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Real-time identification of the best performances of a sailboat

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Abstract — **In this paper we present a new method for real time estimation of the sail boat polar diagrams. The idea of the algorithm is principally based on the standard procedure used to select the best route that guarantees the major boat speed during a sail competition. The method is focused on a continuous comparison of the navigation data with the optimal polar diagram computed until then. The optimal surface is real time updated if the best performances reached are overcome. The outcome is the Real Time Polar Diagram, that describe the real performance of a sailboat with more accuracy with respect to the maps provided by VPPs. The feasibility of the method is tested on simulations and experimental data collected with an America's Cup Class and amateur sailboat.**

I. Introduction

This work concerns the performance estimation of a sailboat. In particular, the paper is focused on a new algorithm to reconstruct the polar diagram of a ship in a given environmental condition. Commonly the performances (defined in terms of boat speed) of a sailboat are derived off-line by the *Velocity Prediction Program* (VPP) and then are summarized in the polar diagrams. The presented real-time performance estimator is based on the methodology commonly adopted during a sail competition to plan the race strategy. Briefly, this approach is based on the real-time comparison of the data collected during the navigation with a surface, that represents the maximum boat speed as a function of the wind condition (direction and intensity). The outcome of the algorithm is the *Real Time Performance Diagram* (RTPD) that is a 3D static map that has the same meaning of polar diagram. However, with respect to the map generated by the VPP, the RTPD represents the really reachable boat speed and provides a continuously indication of how far the instantaneous speed is from the target.

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Reviewing the scientific literature some contributions in the estimation of the sailboat's performances with a VPP can be found. In [1] and [2] a new methodology based on the VPP are presented in order to optimize the sail and the boat shape in the design stage. In [3] and [4] some finite volume simulation are shown to the non-linear optimization of sail performance. Some works (i.e. [5] and [6]) concern the hydro and aerodynamics analysis to assess the improvement due to the change of the hull profile. Finally, some works regard numerical computations for the optimization of the route during the navigation (see [7], [8] and [9]). The real-time estimation of the sailboat performance treated in this paper is a new topic in the scientific literature.

In the patent literature some contributions that describe particular systems for the identification of the polar diagrams can be found. These documentations present some methods to define the optimal performances of the sailboat in relation with some parameters such as: wind status, sea current and sail trim. For example, in [10] a method based on neural networks is described. In [11] a system for the real-time description of the *Velocity Made Good* (VMG) for a boat is presented.

The paper is organized as follows. In Section II some preliminaries are briefly presented. In particular the Section is dedicated to the VPP approach and to the description of polar diagrams. In Section III the structure of the proposed real-time estimation algorithm is shown highlighting the different steps performed to reach the final results. In Section IV the resulting polar maps evaluated by the novel approach are shown using simulated data. In Section V the estimator is applied in an experimental environment and in particular on two different sailboat classes. Section VI is devoted to the conclusions.

II. Preliminaries

In this Section we present the concept of the polar map [12] and how this representation can be used to express the performances of a sailboat. In detail, this representation highlights the maximum vessel speed for each angle that the boat forms with the wind and for each value of wind intensity. The data contained in this diagram are usually obtained via VPP. The VPPs are iterative programs that solve the dynamic equations which describe the boat model. This method is used also to assess the different sail geometries at the design stage and to determine the performances of the ship for different sail trim. A typical result provided by these simulation algorithms is summarized in Table I.

It is worth noticing that the VPP provides the sailboat speed in the range of value between 0° and 180°. In fact, if the measurement system is correctly calibrated, the ship behaviour is symmetric in the range of TWA (0°,180°) and (180°,360°).

TABLE I
YARD TABLE FOR A GRAND SOLEIL 37

TWS	TUWA	TUWS	52	60	75	…	120	135	150	TDWA	TDWS
6	52	5.3	5.3	5.7	6.1	…	5.66	4.92	4.11	150	4.11
8	52	6.38	6.38	6.71	6.99	…	6.76	6.12	5.2	150	5.2
10	52	6.94	6.94	7.3	7.57	…	7.45	6.95	6.21	150	6.21
12	52	7.22	7.22	7.56	7.94	…	7.94	7.54	6.93	150	6.93
14	52	7.39	7.39	7.71	8.11	…	8.38	7.97	7.49	150	7.49
16	52	7.49	7.49	7.8	8.23	…	8.85	8.37	7.91	150	7.91
20	52	7.56	7.56	7.88	8.36	…	9.46	9.27	8.67	150	8.67

The table represent the significant points that describe the ship performance for different TWS; these point are derived by Velocity Prediction Program (VPP).

