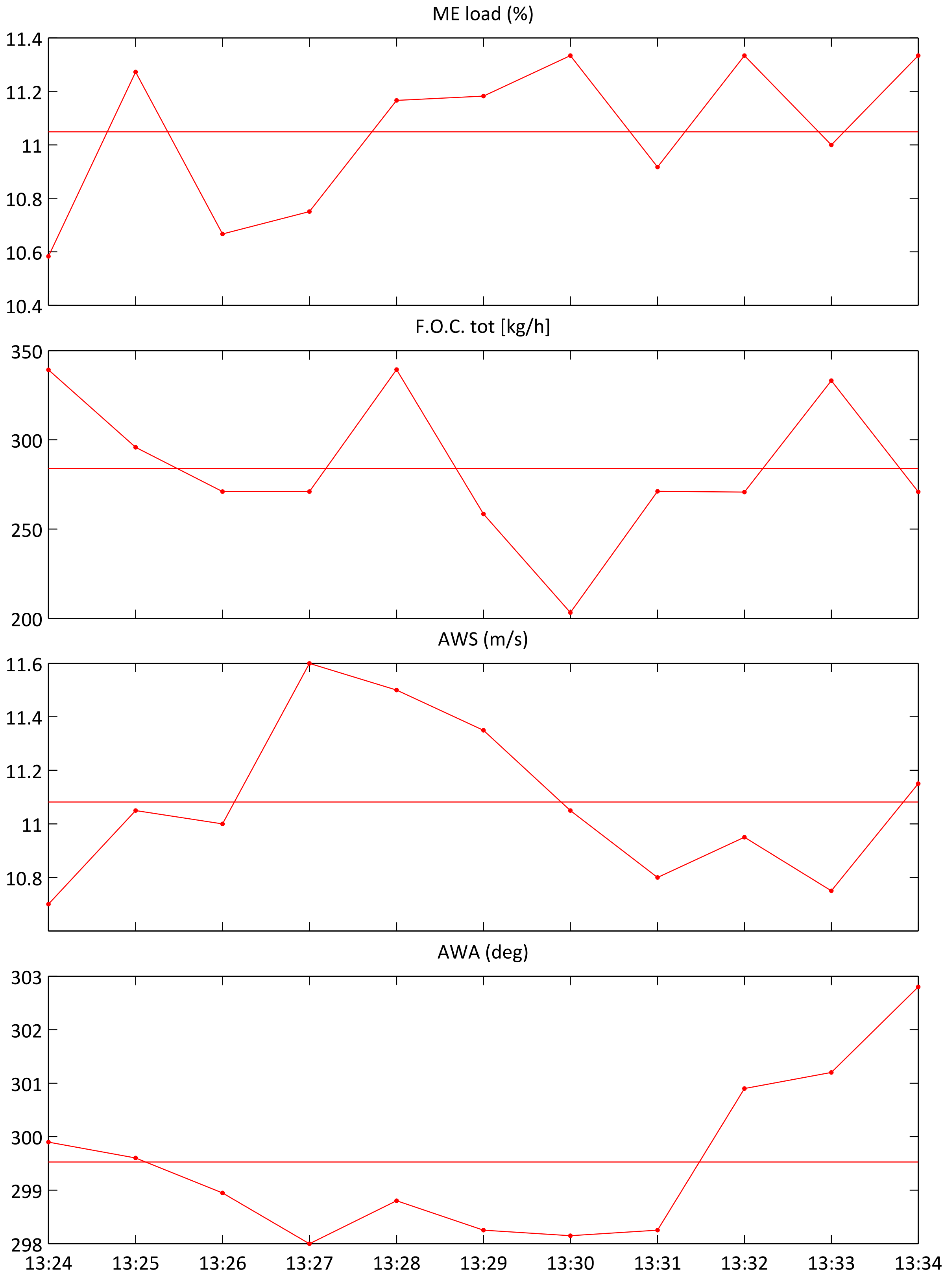
Run 14 Figure: 43



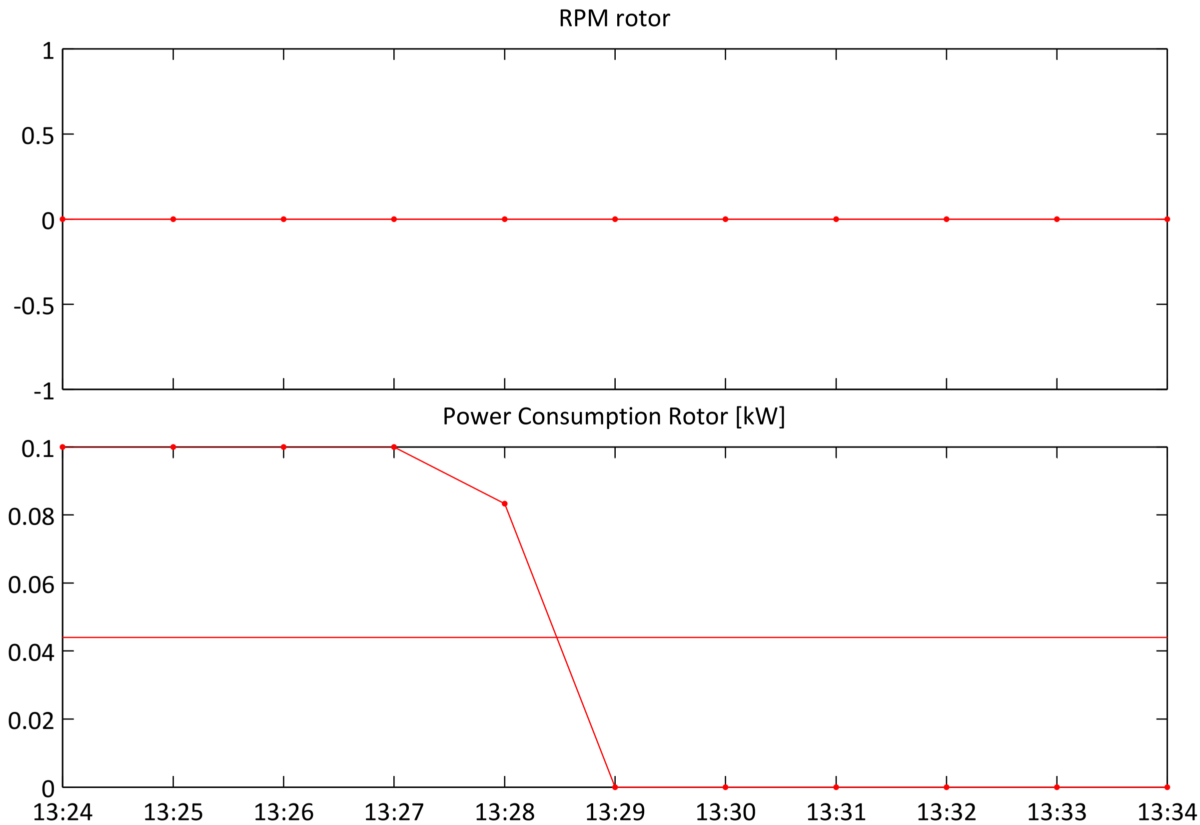
Run 15 Figure: 44



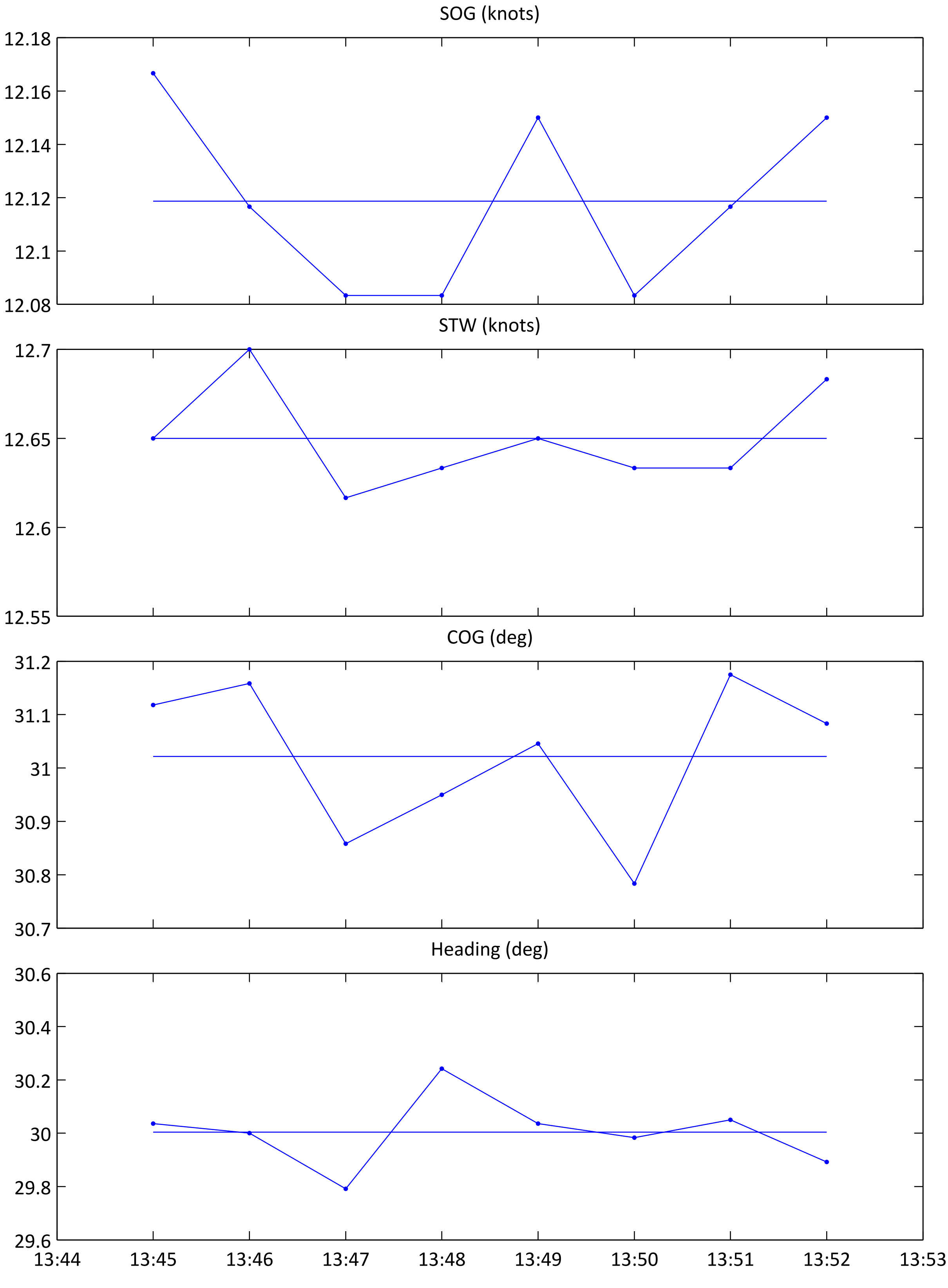
Run 15 Figure: 45



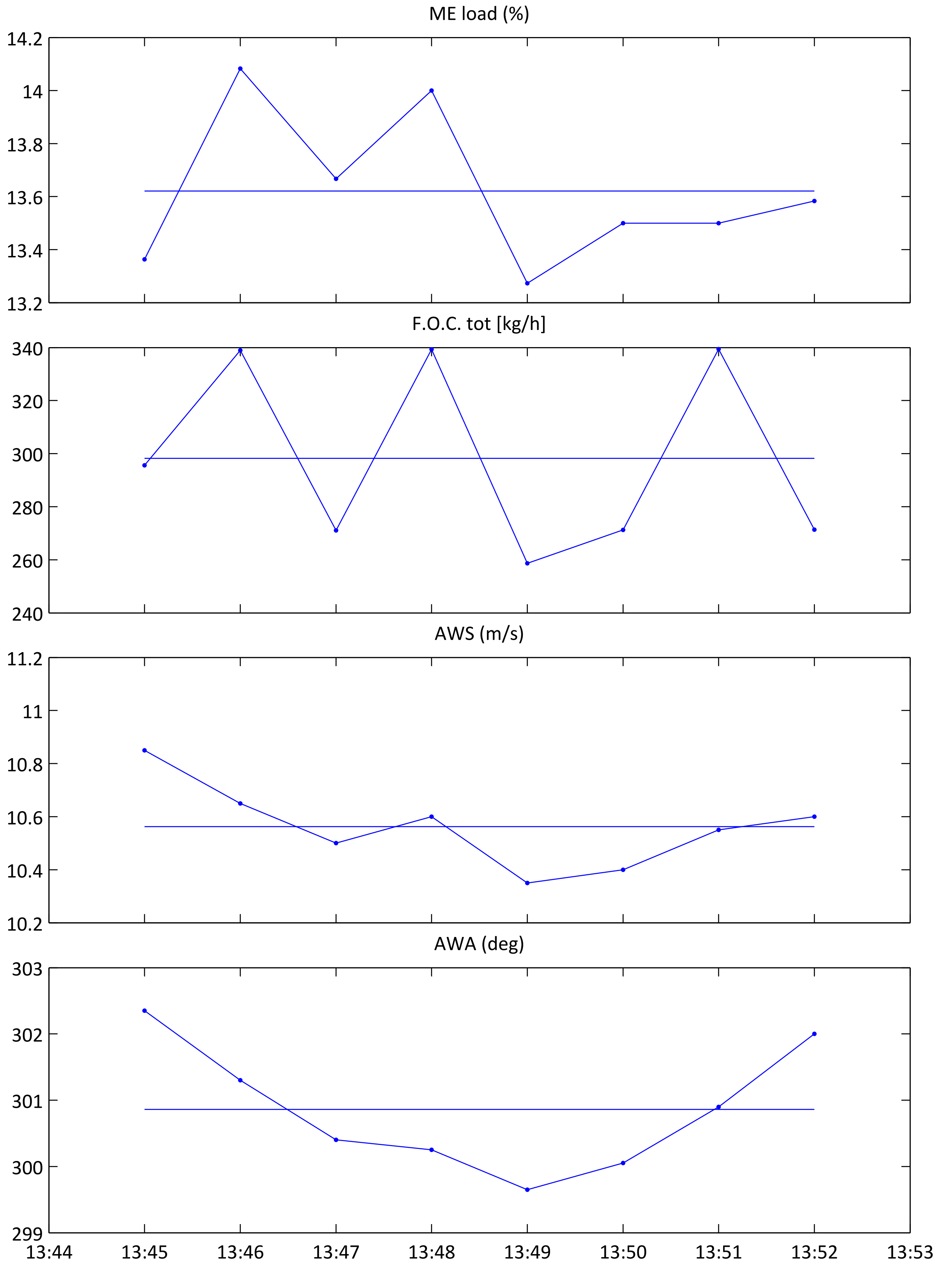
Run 15 Figure: 46



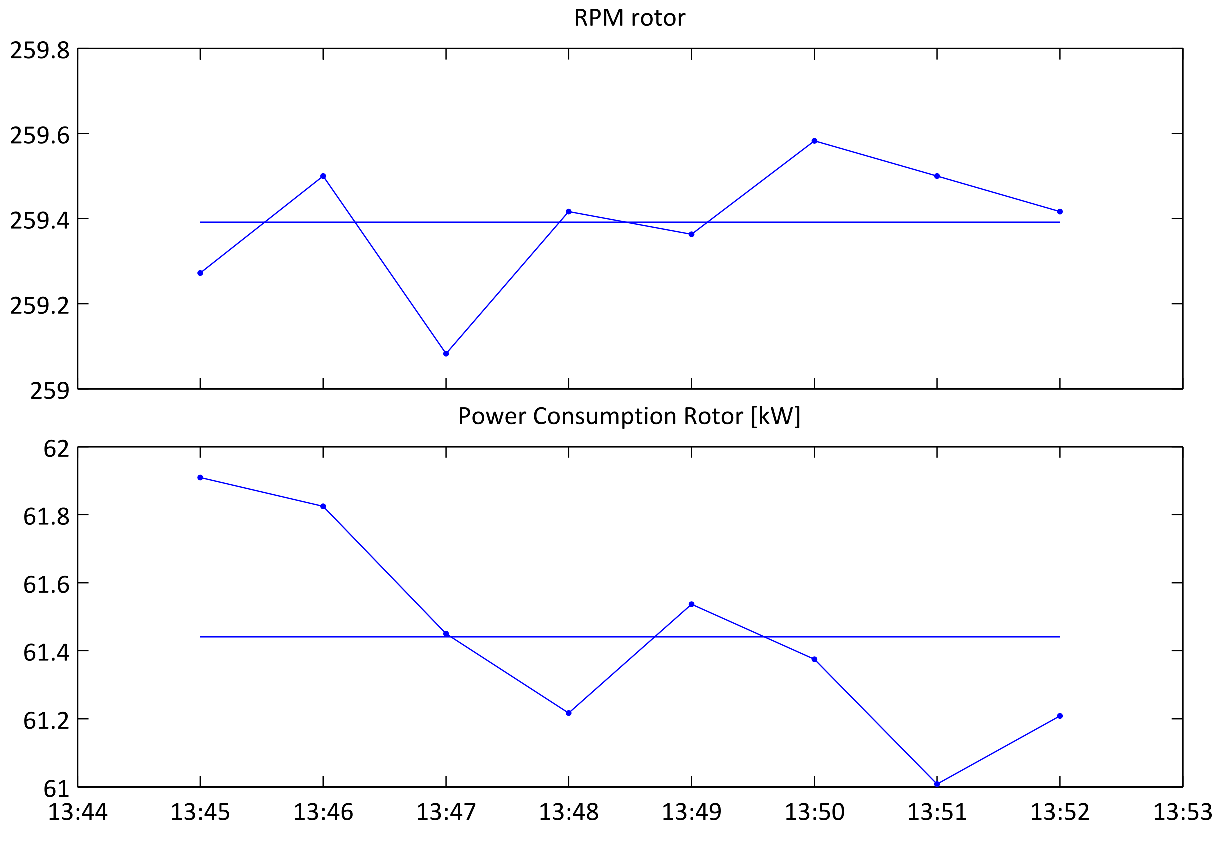
Run 16 Figure: 47



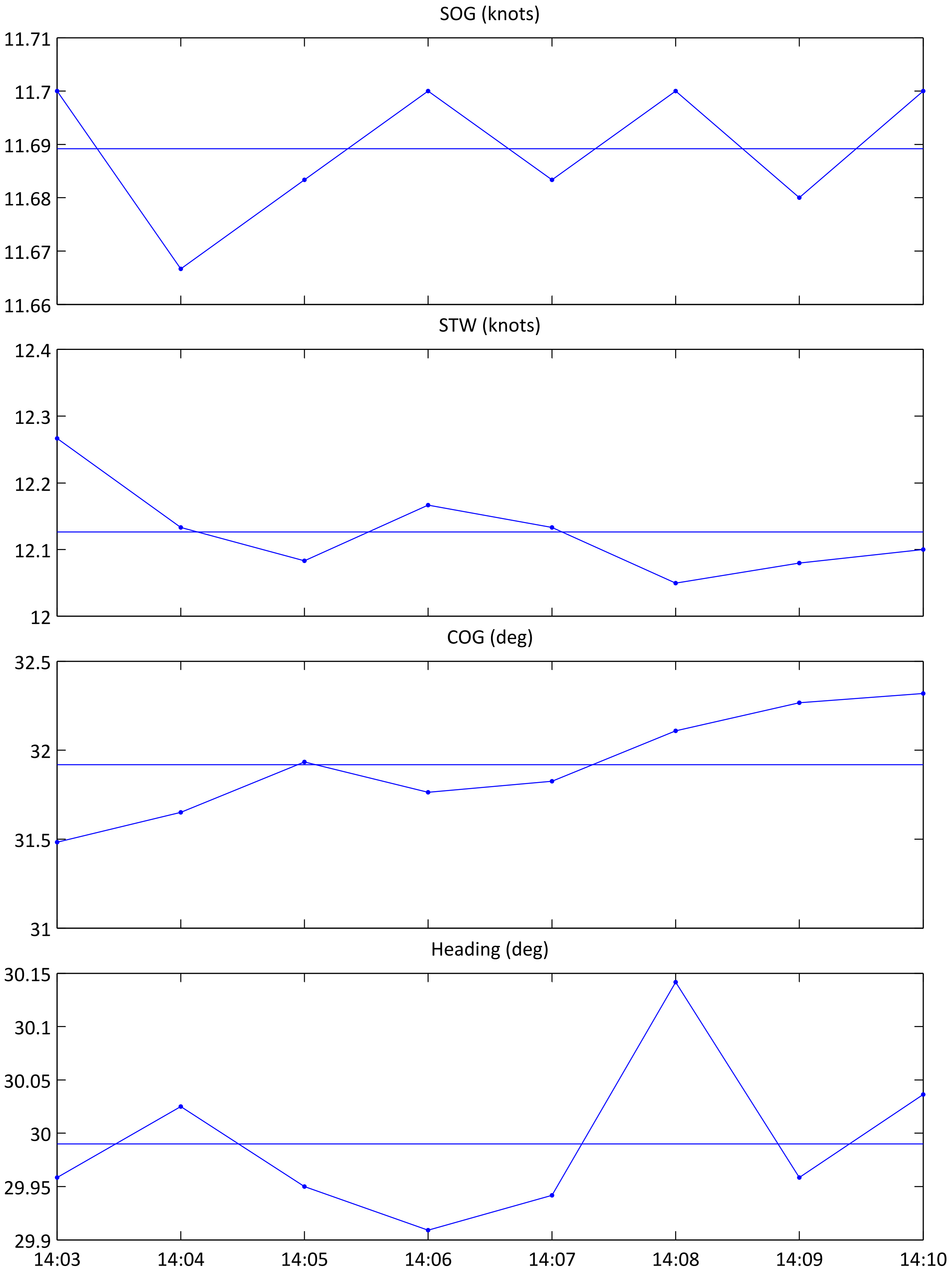
Run 16 Figure: 48



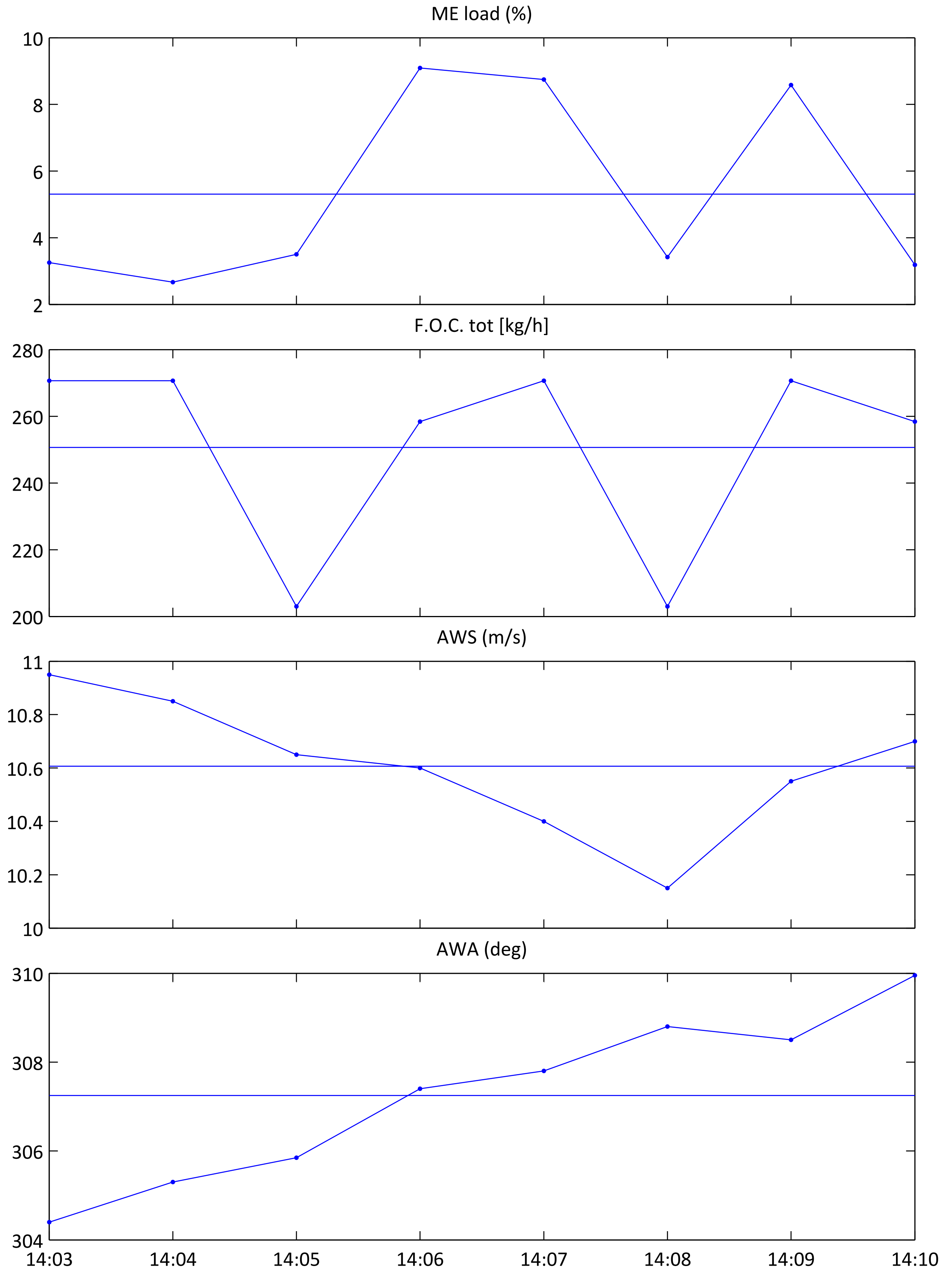
Run 16 Figure: 49



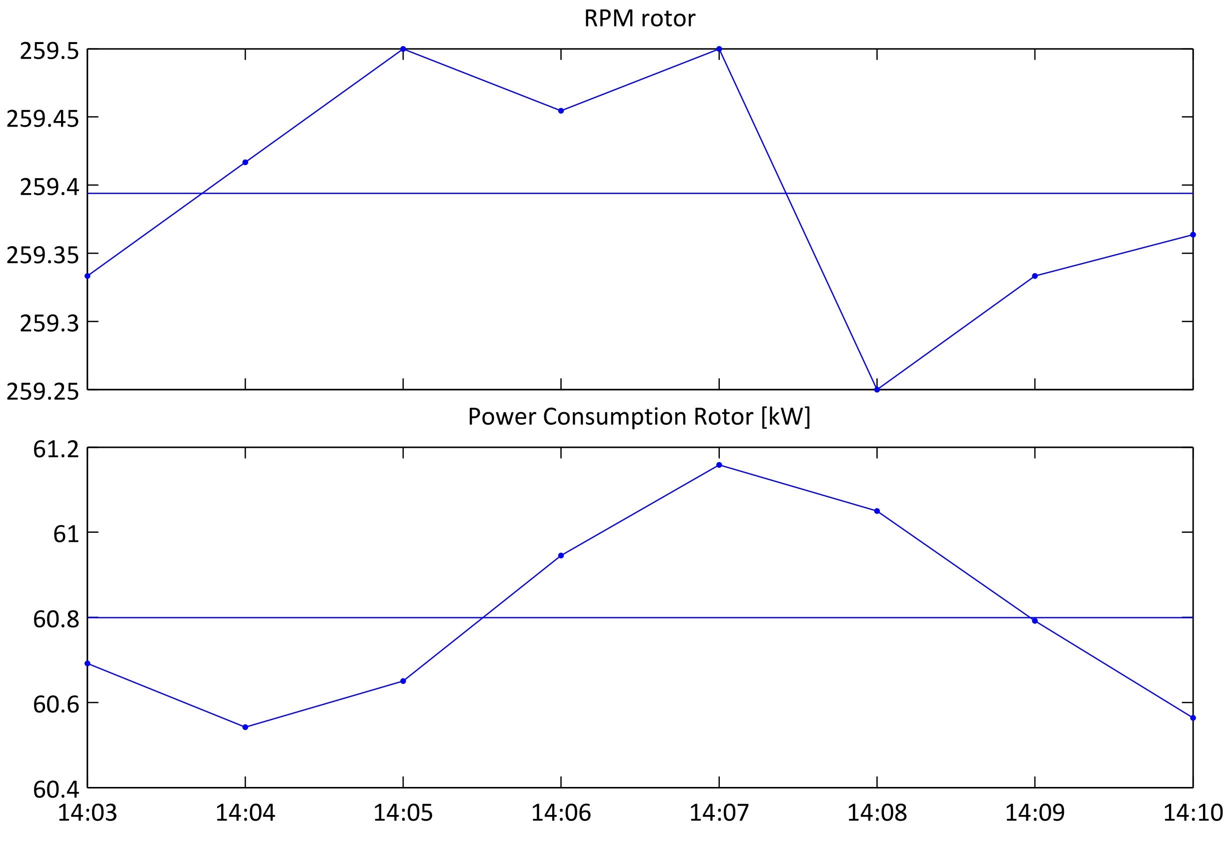
Run 17 Figure: 50



Run 17 Figure: 51



Run 17 Figure: 52



Ship particulars		Propulsion particulars	
SSPA hull no.		SSPA propeller no.	x
Length L_{PP} [m]	85.00	Number of propellers	1
Length L_{WL} [m]	85.00	Number of blades (each)	
Beam B [m]	15.00	Propeller diameter [m]	
Cb [-]	0.72	Pitch ratio [-]	
C_p [-]	1.00	C_n [-]	1.000
ESD	no	MCR [kW]	1850

Loading condition	Baseline	Sea trial	Warnings
Displacement [metric tonnes]	3541	3541	
Draft at aft perpendicular (T_A) [m]	4.00	4.25	
Draft at forward perpendicular (T_F) [m]	2.80	3.35	Dev. of draft at FP: 0.55m > 0.1m
Transverse projected area‡ (A_T) [m²]	202	195	

Nomenclature of environmental parameters					
TWD	True wind direction	$H_{W1/3}$	Significant height of local wind driven waves	h	Water depth
AWA	Apparent wind angle	θ_{WT}	True wave direction	ρ_{air}	Density of air
AWS	Apparent wind speed	θ_{SR}	Relative swell direction	ν_{water}	Kinematic viscosity of sea water
TWS	True wind speed	θ_{ST}	True swell direction	ρ_{water}	Density of sea water
TWA	True wind angle	$H_{S1/3}$	Significant height of local swell	T_{water}	Water temperature
T_{Wm}	Mean wave period	T_{Sm}	Swell period	T_{air}	Air temperature
		θ_{WR}	Relative wave direction		
Remarks: Relative directions are defined from bow, positive to s.b. All wave and wind directions are defined as the direction the waves or wind come from. 0º=from the bow.					

Environment			
Air temperature [deg C]	14.0	Water temperature [deg C]	14
Air density [kg/m³]	1.230	Water density [kg/m³]	1000
Water depth [m]	1000		

Onboard measurements					
Run		Heading [deg]	V_S (STW) [knots]	Shaft rate [1/min]	P_d [kW]
1		101	10.45	144.0	946
2		158	10.41	146.0	864
5		196	11.57	146.0	1157
8		231	11.51	144.0	1248
11		290	11.64	144.0	1349
12		245	11.19	144.0	1128
15		30	12.35	144.0	1340
3		160	10.74	146.0	793
4		160	10.58	146.0	793
6		196	12.07	146.0	1109
7		196	11.45	144.0	946
9		231	11.87	144.0	1197
10		231	11.34	144.0	1043
13		245	11.49	144.0	1119
14		245	11.26	144.0	1086
16		30	12.65	144.0	1316
17		30	12.13	144.0	1143

Wind at the height of anemometer					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	TWD [deg]
1	2.79	-158	8.03	-172	288
2	6.26	99	8.88	136	294
5	9.01	80	9.94	117	312
8	15.41	50	12.46	71	303
11	15.80	0	9.81	-0	290
12	14.86	33	10.53	51	296
15	11.08	-60	9.68	-95	295
3	6.48	98	9.06	135	295
4	6.08	99	8.78	137	297
6	9.69	76	10.18	112	308
7	9.71	75	9.99	110	306
9	15.34	41	11.48	62	293
10	14.76	40	10.97	60	291
13	14.46	30	9.79	47	292
14	14.25	30	9.64	47	292
16	10.56	-59	9.13	-97	293
17	10.61	-53	8.44	-89	301

Wind at the height of anemometer - averaged over double runs (only run 1 and 11)					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	GWA [deg]
1	3.69	-159	8.92	-172	289
11	14.91	-0	8.92	-1	289

Wind at reference height					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	TWD [deg]
2	5.46	93	7.84	136	294
5	8.10	76	8.77	117	312
8	14.06	48	11.00	71	303
12	13.69	32	9.29	51	296
15	10.17	-57	8.55	-95	295
3	5.67	91	7.99	135	295
4	5.30	92	7.75	137	297
6	8.76	71	8.98	112	308
7	8.77	71	8.82	110	306
9	14.08	39	10.13	62	293
10	13.56	38	9.68	60	291
13	13.37	28	8.64	47	292
14	13.17	28	8.51	47	292
16	9.74	-55	8.06	-97	293
17	9.82	-49	7.45	-89	301
1*)	2.67	-154	7.87	-172	289
11*)	13.86	-0	7.87	-1	289

Corrections						
Run no.	Wind [kN]	Waves [kN]	Depth [knots]	Temp/Dens [kN]	Idling WPU [kN]	Current [knots]
2	-2.1	0.0	0.00	-1.7	0.0	
5	-2.3	0.0	0.00	-2.0	0.0	
8	6.8	0.0	0.00	-2.0	1.6	
12	9.8	0.0	0.00	-1.9	2.6	
15	0.3	0.0	0.00	-2.3	0.5	
3	-2.2	0.0	0.00	-1.8	0.0	
4	-2.1	0.0	0.00	-1.8	0.0	
6	-2.3	0.0	0.00	-2.2	0.0	
7	-2.0	0.0	0.00	-2.0	0.0	
9	9.3	0.0	0.00	-2.1	0.0	
10	8.8	0.0	0.00	-2.0	0.0	
13	9.3	0.0	0.00	-2.0	0.0	
14	9.1	0.0	0.00	-1.9	0.0	
16	0.2	0.0	0.00	-2.4	0.0	
17	1.5	0.0	0.00	-2.2	0.0	
1*)	-2.5	0.0	0.00	-1.7	0.2	
11*)	11.1	0.0	0.00	-2.1	3.7	

Corrections in percent of total resistance							
Run no.	Wind [%]	Waves [%]	Depth [%]	Temp/dens [%]	Idling WPU [%]	Displ. [%]	Eff. [%]
2	-1.7	0.0	0.0	-1.4	0.0	1.7	0.3
5	-1.6	0.0	0.0	-1.4	0.0	1.7	0.3
8	4.7	0.0	0.0	-1.4	1.1	1.7	0.3
12	7.8	0.0	0.0	-1.5	2.0	1.7	0.4
15	0.2	0.0	0.0	-1.5	0.3	1.7	0.4
3	-2.0	0.0	0.0	-1.7	0.0	1.7	0.0
4	-2.0	0.0	0.0	-1.6	0.0	1.7	0.0
6	-1.7	0.0	0.0	-1.6	0.0	1.7	0.2
7	-1.7	0.0	0.0	-1.7	0.0	1.7	0.2
9	6.8	0.0	0.0	-1.6	0.0	1.7	0.1
10	7.5	0.0	0.0	-1.7	0.0	1.7	0.1
13	7.2	0.0	0.0	-1.6	0.0	1.7	0.2
14	7.3	0.0	0.0	-1.6	0.0	1.7	0.2
16	0.1	0.0	0.0	-1.6	0.0	1.7	0.2
17	1.2	0.0	0.0	-1.7	0.0	1.7	0.2
1*)	-2.1	0.0	0.0	-1.4	0.2	1.7	0.9
11*)	7.2	0.0	0.0	-1.3	2.4	1.7	0.9