This table represents the most important points that are useful to describe the behavior of the vessel. In particular for each values of *true wind speed* (TWS) and *true wind angle* (TWA) a *boat speed* (BS) value is reported. It is worth noticing that the TWA represents the wind direction with respect to the vessel. Moreover, in this table the two most important points that describe the performance of a sailboat are highlighted. These points are related with the concept of *Velocity Make Good* (VMG) that refers to the component of a sailboat's velocity towards the target, that is the wind direction. These two points concern the upwind and the downwind rate and they are indicated by the couples (TUWS,TUWA) and (TDWS,TDWA) respectively.

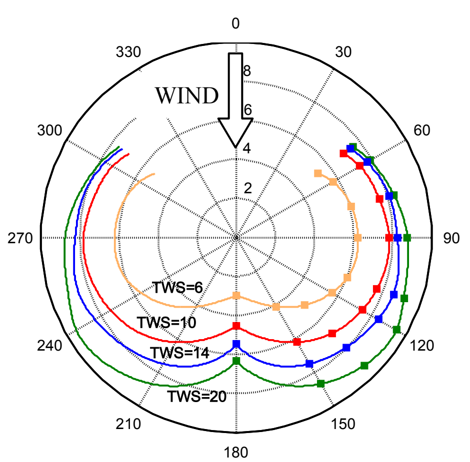


Fig. 1. Polar map for four different definite TWS intensity (6, 10, 14, 20kn) concern a Grand Soleil 37 (the dots represent the data in TABLE I).

The points summurized in Table I can be represented in a polar diagram that grapically indicates the speed of the sailboat in different wind conditions. An example of this representation is depicted in Fig. 1, where the point are referred to Table I.

The information represented in Fig. 1 are adopted by the sailors as *Reference Boat Speed* (RBS) and they are usefull to verify if the sails are optimally trimmed. On this point of view, the output of the VPP present two important limits:

- It is just a prediction of the performances reachable by the boat;
- It does not depend on the sea conditions.

Another representation of the information held in Table I is reported in Fig.2, where the domain represents the wind characteristics and the co-domain concerns to the boat speed.

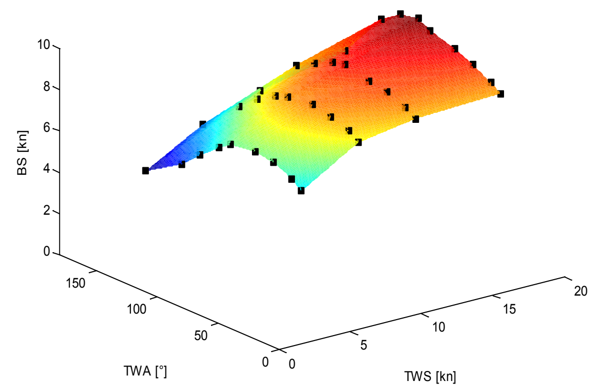


Fig. 2. 3D representation of the polar map result on Grand Soleil 37.

This is not a commonly representation of the reference performance of a sailboat. However, the algorithm presented in the following section bases its analysis on this peculiar representation and on the concept that the ship performance can be expressed by a triad of value (TWS,TWA,BS). In detail, TWS and TWA are interpreted as input variables of the system and the BS is seen as the output variable. In the method described in this paper, the *Reference Boat Speed* (RBS) is considered as a function of the wind condition $RBS = f(TWS, TWA)$. The aim of this work is the real-time identification of the surface reported in Fig. 2. In particular, the algorithm find the main points that approximate the function $f(\cdot)$.

III. SAILBOAT PERFORMANCES IDENTIFICATION

As described in the previous Section the polar map represents the performance of a sailboat in terms of boat speed, for different wind conditions. This result is obtained in a simulation environment by VPPs, for this reason it can't describe totally the real capabilities of a sailboat. In this Section we present a novel method used to obtain the *Real Time Performance Diagram* (RTPD). Differently to the VPPs, this estimation process is based on processing the data collected during the navigation and on a real-time updating of a representing the vessel reference performance.