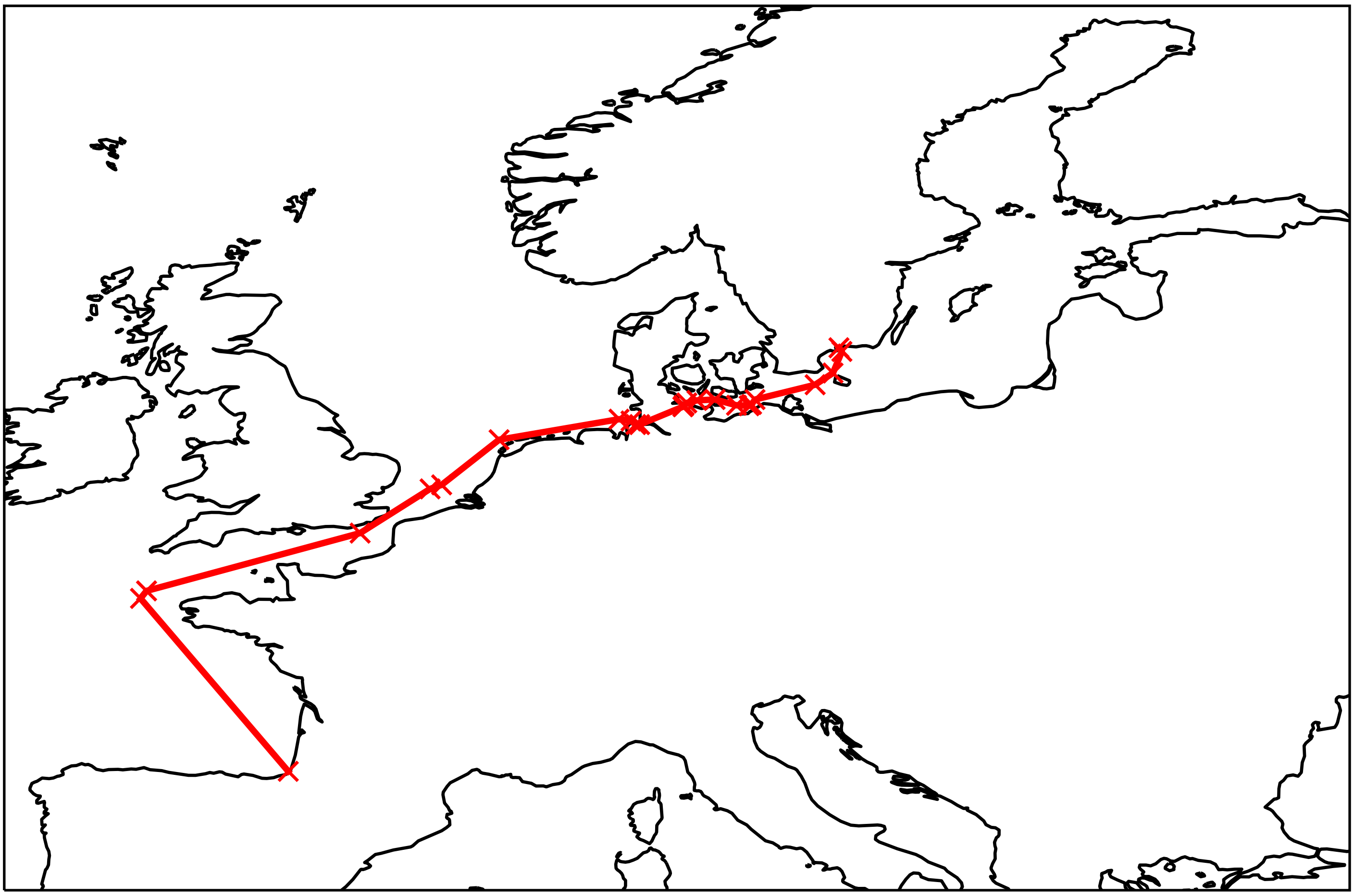
Corrected power		
Run no.	Pdt (ST) [kW]	Nt (ST) [RPM]
2	912	147.2
5	1218	147.1
8	1207	142.4
12	1046	141.0
15	1377	144.4
3	842	147.4
4	841	147.3
6	1171	147.2
7	1001	145.2
9	1146	142.1
10	994	141.9
13	1067	141.9
14	1035	141.9
16	1361	144.5
17	1169	144.2
1&11*)	999	144

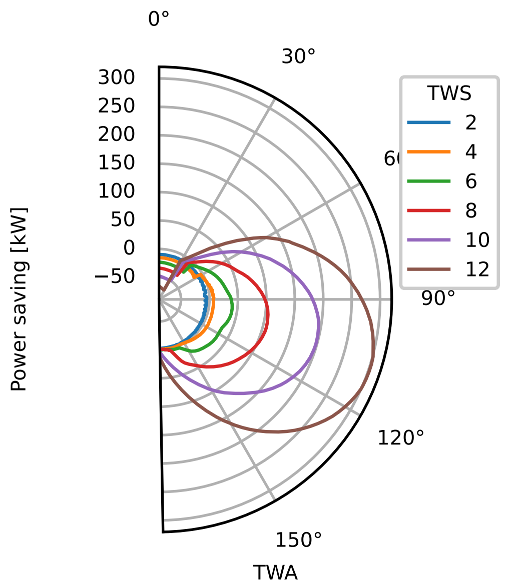
*) Run 1 and 11 evaluated as a double-run using wind averaging method

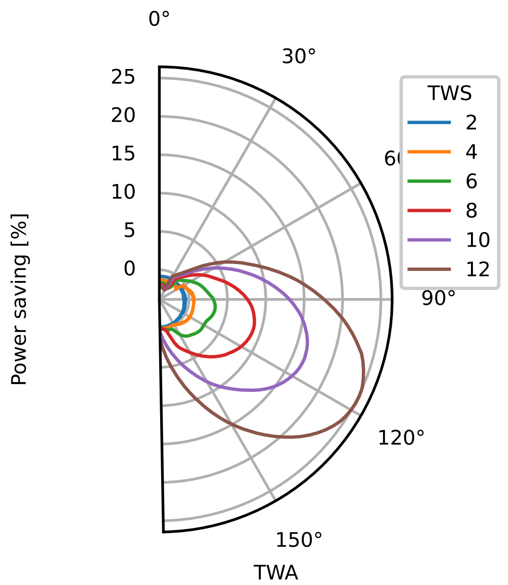
Route analysis report: WPS evaluation

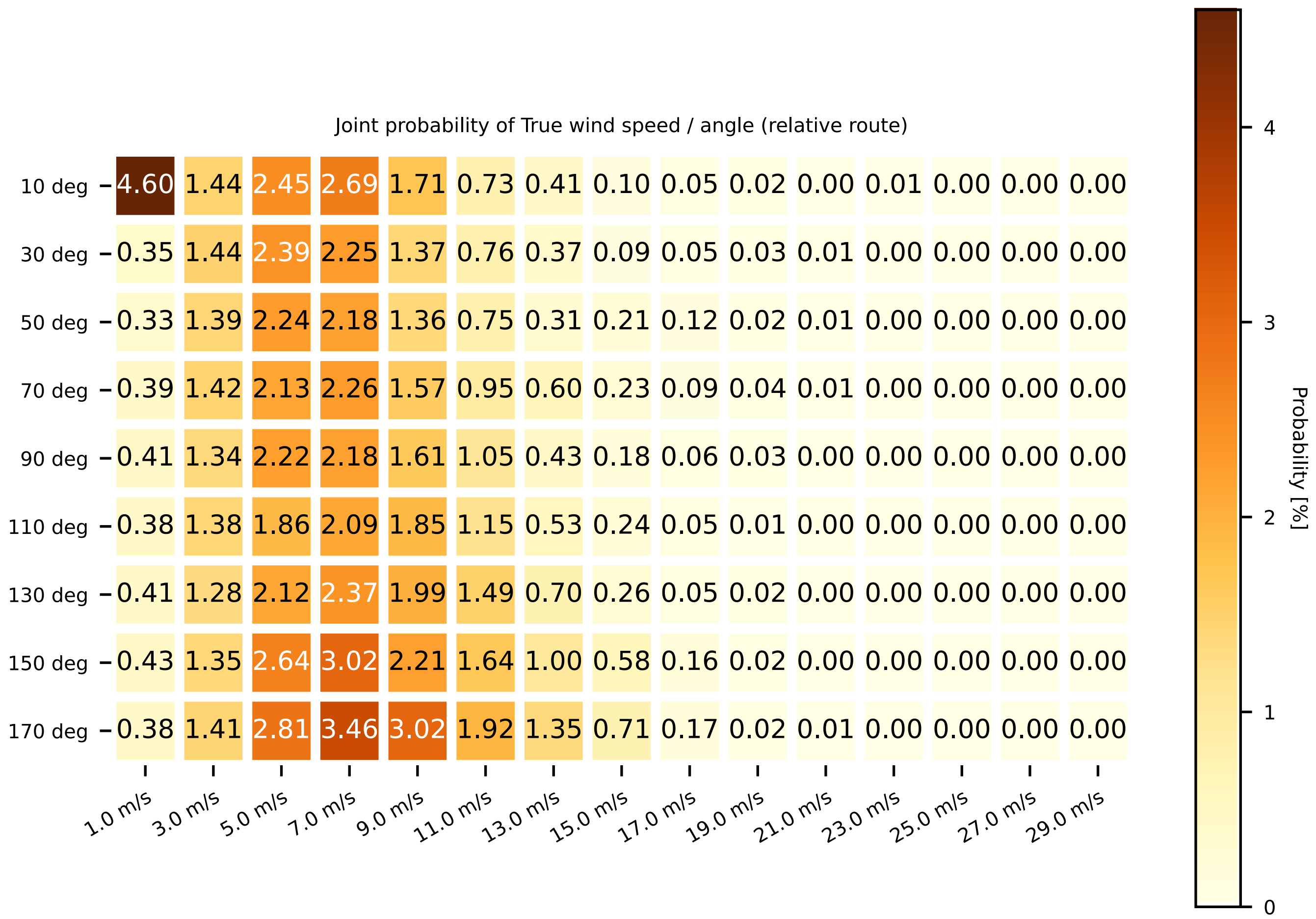
Results for a route analysis for ship: Annika Braren (ballast) on route: Karlshamn - Pasajes (inbound) with total distance: 1313.4 nm

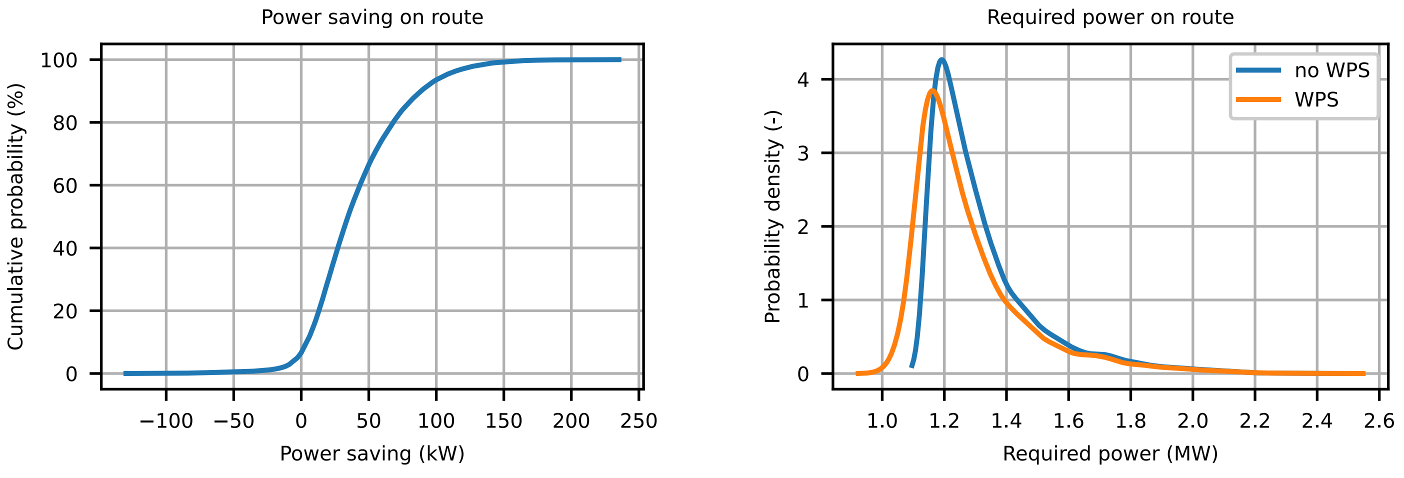
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	40.91	-10.67	123.39
Energy saving on route (MWh)	4.67	-1.22	14.09
Energy saving on route (%)	3.2	-0.7	9.7




Power saving [kW]
0°
30°
90°
120°
150°
300
250
200
150
100
50
0
−50
TWA
TWS
2
4
6
8
10
12


Power saving [%]
0°
30°
90°
120°
150°
25
20
15
10
5
0
TWA
TWS
2
4
6
8
10
12

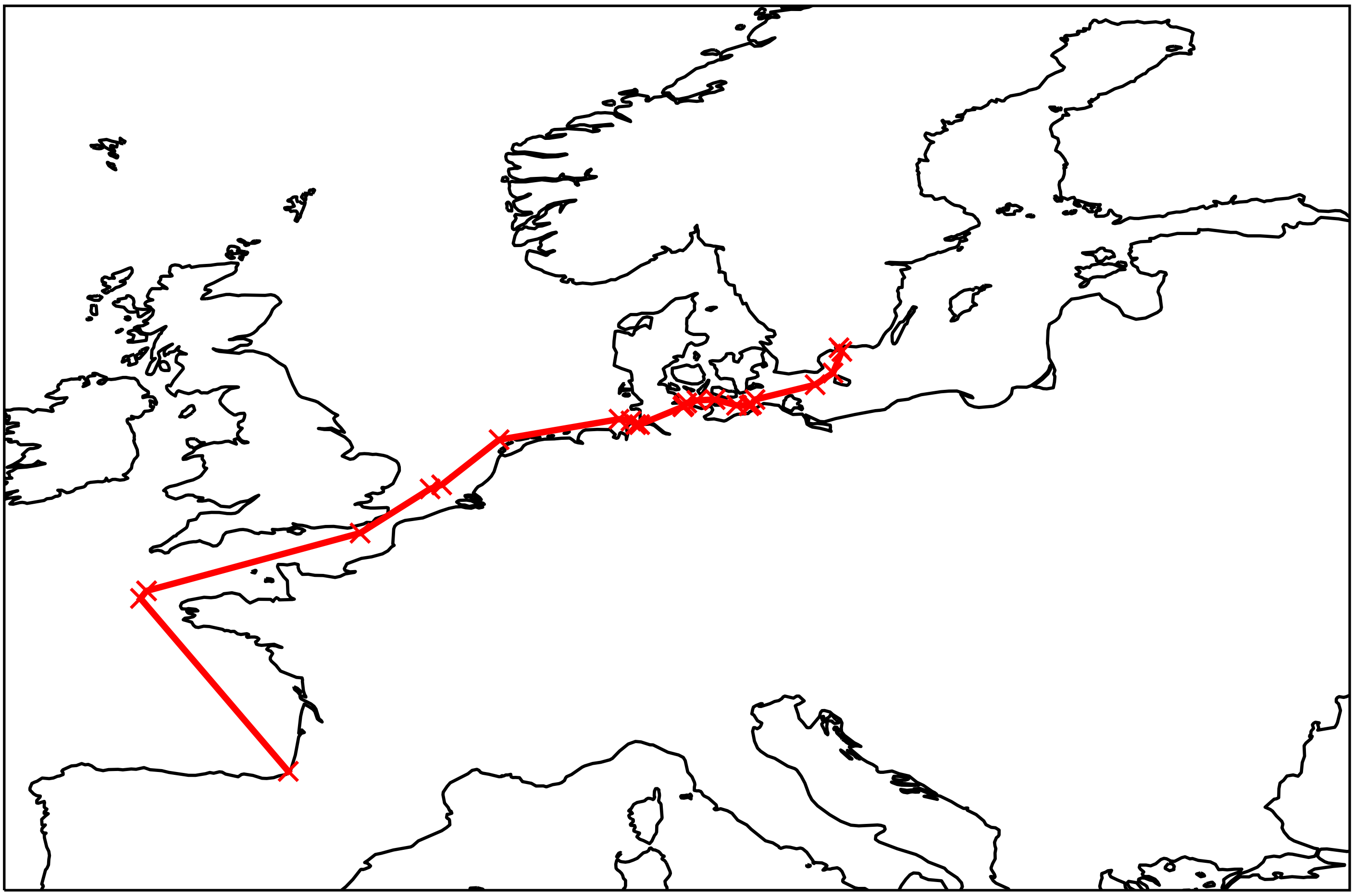

Joint probability of True wind speed / angle (relative route)
10 deg 4.60 1.44 2.45 2.69 1.71 0.73 0.41 0.10 0.05 0.02 0.00 0.01 0.00 0.00 0.00
30 deg 0.35 1.44 2.39 2.25 1.37 0.76 0.37 0.09 0.05 0.03 0.01 0.00 0.00 0.00 0.00
50 deg 0.33 1.39 2.24 2.18 1.36 0.75 0.31 0.21 0.12 0.02 0.01 0.00 0.00 0.00 0.00
70 deg 0.39 1.42 2.13 2.26 1.57 0.95 0.60 0.23 0.09 0.04 0.01 0.00 0.00 0.00 0.00
90 deg 0.41 1.34 2.22 2.18 1.61 1.05 0.43 0.18 0.06 0.03 0.00 0.00 0.00 0.00 0.00
110 deg 0.38 1.38 1.86 2.09 1.85 1.15 0.53 0.24 0.05 0.01 0.00 0.00 0.00 0.00 0.00
130 deg 0.41 1.28 2.12 2.37 1.99 1.49 0.70 0.26 0.05 0.02 0.00 0.00 0.00 0.00 0.00
150 deg 0.43 1.35 2.64 3.02 2.21 1.64 1.00 0.58 0.16 0.02 0.00 0.00 0.00 0.00 0.00
170 deg 0.38 1.41 2.81 3.46 3.02 1.92 1.35 0.71 0.17 0.02 0.01 0.00 0.00 0.00 0.00
1.0 m/s
3.0 m/s
5.0 m/s
7.0 m/s
9.0 m/s
11.0 m/s
13.0 m/s
15.0 m/s
17.0 m/s
19.0 m/s
21.0 m/s
23.0 m/s
25.0 m/s
27.0 m/s
29.0 m/s
Probability [%]
4
3
2
1
0

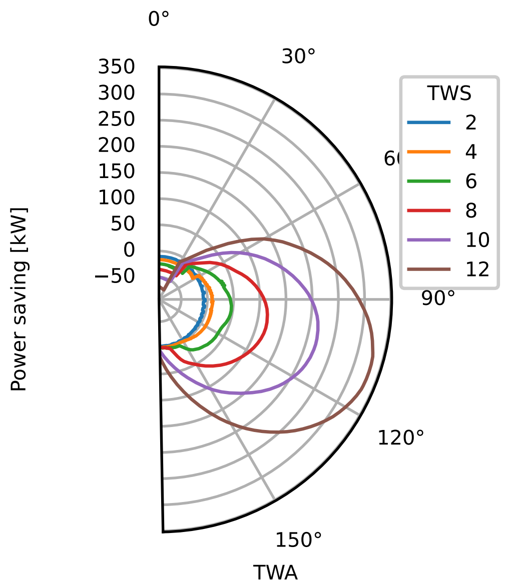

Power saving on route
Cumulative probability (%)
Power saving (kW)
Required power on route
Probability density (-)
Required power (MW)
no WPS
WPS

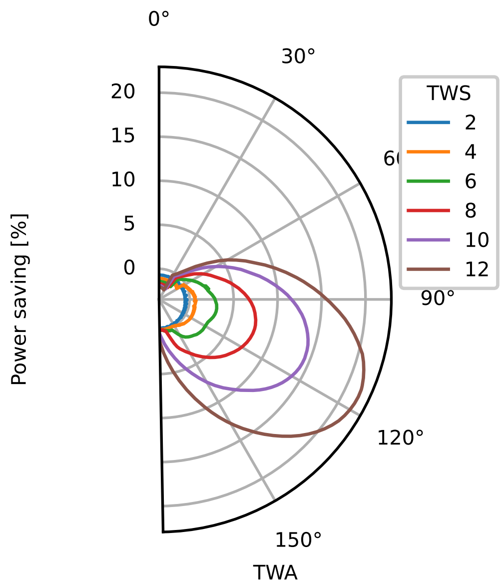
Route analysis report: WPS evaluation

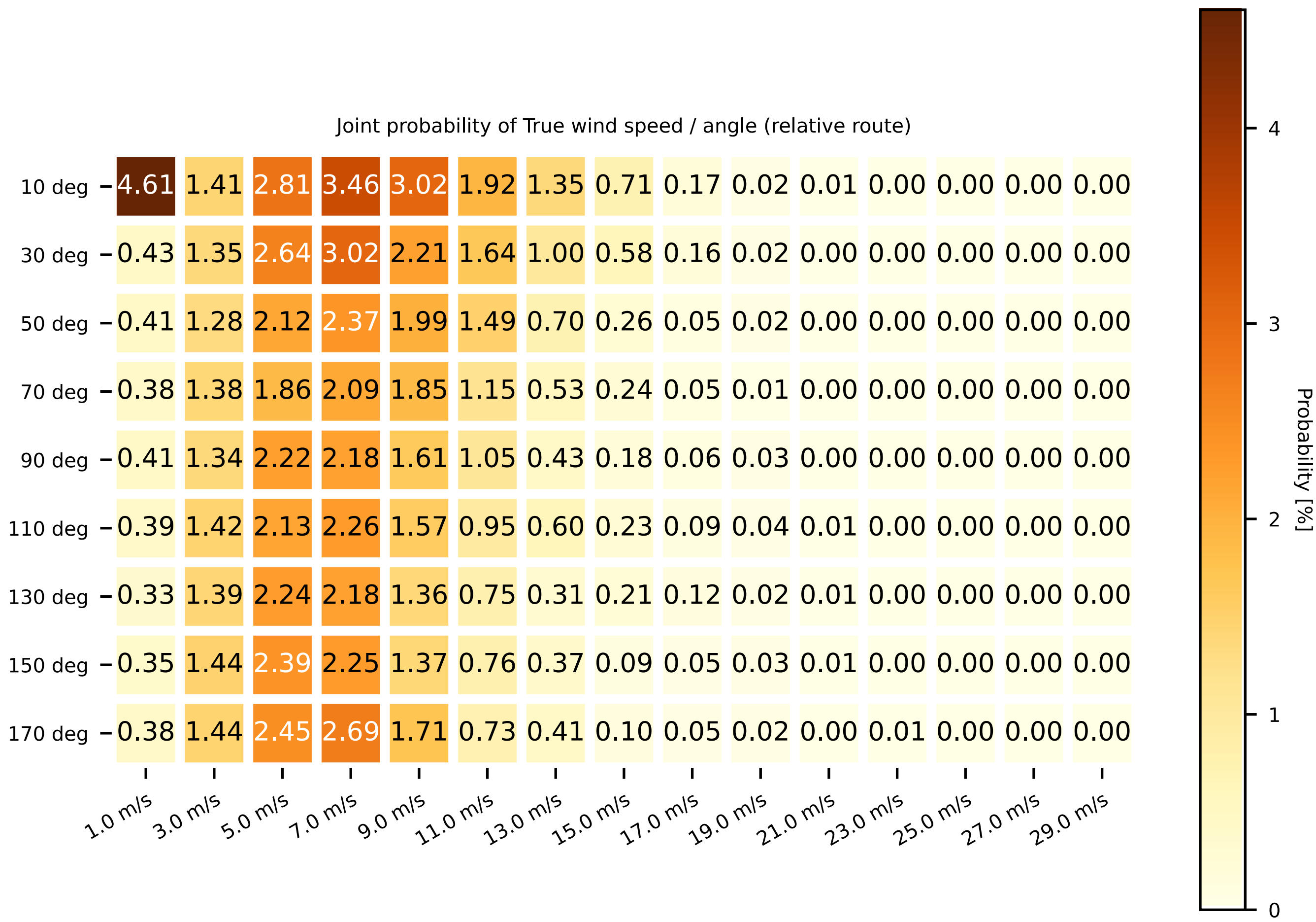
Results for a route analysis for ship: Annika Braren (laden) on route: Karlshamn - Pasajes (outbound) with total distance: 1313.4 nm

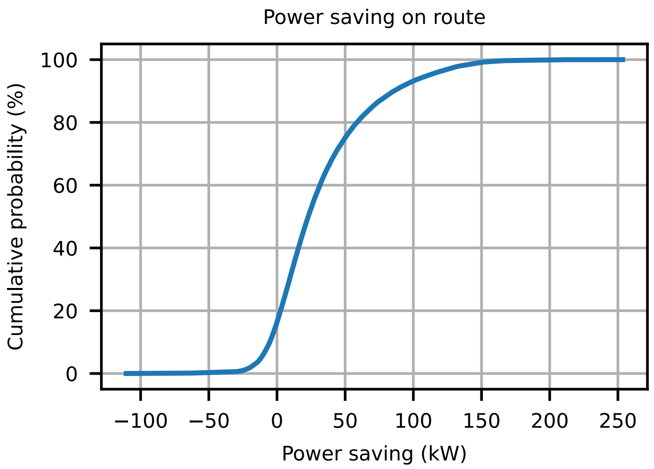
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	32.17	-17.50	129.37
Energy saving on route (MWh)	3.67	-2.00	14.77
Energy saving on route (%)	1.9	-0.9	7.5

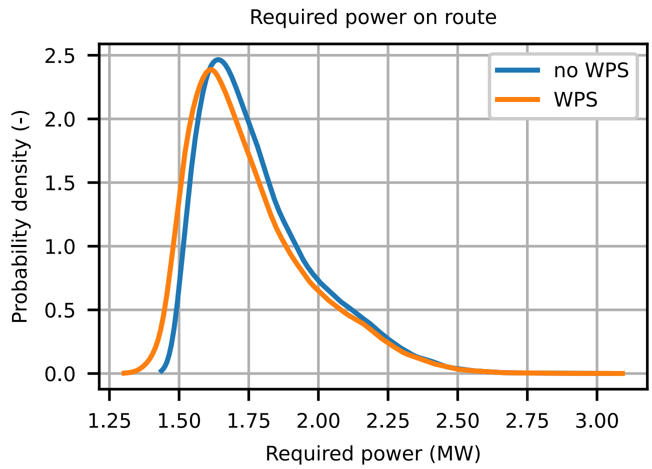



0°
30°
60°
90°
120°
150°
350
300
250
200
150
100
50
0
−50
Power saving [kW]
TWA
TWS
2
4
6
8
10
12


0°
30°
60°
90°
120°
150°
20
15
10
5
0
Power saving [%]
TWA
TWS
2
4
6
8
10
12


Joint probability of True wind speed / angle (relative route)
10 deg 4.61 1.41 2.81 3.46 3.02 1.92 1.35 0.71 0.17 0.02 0.01 0.00 0.00 0.00 0.00
30 deg 0.43 1.35 2.64 3.02 2.21 1.64 1.00 0.58 0.16 0.02 0.00 0.00 0.00 0.00 0.00
50 deg 0.41 1.28 2.12 2.37 1.99 1.49 0.70 0.26 0.05 0.02 0.00 0.00 0.00 0.00 0.00
70 deg 0.38 1.38 1.86 2.09 1.85 1.15 0.53 0.24 0.05 0.01 0.00 0.00 0.00 0.00 0.00
90 deg 0.41 1.34 2.22 2.18 1.61 1.05 0.43 0.18 0.06 0.03 0.00 0.00 0.00 0.00 0.00
110 deg 0.39 1.42 2.13 2.26 1.57 0.95 0.60 0.23 0.09 0.04 0.01 0.00 0.00 0.00 0.00
130 deg 0.33 1.39 2.24 2.18 1.36 0.75 0.31 0.21 0.12 0.02 0.01 0.00 0.00 0.00 0.00
150 deg 0.35 1.44 2.39 2.25 1.37 0.76 0.37 0.09 0.05 0.03 0.01 0.00 0.00 0.00 0.00
170 deg 0.38 1.44 2.45 2.69 1.71 0.73 0.41 0.10 0.05 0.02 0.00 0.01 0.00 0.00 0.00
1.0 m/s
3.0 m/s
5.0 m/s
7.0 m/s
9.0 m/s
11.0 m/s
13.0 m/s
15.0 m/s
17.0 m/s
19.0 m/s
21.0 m/s
23.0 m/s
25.0 m/s
27.0 m/s
29.0 m/s
Probability [%]
4
3
2
1
0

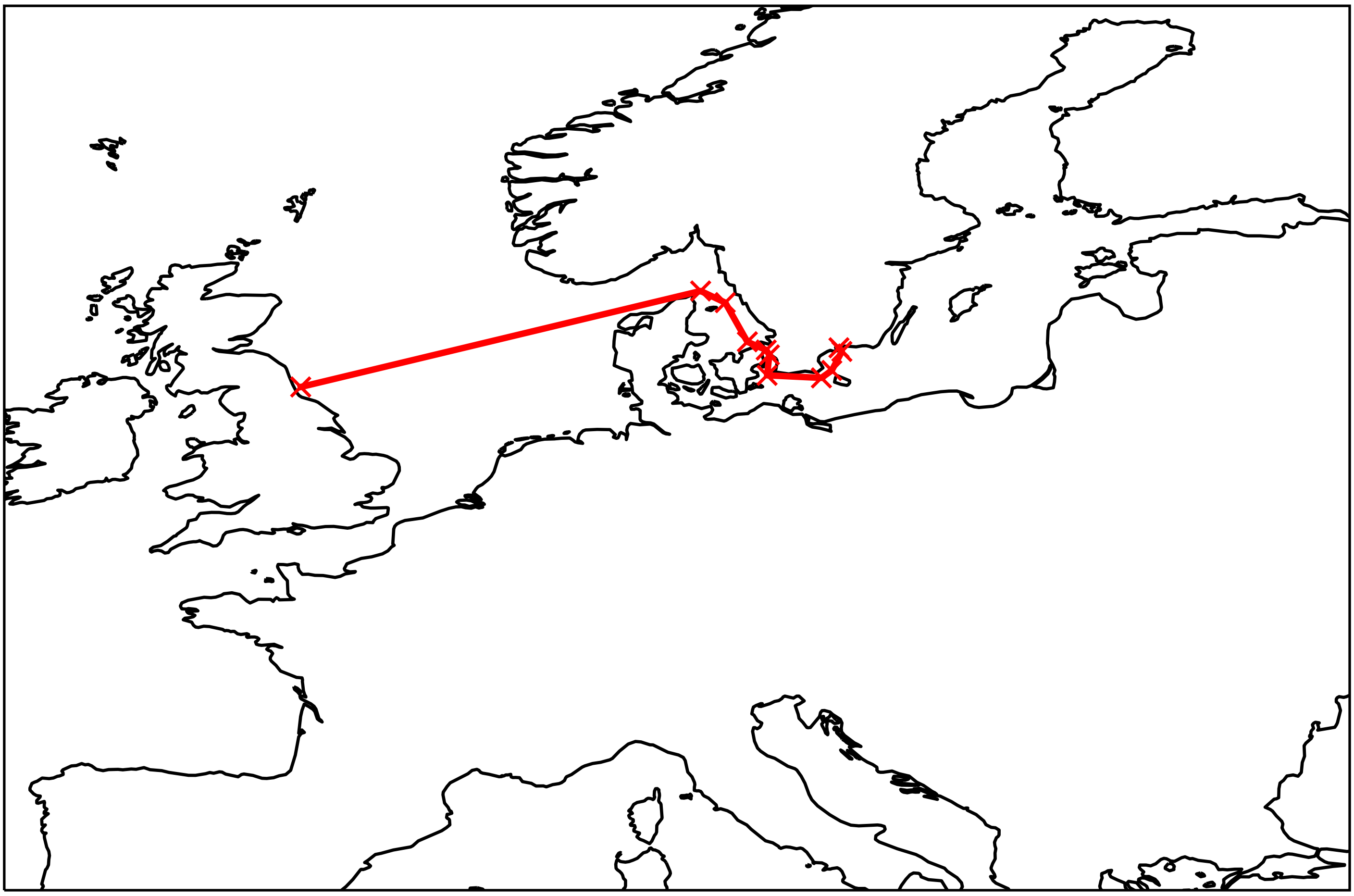

Power saving on route
Cumulative probability (%)
100
80
60
40
20
0
−100
−50
0
50
100
150
200
250
Power saving (kW)

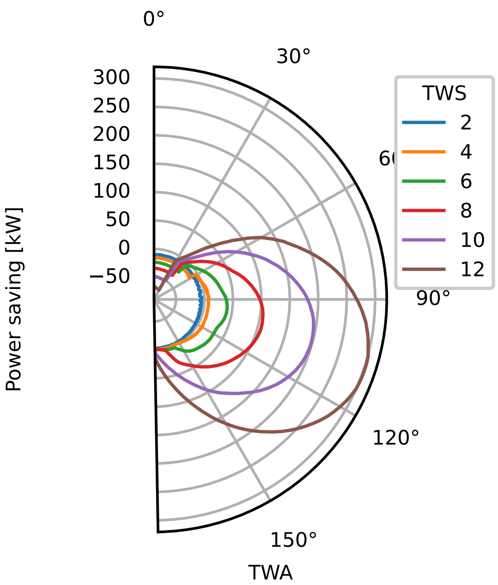

Required power on route
Probability density (-)
2.5
2.0
1.5
1.0
0.5
0.0
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
Required power (MW)
no WPS
WPS

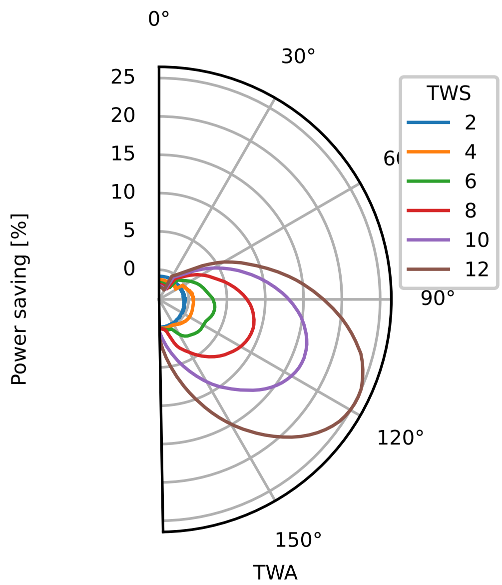
Route analysis report: WPS evaluation

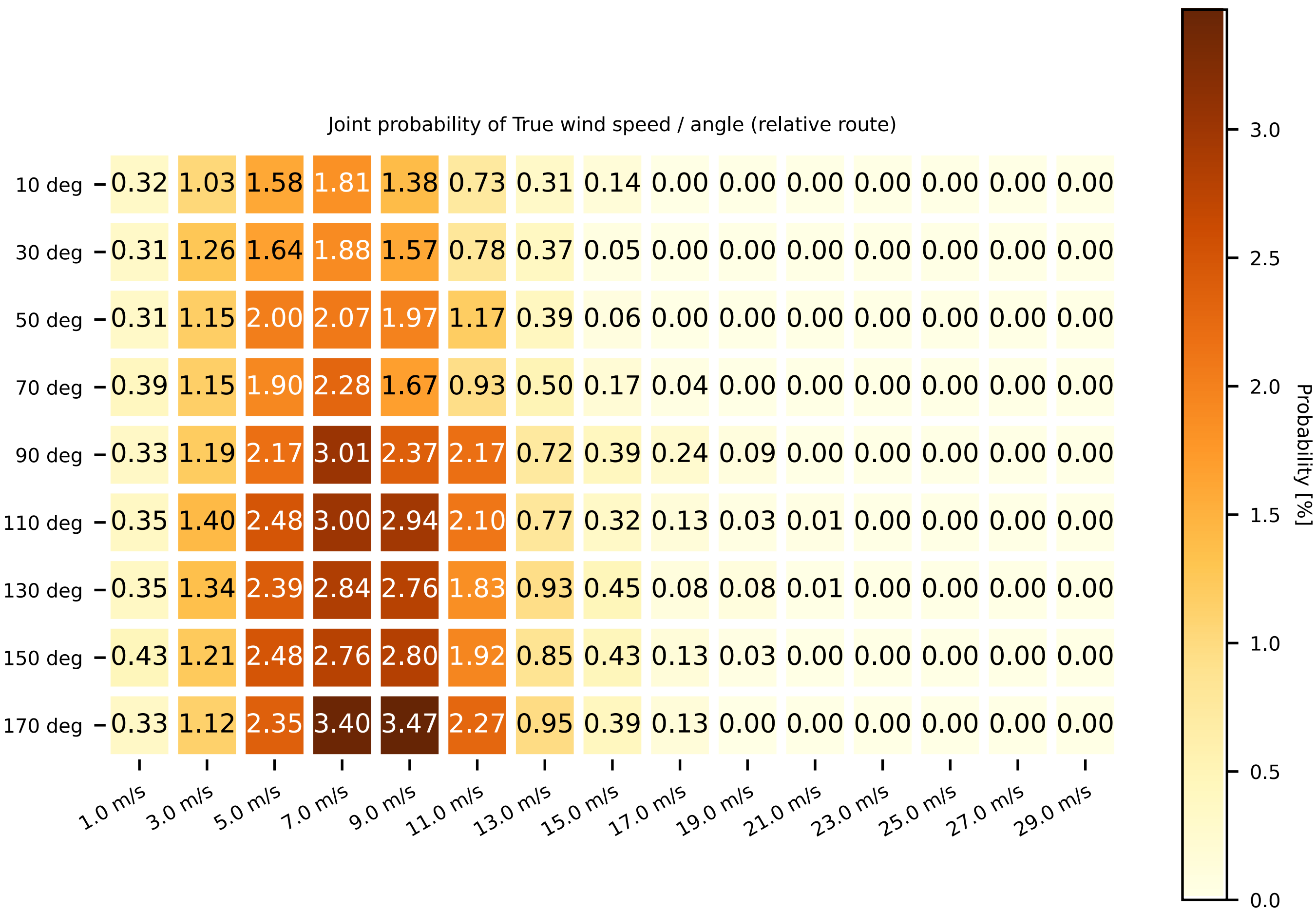
Results for a route analysis for ship: Annika Braren (ballast) on route: Karlshamn - Sunderland (inbound) with total distance: 721.1 nm