The performance estimator can be summarized in three different subsystems as depicted in Fig.3. For the sake of clarity, consider a set $\hat{E}$ of points $p_i \in \Re^3, i = 1,...,n$, that approximates the function $RBS = f^o(TWS, TWA)$. In particular, $\hat{E}$ is a set of points collected by the algorithm that approximates f^0. All the points collected in $\hat{E}$ represent a triad of information concern the TWS, TWA and BS. Furthermore, for the set $\hat{E}$ we can define a domain set $\hat{D}$ that contains information about the wind conditions (TWS,TWA) and a co-domain $\hat{C}$ correlated with the BS.

$$\begin{aligned} \hat{E} &= \{p_1, p_2, ..., p_n\} \quad p_i \in \Re^3 \\ \hat{D} &= \{d_1, d_2, ..., d_n\} \quad d_i \in \Re^2 \\ \hat{C} &= \{c_1, c_2, ..., c_n\} \quad c_i \in \Re \end{aligned} \tag{1}$$

It is important to analyze that every point contained in the set $\hat{E}$ have a correspondent point into the set $\hat{D}$ and $\hat{C}$.

The principle applied by the algorithm is summarized in Fig. 3 and it can be summarized as follows:

1. it is necessary to recognize if the sailboat is in a steady state condition; this analysis is necessary because the RTPD represents a static map. This step avoids error due to transient interval and rapid changes in the wind conditions;
2. verify if the identified stationary data belongs to the domain $\hat{D}$ and if this information is useful to update the actual reference performance $\hat{E}$.

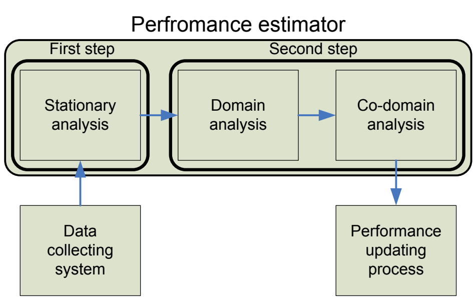


Fig. 3. Flowchart representation of the fundamental steps of the real-time performance estimator.

In detail, the stationary analysis accomplished by the algorithm is principally based on the mean and variance computation in a moving time windows of length T_w, as reported in (2); where *s(t)* is the input signal (*s(t)=TWS,TWA,BS*) and *n* is the number of data stored in the time window.

$$\begin{aligned} \mu_s(t) &= \frac{1}{n}\sum_{i=t-T_w}^{t} s(i) \\ \sigma_s(t) &= \sqrt{\frac{1}{n}\sum_{i=t-T_w}^{t}\left(s(i)-\mu_{s(t)}\right)^2} \end{aligned} \tag{2}$$

When a new data at time *t* is collected, the standard deviations $\sigma_{TWS}(t), \sigma_{TWA}(t)$ and $\sigma_{BS}(t)$ are computed in the time window T_w. If the calculated variance are minor than the thresholds $\overline{\sigma}_{TWS}, \overline{\sigma}_{TWA}$ and $\overline{\sigma}_{BS}$, a new stationary point $p_{ss}(t)$ described by $p_{ss}(t) = (\mu_{TWS}(t), \mu_{TWA}(t), \mu_{BS}(t))$ is considered as available stationary data (see eq.(3)).

$$\begin{aligned} &if\ (\sigma_{TWS}(t) < \overline{\sigma}_{TWS} \wedge \sigma_{TWA}(t) < \overline{\sigma}_{TWA} \wedge \sigma_{BS}(t) < \overline{\sigma}_{BS}) \\ &then\ p_{ss}(t) = (\mu_{TWS}(t), \mu_{TWA}(t), \mu_{BS}(t)) \end{aligned} \tag{3}$$

As depicted in Fig. 4, the second step of the algorithm is divided in two blocks that are referred to the domain and the co-domain analysis of the point $p_{ss}(t)$ with respect to $\hat{E}$.