	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	60.32	-16.66	232.97
Energy saving on route (MWh)	3.78	-1.05	14.61
Energy saving on route (%)	4.7	-1.0	17.7

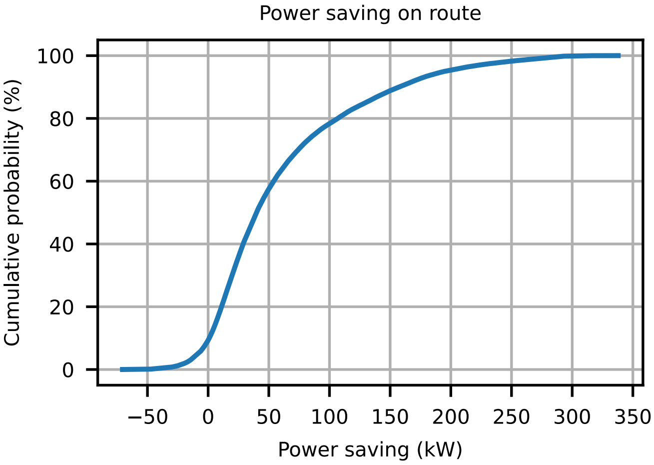


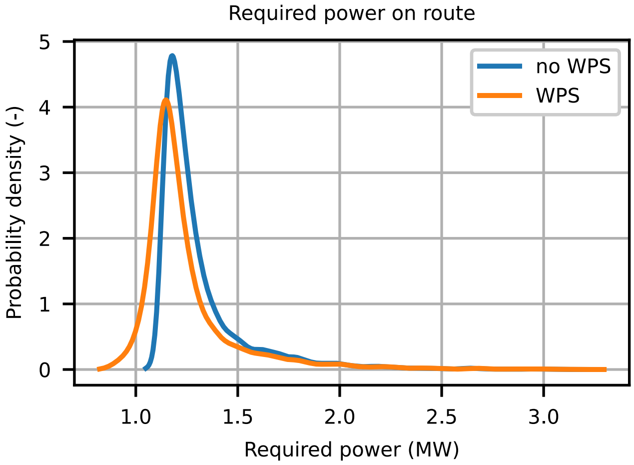






	1.0 m/s	3.0 m/s	5.0 m/s	7.0 m/s	9.0 m/s	11.0 m/s	13.0 m/s	15.0 m/s	17.0 m/s	19.0 m/s	21.0 m/s	23.0 m/s	25.0 m/s	27.0 m/s	29.0 m/s
10 deg	0.32	1.03	1.58	1.81	1.38	0.73	0.31	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30 deg	0.31	1.26	1.64	1.88	1.57	0.78	0.37	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50 deg	0.31	1.15	2.00	2.07	1.97	1.17	0.39	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70 deg	0.39	1.15	1.90	2.28	1.67	0.93	0.50	0.17	0.04	0.00	0.00	0.00	0.00	0.00	0.00
90 deg	0.33	1.19	2.17	3.01	2.37	2.17	0.72	0.39	0.24	0.09	0.00	0.00	0.00	0.00	0.00
110 deg	0.35	1.40	2.48	3.00	2.94	2.10	0.77	0.32	0.13	0.03	0.01	0.00	0.00	0.00	0.00
130 deg	0.35	1.34	2.39	2.84	2.76	1.83	0.93	0.45	0.08	0.08	0.01	0.00	0.00	0.00	0.00
150 deg	0.43	1.21	2.48	2.76	2.80	1.92	0.85	0.43	0.13	0.03	0.00	0.00	0.00	0.00	0.00
170 deg	0.33	1.12	2.35	3.40	3.47	2.27	0.95	0.39	0.13	0.00	0.00	0.00	0.00	0.00	0.00

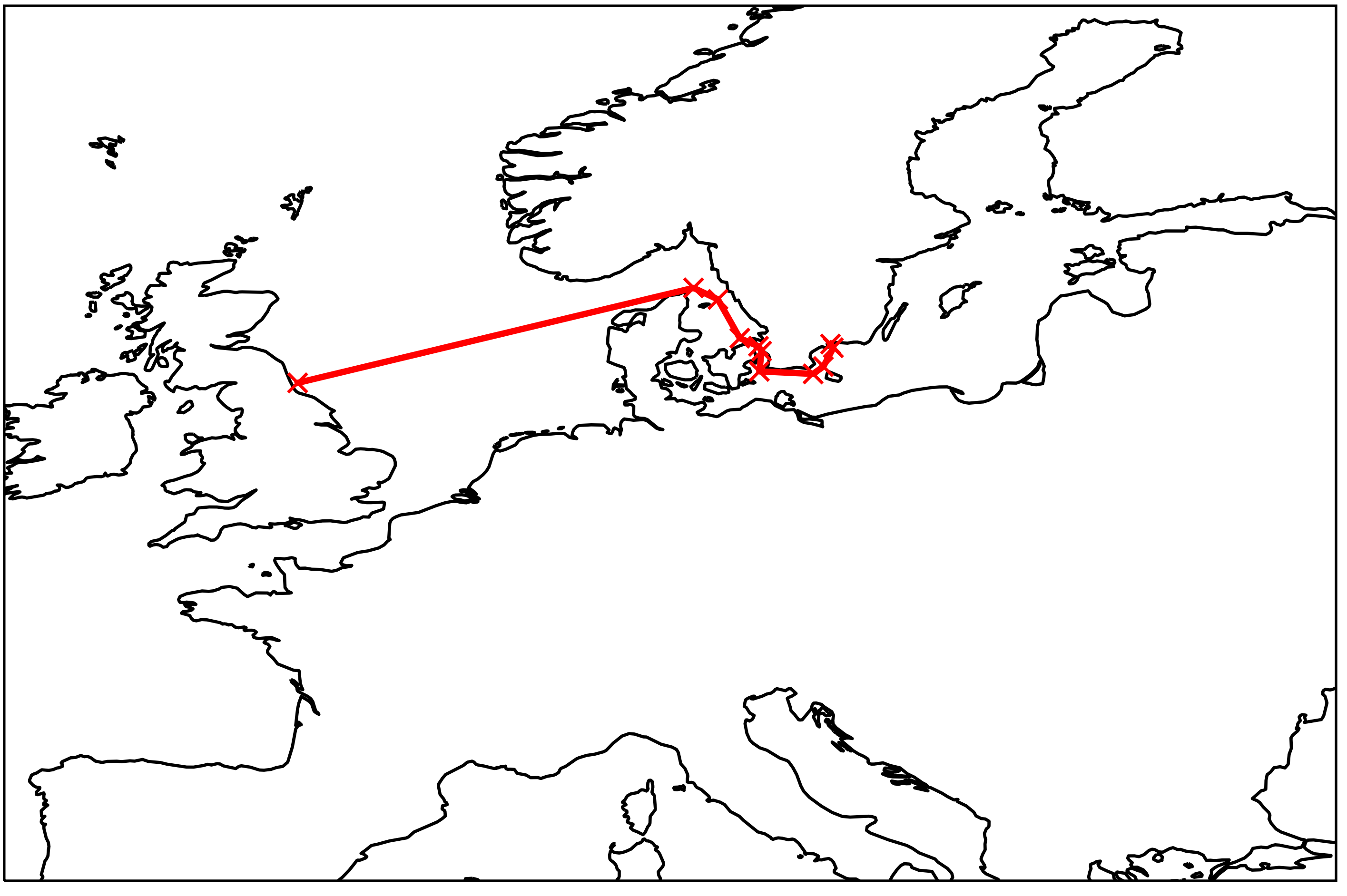

Power saving on route
Cumulative probability (%)
Power saving (kW)
0
20
40
60
80
100
−50
0
50
100
150
200
250
300
350

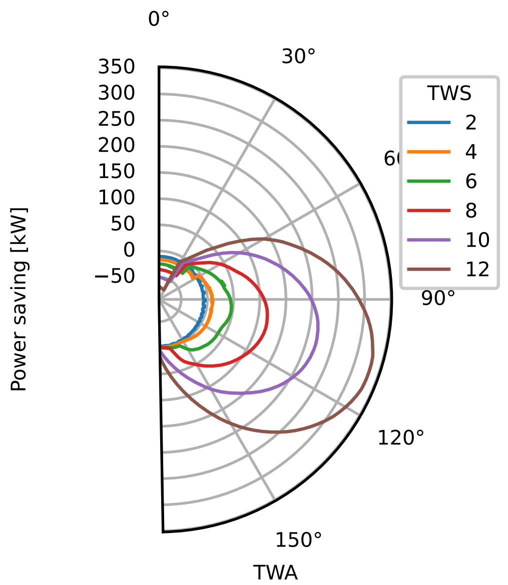

Required power on route
Probability density (-)
Required power (MW)
no WPS
WPS
0
1
2
3
4
5
1.0
1.5
2.0
2.5
3.0

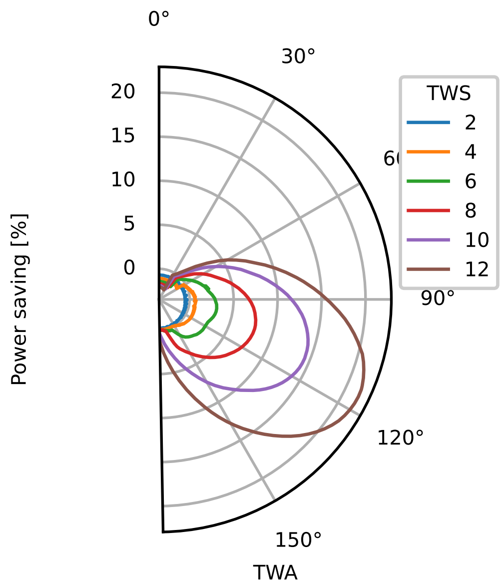
Route analysis report: WPS evaluation

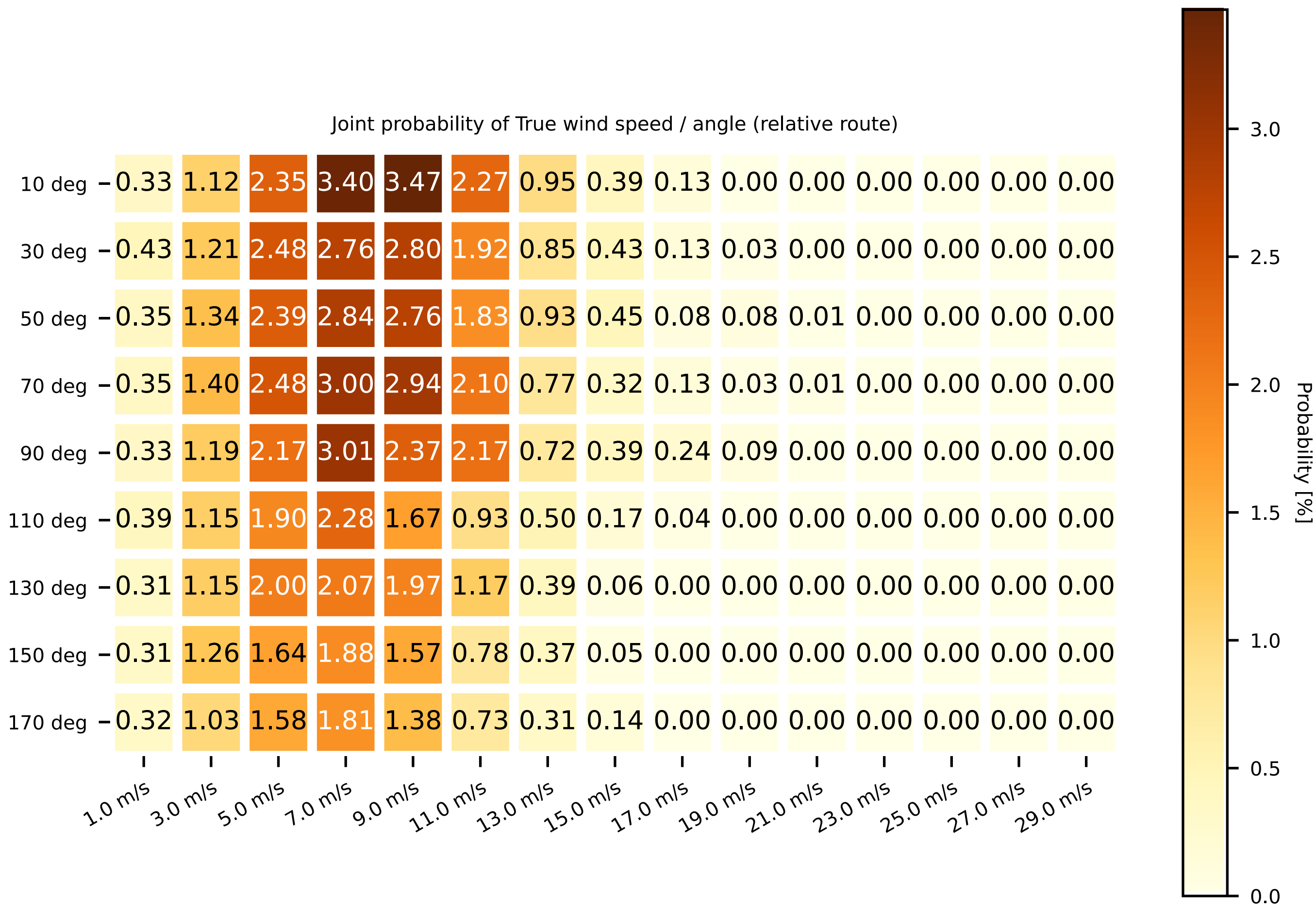
Results for a route analysis for ship: Annika Braren (laden) on route: Karlshamn - Sunderland (outbound) with total distance: 721.1 nm

	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	43.80	-33.44	215.76
Energy saving on route (MWh)	2.74	-2.10	13.52
Energy saving on route (%)	2.6	-1.3	12.3

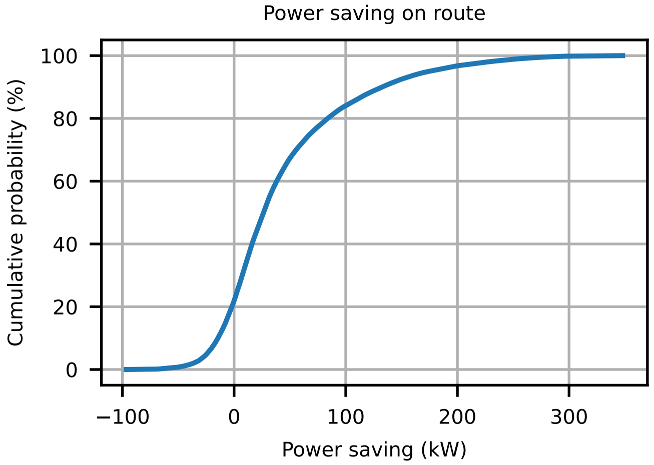


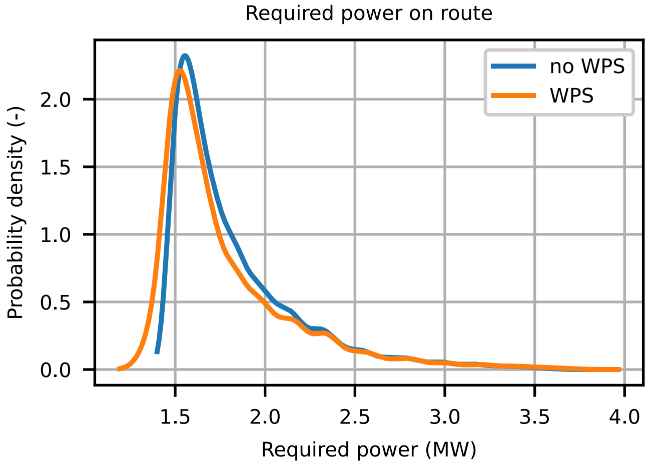






	1.0 m/s	3.0 m/s	5.0 m/s	7.0 m/s	9.0 m/s	11.0 m/s	13.0 m/s	15.0 m/s	17.0 m/s	19.0 m/s	21.0 m/s	23.0 m/s	25.0 m/s	27.0 m/s	29.0 m/s
10 deg	0.33	1.12	2.35	3.40	3.47	2.27	0.95	0.39	0.13	0.00	0.00	0.00	0.00	0.00	0.00
30 deg	0.43	1.21	2.48	2.76	2.80	1.92	0.85	0.43	0.13	0.03	0.00	0.00	0.00	0.00	0.00
50 deg	0.35	1.34	2.39	2.84	2.76	1.83	0.93	0.45	0.08	0.08	0.01	0.00	0.00	0.00	0.00
70 deg	0.35	1.40	2.48	3.00	2.94	2.10	0.77	0.32	0.13	0.03	0.01	0.00	0.00	0.00	0.00
90 deg	0.33	1.19	2.17	3.01	2.37	2.17	0.72	0.39	0.24	0.09	0.00	0.00	0.00	0.00	0.00
110 deg	0.39	1.15	1.90	2.28	1.67	0.93	0.50	0.17	0.04	0.00	0.00	0.00	0.00	0.00	0.00
130 deg	0.31	1.15	2.00	2.07	1.97	1.17	0.39	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00
150 deg	0.31	1.26	1.64	1.88	1.57	0.78	0.37	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
170 deg	0.32	1.03	1.58	1.81	1.38	0.73	0.31	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00

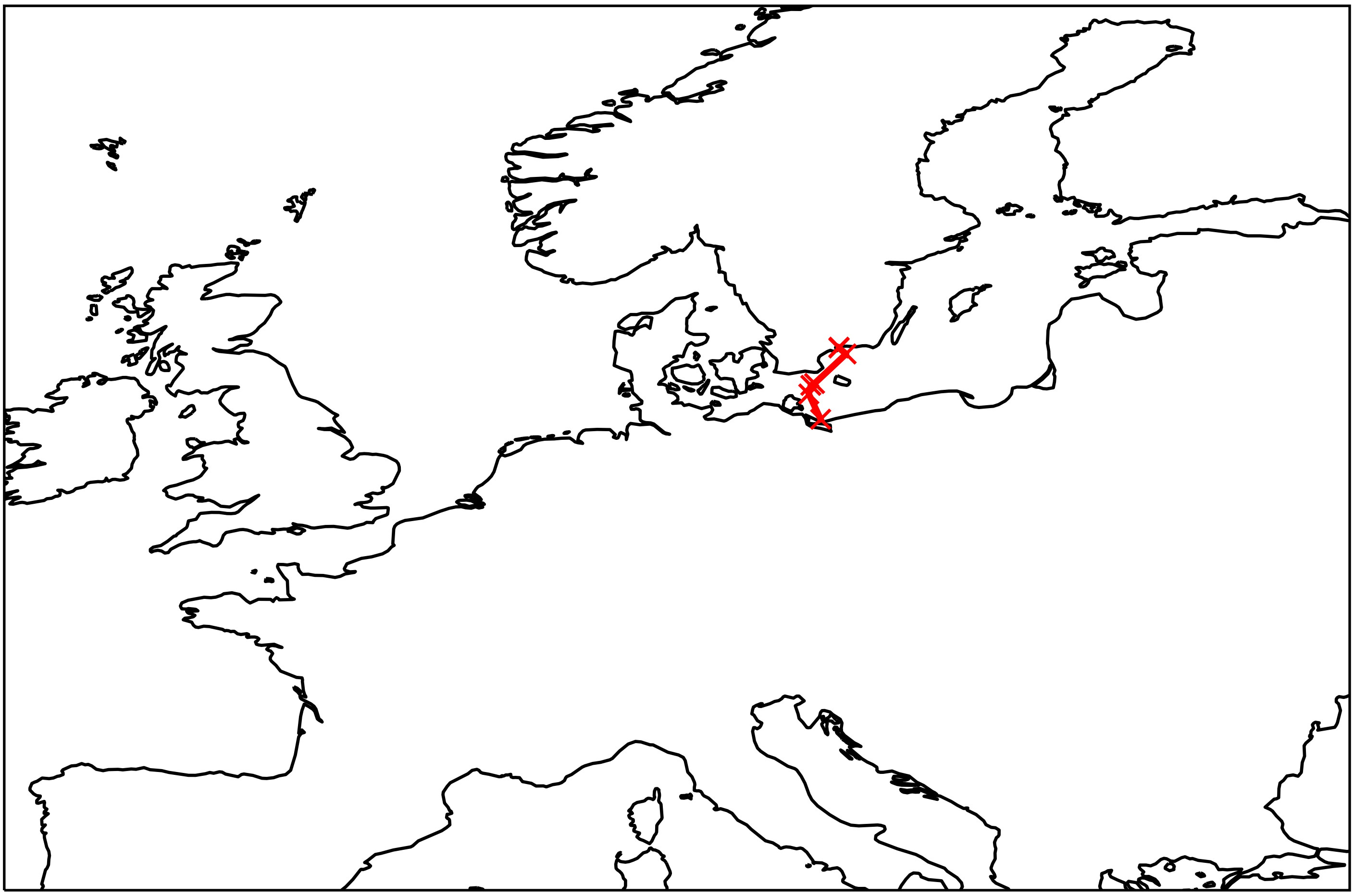

Power saving on route
Cumulative probability (%)
100
80
60
40
20
0
−100
0
100
200
300
Power saving (kW)

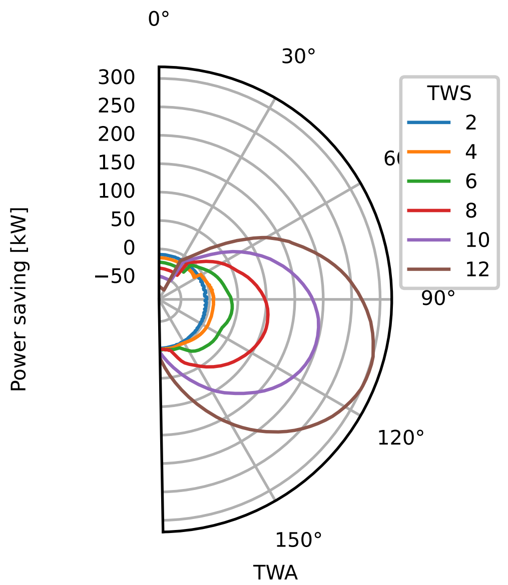

Required power on route
Probability density (-)
2.0
1.5
1.0
0.5
0.0
1.5
2.0
2.5
3.0
3.5
4.0
Required power (MW)
no WPS
WPS

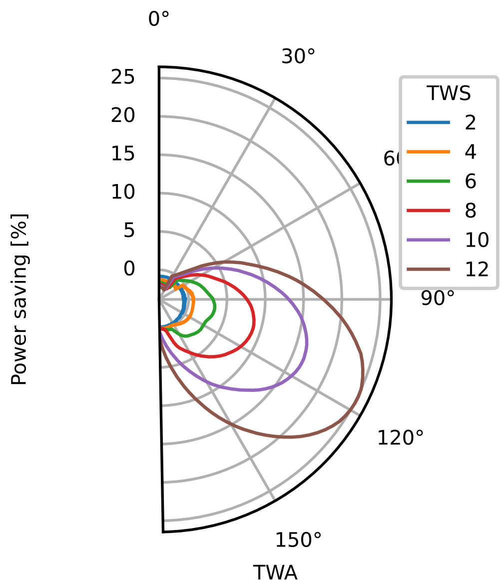
Route analysis report: WPS evaluation

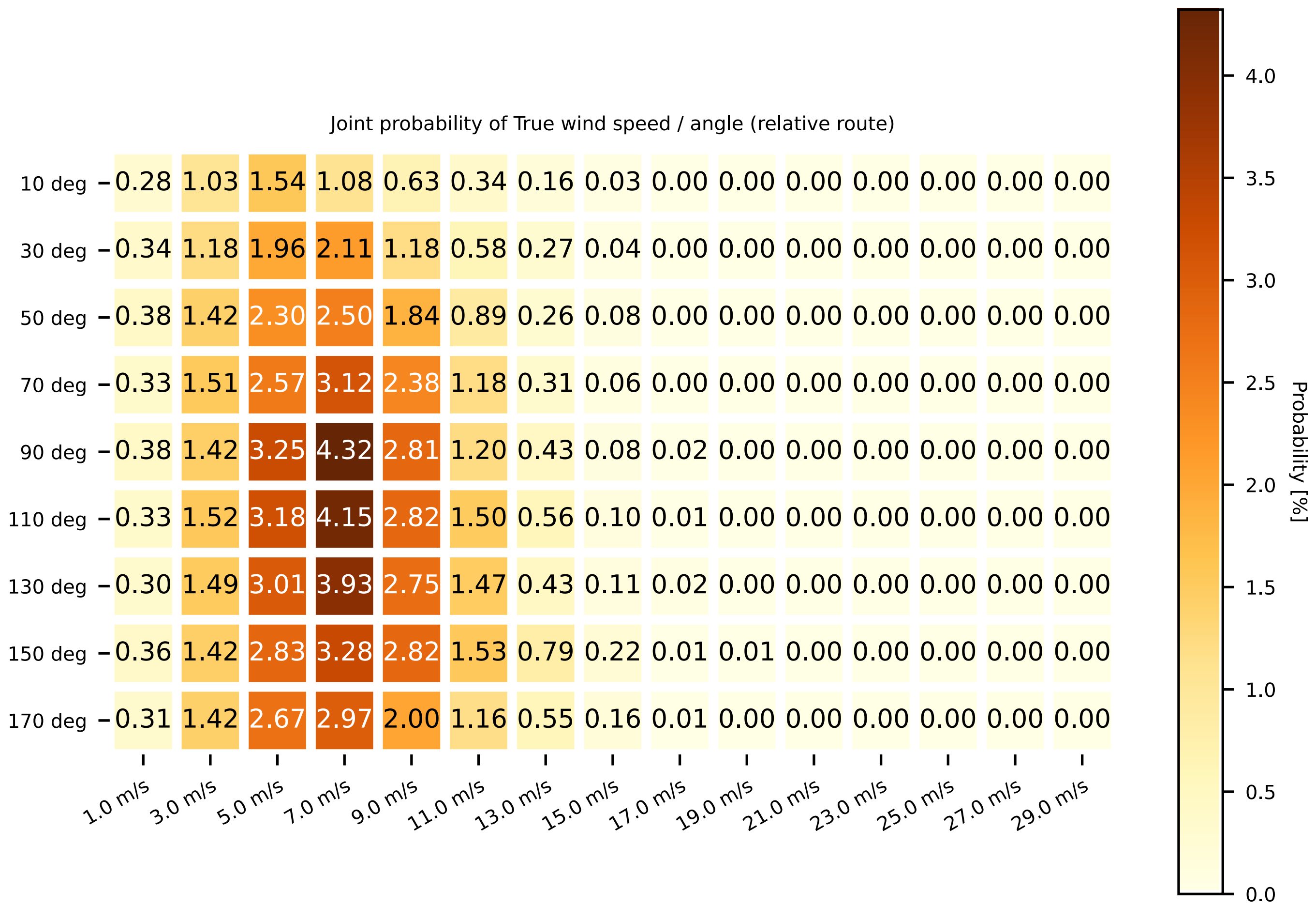
Results for a route analysis for ship: Annika Braren (ballast) on route: Karlshamn - Swinoujscie (inbound) with total distance: 143.4 nm

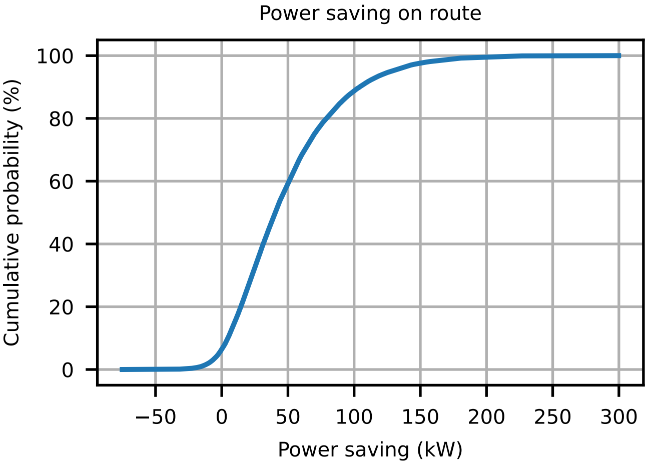
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	48.41	-8.28	148.47
Energy saving on route (MWh)	0.60	-0.10	1.85
Energy saving on route (%)	3.9	-0.6	11.9

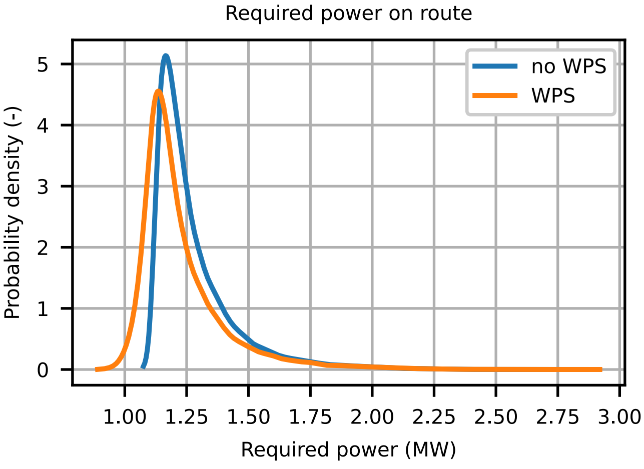



TWS
2
4
6
8
10
12
Power saving [kW]
300
250
200
150
100
50
0
−50
0°
30°
90°
120°
150°
TWA


TWS
2
4
6
8
10
12
Power saving [%]
25
20
15
10
5
0
0°
30°
90°
120°
150°
TWA


Joint probability of True wind speed / angle (relative route)
10 deg 0.28 1.03 1.54 1.08 0.63 0.34 0.16 0.03 0.00 0.00 0.00 0.00 0.00 0.00 0.00
30 deg 0.34 1.18 1.96 2.11 1.18 0.58 0.27 0.04 0.00 0.00 0.00 0.00 0.00 0.00 0.00
50 deg 0.38 1.42 2.30 2.50 1.84 0.89 0.26 0.08 0.00 0.00 0.00 0.00 0.00 0.00 0.00
70 deg 0.33 1.51 2.57 3.12 2.38 1.18 0.31 0.06 0.00 0.00 0.00 0.00 0.00 0.00 0.00
90 deg 0.38 1.42 3.25 4.32 2.81 1.20 0.43 0.08 0.02 0.00 0.00 0.00 0.00 0.00 0.00
110 deg 0.33 1.52 3.18 4.15 2.82 1.50 0.56 0.10 0.01 0.00 0.00 0.00 0.00 0.00 0.00
130 deg 0.30 1.49 3.01 3.93 2.75 1.47 0.43 0.11 0.02 0.00 0.00 0.00 0.00 0.00 0.00
150 deg 0.36 1.42 2.83 3.28 2.82 1.53 0.79 0.22 0.01 0.01 0.00 0.00 0.00 0.00 0.00
170 deg 0.31 1.42 2.67 2.97 2.00 1.16 0.55 0.16 0.01 0.00 0.00 0.00 0.00 0.00 0.00
1.0 m/s
3.0 m/s
5.0 m/s
7.0 m/s
9.0 m/s
11.0 m/s
13.0 m/s
15.0 m/s
17.0 m/s
19.0 m/s
21.0 m/s
23.0 m/s
25.0 m/s
27.0 m/s
29.0 m/s
Probability [%]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

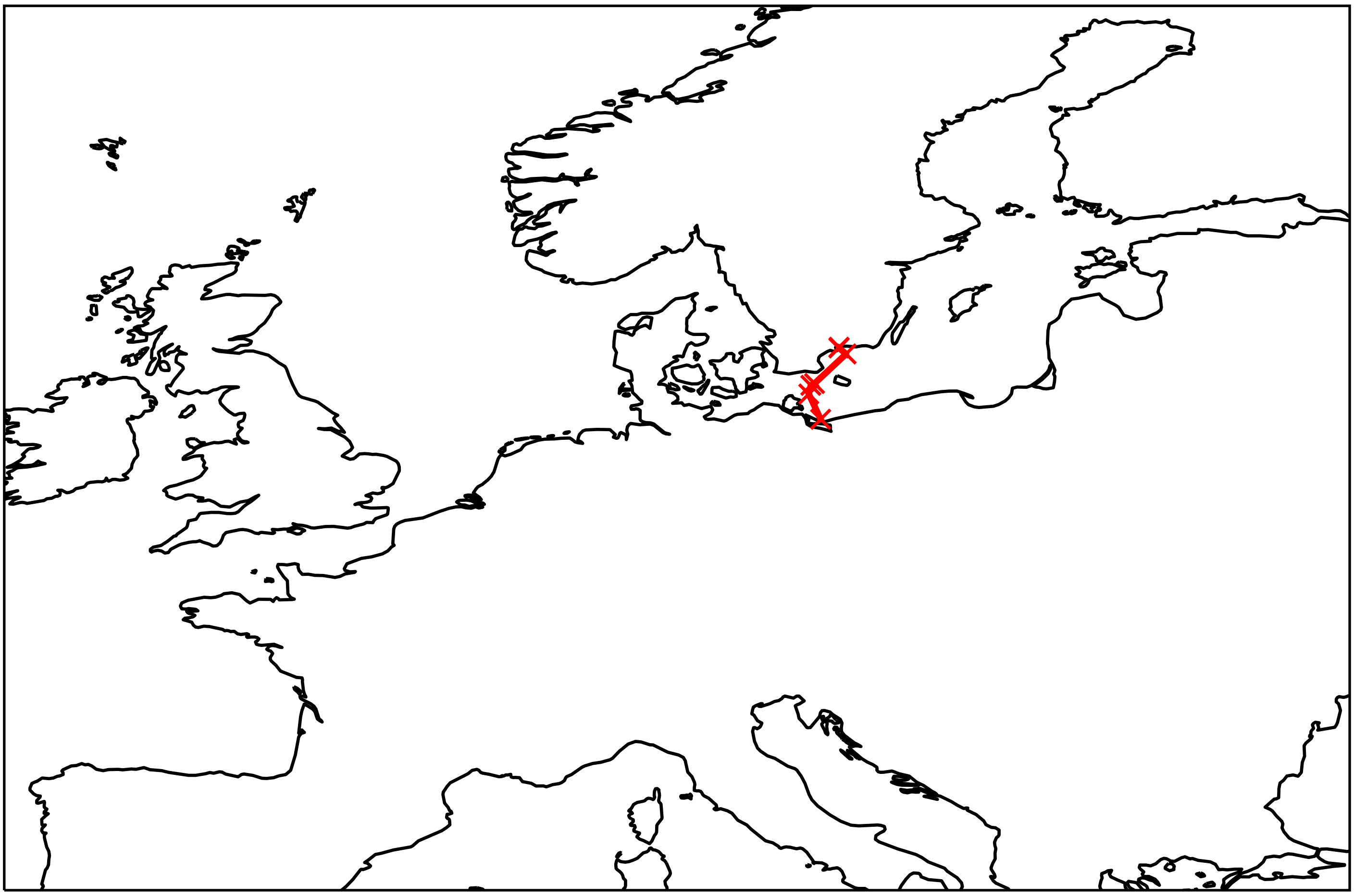

Power saving on route
Cumulative probability (%)
100
80
60
40
20
0
−50
0
50
100
150
200
250
300
Power saving (kW)