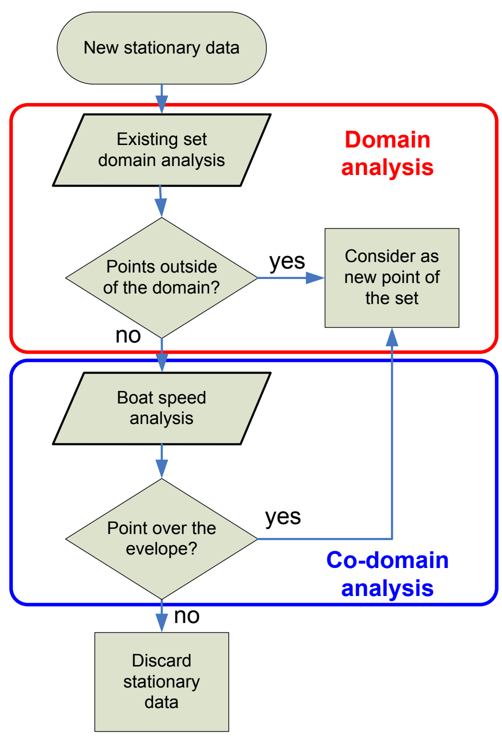


Fig.4. Flowchart description for the domain and co-domain analysis performed by the performance estimator

The domain analysis can be summarized as follow:

a. If the new point $p_{ss}(t)$ is described by a couple of value ($\mu_{TWS}(t), \mu_{TWA}(t)$) out of the domain $\hat{D}$, $p_{ss}(t)$ is consider as new point in the set $\hat{E}$.

b. If the new point $p_{ss}(t)$ has a couple ($\mu_{TWS}(t), \mu_{TWA}(t)$) that belongs to $\hat{D}$, it is analyzed in the co-domain.

A formalization of this point is presented in (4).

$$\begin{aligned} &\textit{if } (\mu_{TWS}(t), \mu_{TWA}(t)) \not\subset \hat{D} \\ &\textit{then } \hat{E} = \{p_1, p_2, ..., p_n, p_{ss}\} \\ &\textit{else co-domain analysis} \end{aligned} \tag{4}$$

The co-domain analysis works in the third dimension of the set $\hat{E}$. This step is based on a comparison between the value of the boat speed μ_{BS} and the co-domain $\hat{C}$ that represents the best boat speed reached till the instant *t*. For example, consider the coordinate ($\mu_{TWS}(t), \mu_{TWA}(t)$) of the point $p_{ss}(t)$ and $d_1^{'}, d_2^{'}, d_3^{'} \in \hat{D}$ that define the vertices of a triangle T that inscribes ($\mu_{TWS}(t), \mu_{TWA}(t)$) in the domain (Fig. 5).

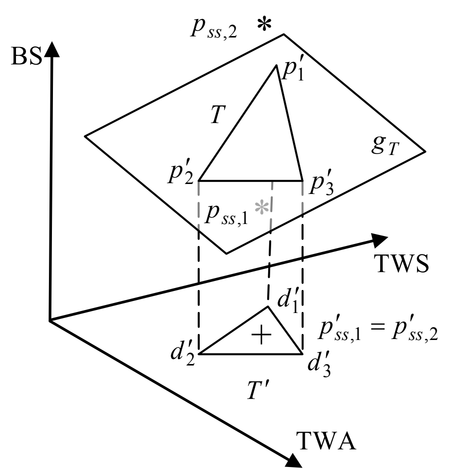


Fig. 5. 3D representation of the co-domain analysis for the new steady state point; $p_{ss,2}$ is a point that updates the RTPD, while $p_{ss,1}$ is discarded.

The point $p_{ss}(t)$ is added to the cluster $\hat{E}$ if and only if μ_{BS} is such that:

$$\mu_{BS}(t) > g_T(\mu_{TWS}(t), \mu_{TWA}(t)) \tag{5}$$

where $g_T(\cdot)$ is the plane that passes through the points $p_1', p_2', p_3' \in \hat{E}$, that are associated to their projection on the domain $d_1^{'}, d_2^{'}, d_3^{'} \in \hat{D}$.

The described procedure is performed at each time instant, so that the points in $\hat{E}$ at instant *t* represent the RTPD of the sailboat that corresponds to the optimal performance reached by the vessel till the current moment. The accuracy of the algorithm can be further improved introducing a discretization procedure to reduce the number of points in the set $\hat{E}$ and a smoothing procedure to avoid suddenly variation in the estimated surface. It is worth noticing that the estimator provides more accurate information if the system is used for a large time interval, because it needs a train step to achieve a benchmark data set.

IV. SIMULATION RESULTS

In this Section the RTPD estimator is tested on simulated data provides by Stentec Sail Simulator V®. This program is a commercial simulator commonly used to teach beginner sailors. In order to help users during the navigation, it provides many analogue and digital indicators that report important information such as apparent and real wind intensity and angle, compass heading and vessel speed (Fig. 6). These information are fundamental to the sailor to trim the sail and to chose the route towards the target.