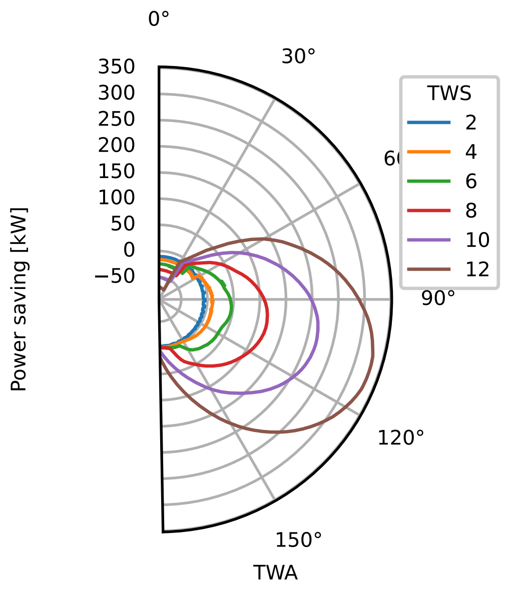

Required power on route
Probability density (-)
5
4
3
2
1
0
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
Required power (MW)
no WPS
WPS

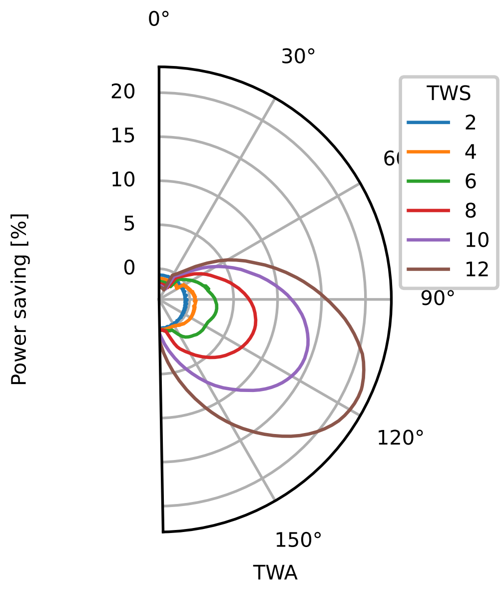
Route analysis report: WPS evaluation

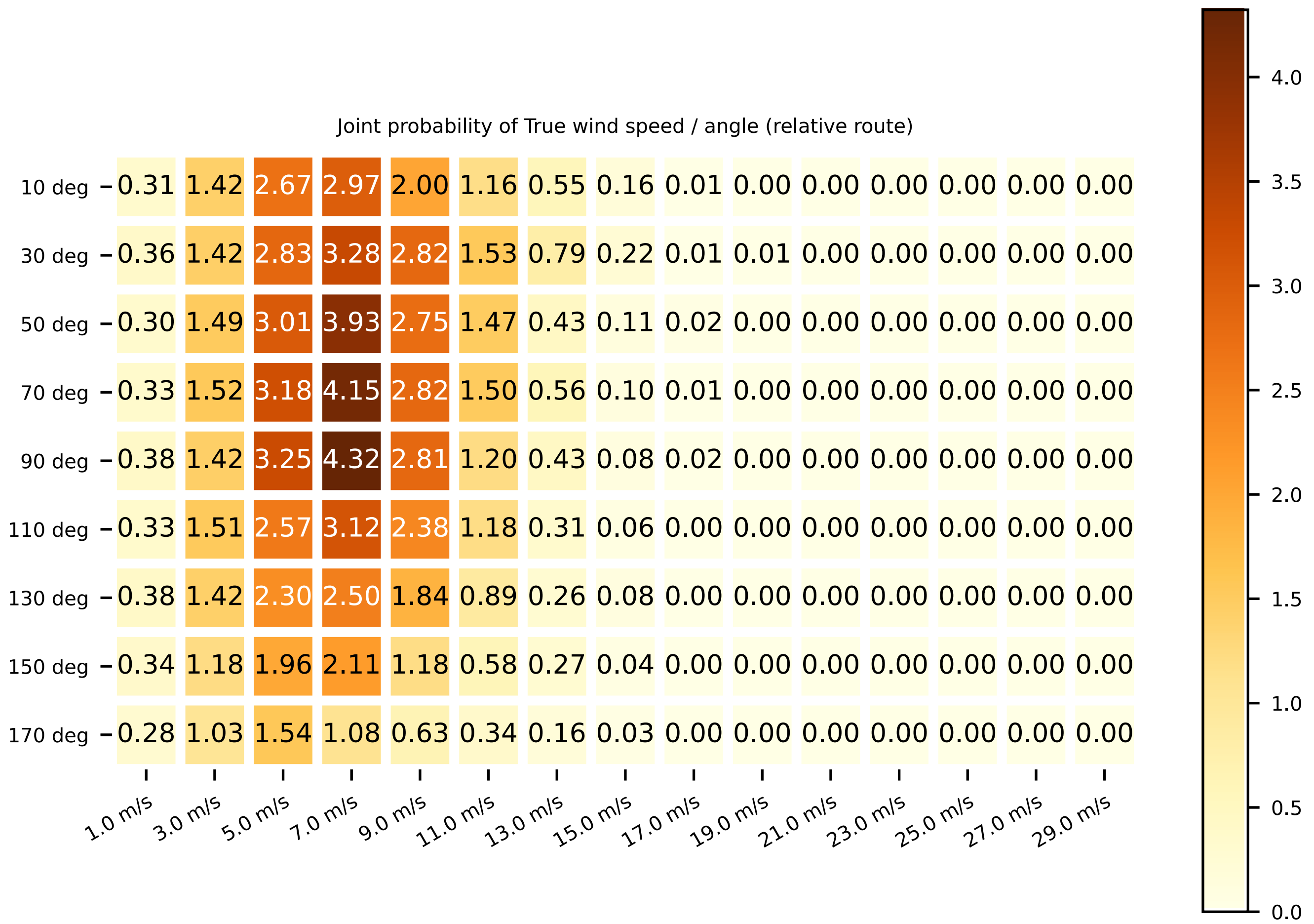
Results for a route analysis for ship: Annika Braren (laden) on route: Karlshamn - Swinoujscie (outbound) with total distance: 143.4 nm

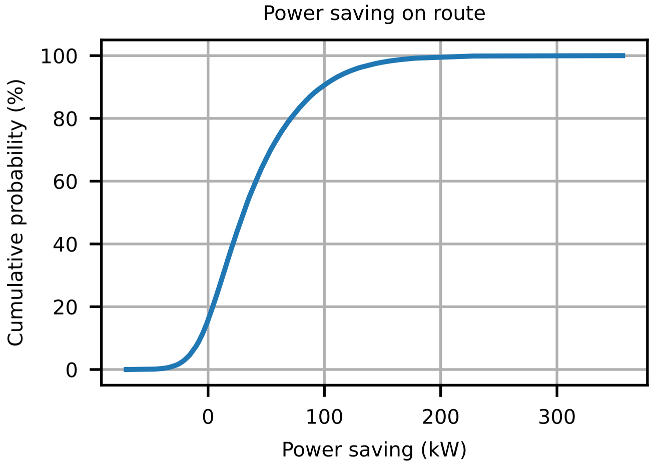
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	39.14	-22.11	144.40
Energy saving on route (MWh)	0.49	-0.28	1.80
Energy saving on route (%)	2.4	-1.1	8.8



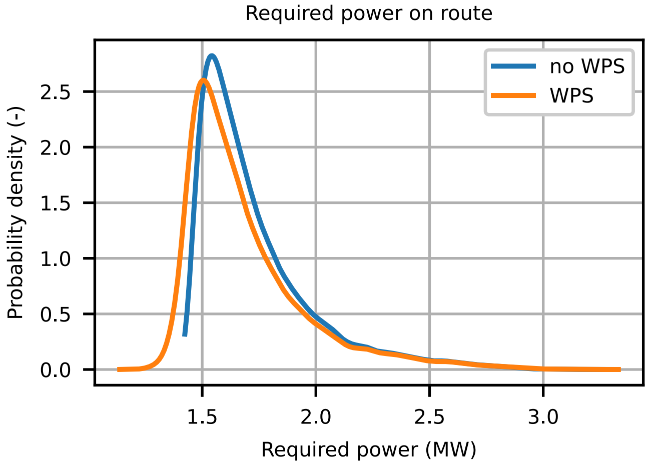

0°
30°
60°
90°
120°
150°
350
300
250
200
150
100
50
0
−50
Power saving [kW]
TWA
TWS
2
4
6
8
10
12


0°
30°
60°
90°
120°
150°
20
15
10
5
0
Power saving [%]
TWA
TWS
2
4
6
8
10
12


Joint probability of True wind speed / angle (relative route)
10 deg 0.31 1.42 2.67 2.97 2.00 1.16 0.55 0.16 0.01 0.00 0.00 0.00 0.00 0.00 0.00
30 deg 0.36 1.42 2.83 3.28 2.82 1.53 0.79 0.22 0.01 0.01 0.00 0.00 0.00 0.00 0.00
50 deg 0.30 1.49 3.01 3.93 2.75 1.47 0.43 0.11 0.02 0.00 0.00 0.00 0.00 0.00 0.00
70 deg 0.33 1.52 3.18 4.15 2.82 1.50 0.56 0.10 0.01 0.00 0.00 0.00 0.00 0.00 0.00
90 deg 0.38 1.42 3.25 4.32 2.81 1.20 0.43 0.08 0.02 0.00 0.00 0.00 0.00 0.00 0.00
110 deg 0.33 1.51 2.57 3.12 2.38 1.18 0.31 0.06 0.00 0.00 0.00 0.00 0.00 0.00 0.00
130 deg 0.38 1.42 2.30 2.50 1.84 0.89 0.26 0.08 0.00 0.00 0.00 0.00 0.00 0.00 0.00
150 deg 0.34 1.18 1.96 2.11 1.18 0.58 0.27 0.04 0.00 0.00 0.00 0.00 0.00 0.00 0.00
170 deg 0.28 1.03 1.54 1.08 0.63 0.34 0.16 0.03 0.00 0.00 0.00 0.00 0.00 0.00 0.00
1.0 m/s
3.0 m/s
5.0 m/s
7.0 m/s
9.0 m/s
11.0 m/s
13.0 m/s
15.0 m/s
17.0 m/s
19.0 m/s
21.0 m/s
23.0 m/s
25.0 m/s
27.0 m/s
29.0 m/s
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Probability [%]



Power saving on route
Cumulative probability (%)
100
80
60
40
20
0
0
100
200
300
Power saving (kW)

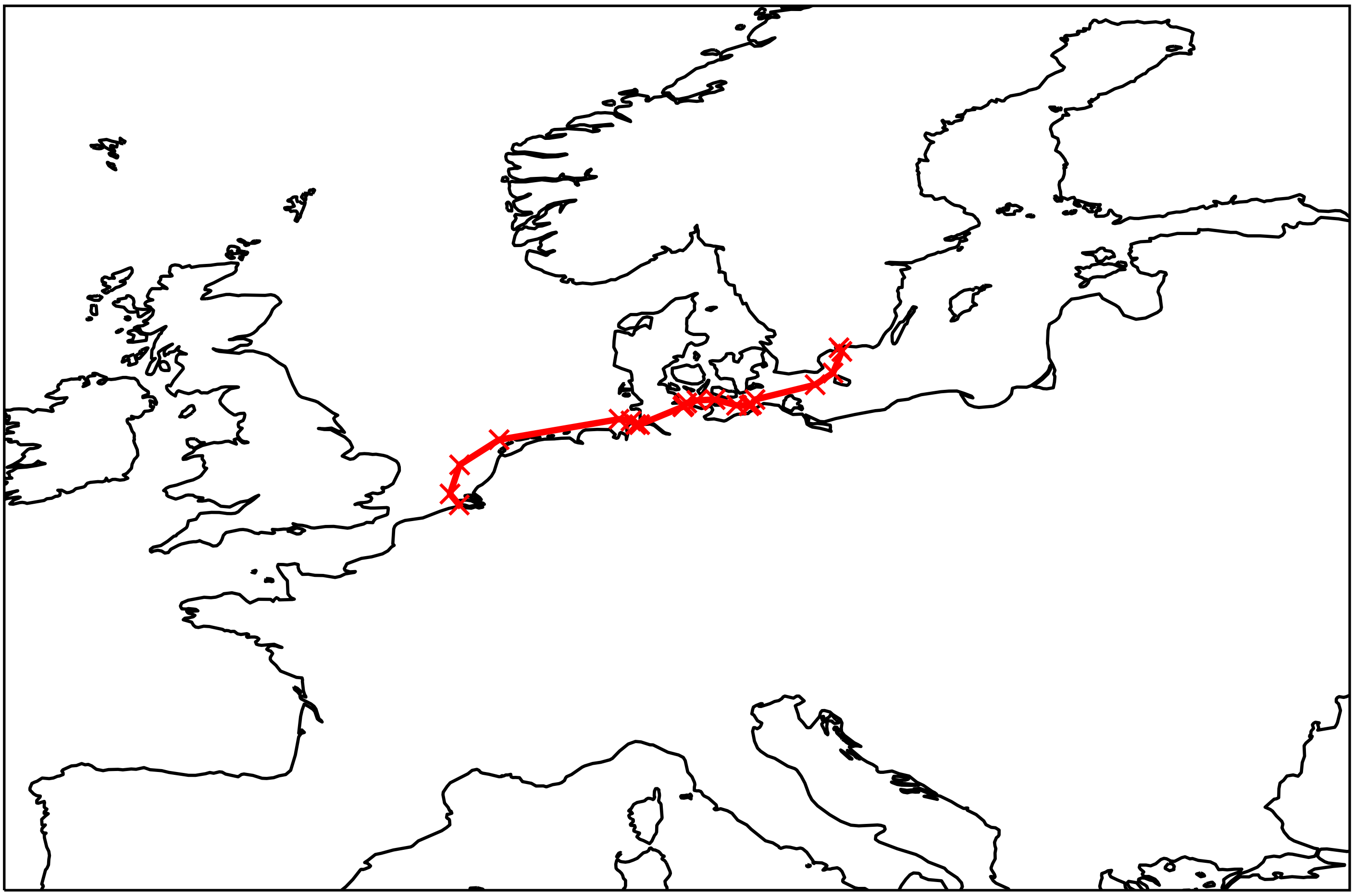


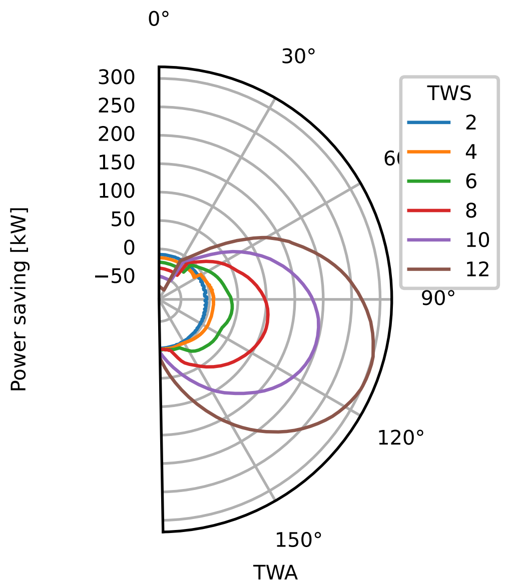
Required power on route
Probability density (-)
2.5
2.0
1.5
1.0
0.5
0.0
1.5
2.0
2.5
3.0
Required power (MW)
no WPS
WPS

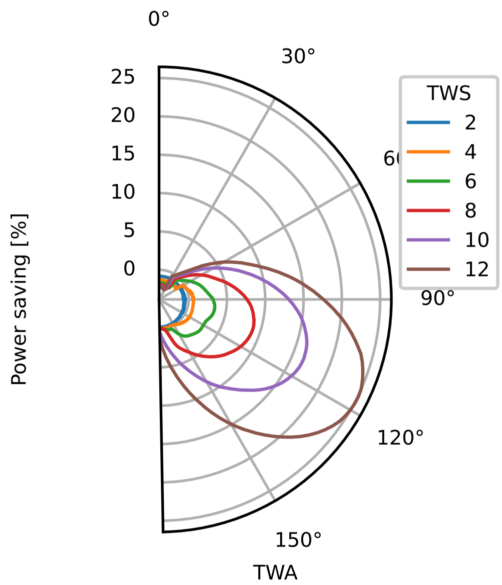
Route analysis report: WPS evaluation

Results for a route analysis for ship: Annika Braren (ballast) on route: Karlshamn - Vlissingen (inbound) with total distance: 581.0 nm

	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	43.53	2.69	111.92
Energy saving on route (MWh)	2.20	0.14	5.65
Energy saving on route (%)	3.5	0.2	9.2

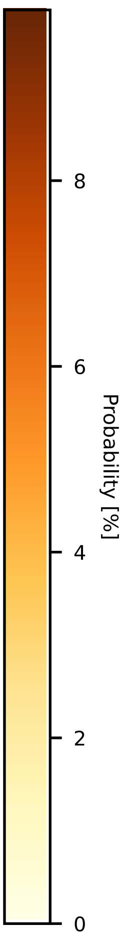


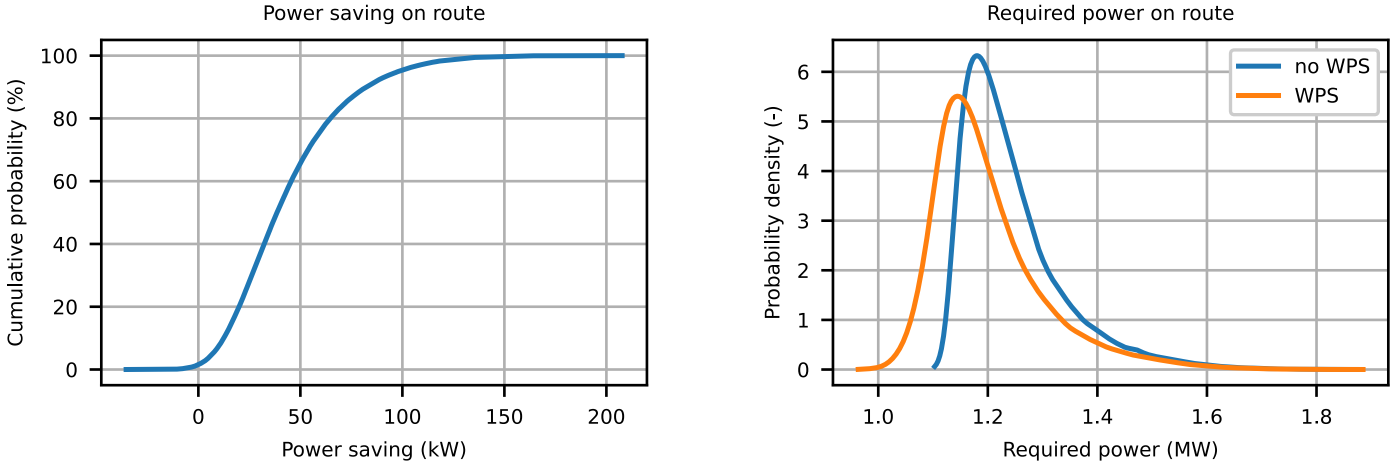




Joint probability of True wind speed / angle (relative route)

	1.0 m/s	3.0 m/s	5.0 m/s	7.0 m/s	9.0 m/s	11.0 m/s	13.0 m/s	15.0 m/s	17.0 m/s	19.0 m/s	21.0 m/s	23.0 m/s	25.0 m/s	27.0 m/s	29.0 m/s
10 deg	9.84	1.03	1.80	2.09	1.26	0.57	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30 deg	0.30	1.07	1.86	1.74	1.08	0.48	0.12	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
50 deg	0.30	1.09	1.70	1.95	1.09	0.42	0.11	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00
70 deg	0.31	1.13	1.85	1.97	1.06	0.45	0.25	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00
90 deg	0.35	1.18	2.02	2.30	1.70	0.73	0.27	0.09	0.04	0.01	0.00	0.00	0.00	0.00	0.00
110 deg	0.36	1.32	2.19	2.84	2.00	1.29	0.54	0.22	0.05	0.01	0.00	0.00	0.00	0.00	0.00
130 deg	0.37	1.34	2.51	3.05	2.77	1.76	0.83	0.29	0.04	0.00	0.00	0.00	0.00	0.00	0.00
150 deg	0.36	1.43	2.67	3.63	2.91	2.00	1.08	0.57	0.15	0.01	0.00	0.00	0.00	0.00	0.00
170 deg	0.37	1.44	2.77	3.67	3.46	2.21	1.00	0.44	0.17	0.01	0.00	0.00	0.00	0.00	0.00

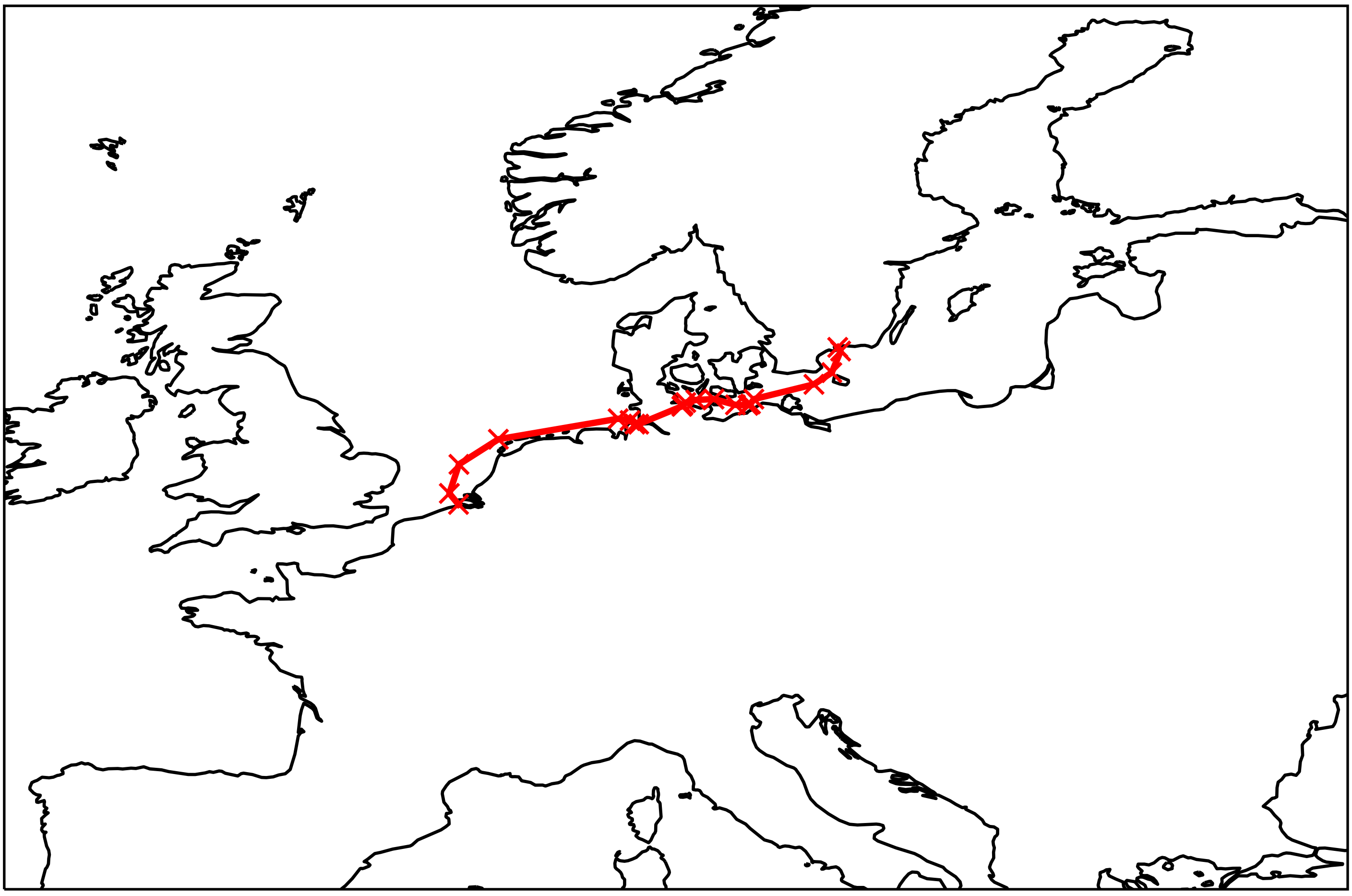


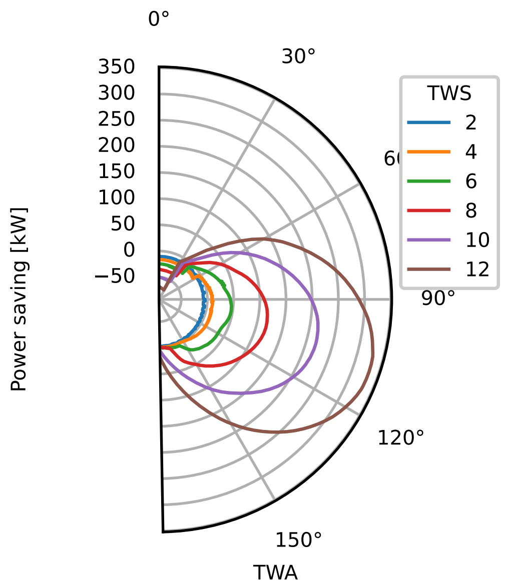

Power saving on route
Cumulative probability (%)
100
80
60
40
20
0
0
50
100
150
200
Power saving (kW)
Required power on route
Probability density (-)
6
5
4
3
2
1
0
1.0
1.2
1.4
1.6
1.8
Required power (MW)
no WPS
WPS

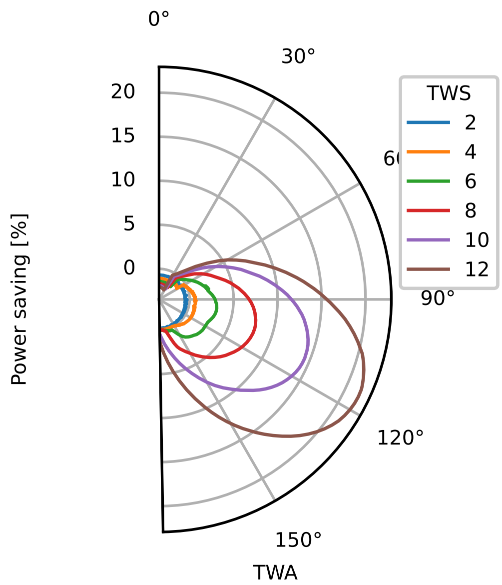
Route analysis report: WPS evaluation

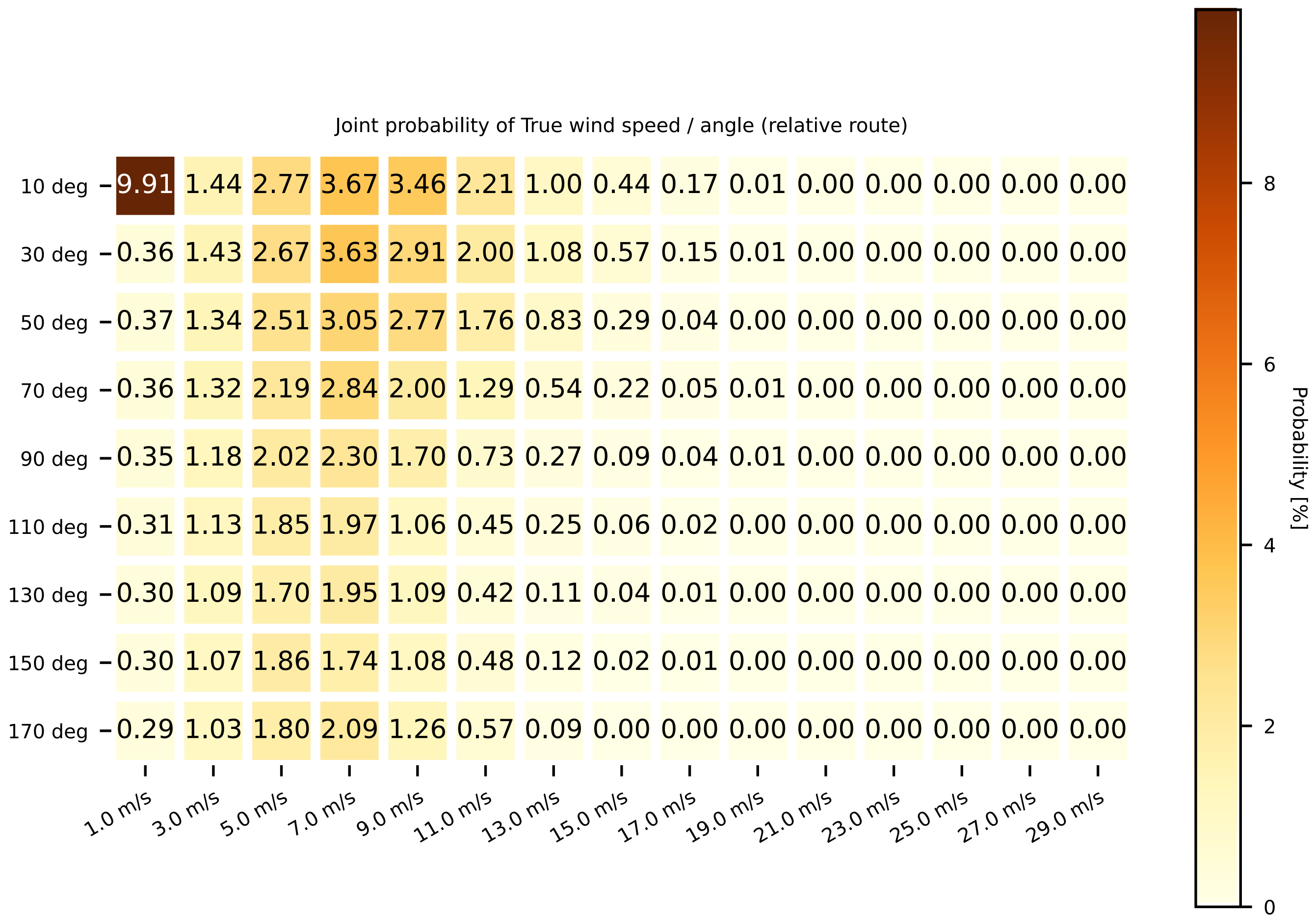
Results for a route analysis for ship: Annika Braren (laden) on route: Karlshamn - Vlissingen (outbound) with total distance: 581.0 nm

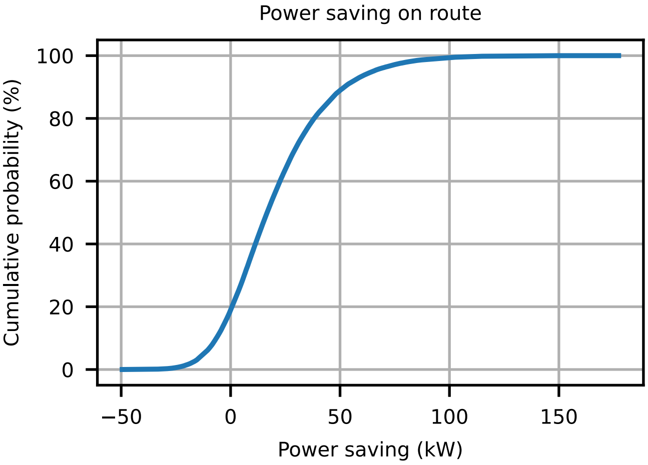
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	20.30	-16.78	77.19
Energy saving on route (MWh)	1.02	-0.85	3.90
Energy saving on route (%)	1.2	-0.8	4.4

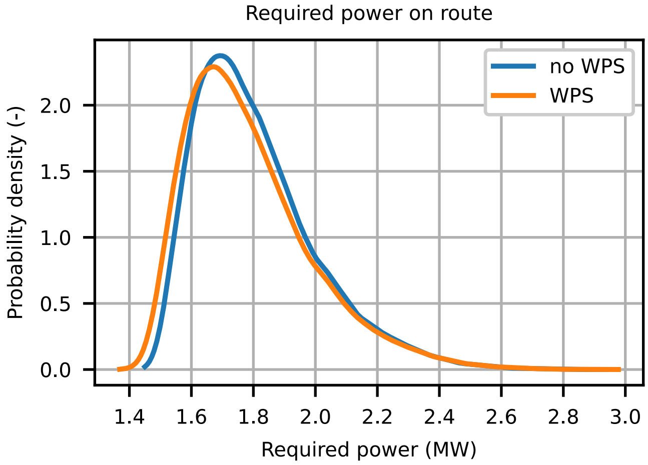



0°
30°
60°
90°
120°
150°
350
300
250
200
150
100
50
0
−50
Power saving [kW]
TWA
TWS
2
4
6
8
10
12


0°
30°
60°
90°
120°
150°
20
15
10
5
0
Power saving [%]
TWA
TWS
2
4
6
8
10
12


Joint probability of True wind speed / angle (relative route)
10 deg 9.91 1.44 2.77 3.67 3.46 2.21 1.00 0.44 0.17 0.01 0.00 0.00 0.00 0.00 0.00
30 deg 0.36 1.43 2.67 3.63 2.91 2.00 1.08 0.57 0.15 0.01 0.00 0.00 0.00 0.00 0.00
50 deg 0.37 1.34 2.51 3.05 2.77 1.76 0.83 0.29 0.04 0.00 0.00 0.00 0.00 0.00 0.00
70 deg 0.36 1.32 2.19 2.84 2.00 1.29 0.54 0.22 0.05 0.01 0.00 0.00 0.00 0.00 0.00
90 deg 0.35 1.18 2.02 2.30 1.70 0.73 0.27 0.09 0.04 0.01 0.00 0.00 0.00 0.00 0.00
110 deg 0.31 1.13 1.85 1.97 1.06 0.45 0.25 0.06 0.02 0.00 0.00 0.00 0.00 0.00 0.00
130 deg 0.30 1.09 1.70 1.95 1.09 0.42 0.11 0.04 0.01 0.00 0.00 0.00 0.00 0.00 0.00
150 deg 0.30 1.07 1.86 1.74 1.08 0.48 0.12 0.02 0.01 0.00 0.00 0.00 0.00 0.00 0.00
170 deg 0.29 1.03 1.80 2.09 1.26 0.57 0.09 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
1.0 m/s
3.0 m/s
5.0 m/s
7.0 m/s
9.0 m/s
11.0 m/s
13.0 m/s
15.0 m/s
17.0 m/s
19.0 m/s
21.0 m/s
23.0 m/s
25.0 m/s
27.0 m/s
29.0 m/s
Probability [%]
8
6
4
2
0


Power saving on route
Cumulative probability (%)
100
80
60
40
20
0
−50
0
50
100
150
Power saving (kW)


Required power on route
Probability density (-)
2.0
1.5
1.0
0.5
0.0
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
Required power (MW)
no WPS
WPS