Fig. 6. Picture of the simulation environment that highlight the command line (on the bottom) and analog and digital indicator on the right and left hand .

One of the most important features provided by this simulator is the possibility to export the navigation information in the NMEA protocol [13]. This communication protocol provides data about the status of the navigation and permits the communication between all the instruments commonly used on the sailboat. This capability allows the employment of the performance estimator as in a real environment. Another important advantage provided by this simulator is the possibility to set the autopilot mode. In this case the trim of the sail is completely assigned to the simulator so that the ship reaches the best performance in term of boat speed and drag force.

To analyze the performance of the method proposed in this work, some simulations are collected for different wind intensities (from 7kn to 13kn) and for different vessel angles with respect to the wind direction. Any simulation is obtained by a combination of manual mode and auto-trim mode. The test of the algorithm with simulated data is useful to study the output of this method in an ideal condition without the influence of uncalibrated sensors.

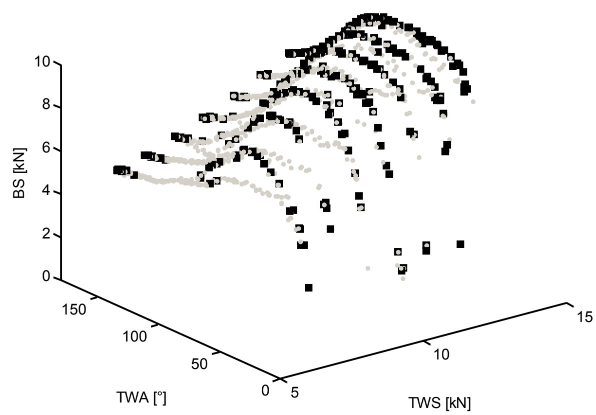


Fig. 7. 3D comparison of the steady-state points collected by the simulator (grey points) and the estimated performance by the algorithm (black points).

The results of the performance estimator are depicted in Fig. 7. The 3D polar map highlights that the estimation process derives the points that describe the maximum performance reached during the navigation and discard the point that are under the best performance surface.

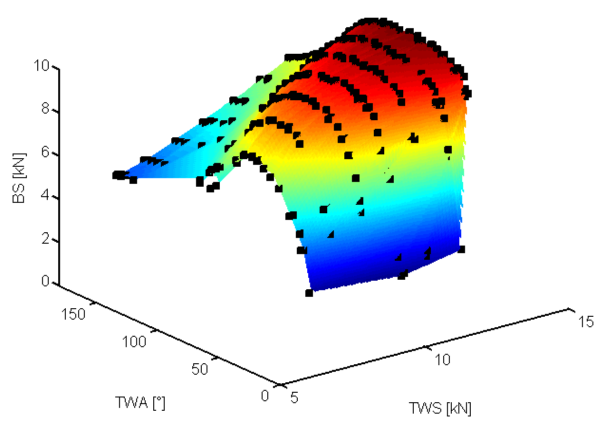


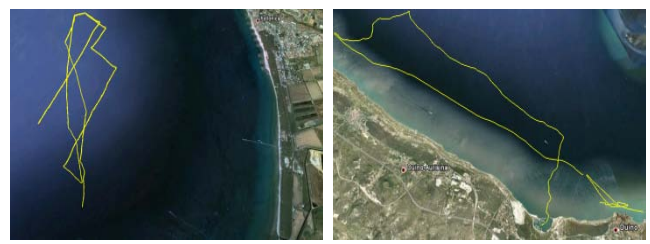
Fig. 8. Least square interpolation of the data provides by the performance estimator.

In Fig. 8 an interpolation surface is represented to describe the performance of the sailboat for every value of the wind intensity and angle. This surface is a real time approximation of the function f^o that describes the performance of the sailboat in every wind conditions.

In conclusion, if the simulation data are collected in an ideal condition, the estimation method provides the best performance that the sailboat can be reach.

V. EXPERIMENTAL RESULTS

As for the simulation data the algorithm is tested in a real environment. The experimental test are conducted with two different classes of sailboats. The first one is an America's Cup Class ship and the collected data concerns a competition stage. The second data batch relates a amatorial class ship. The two different routes for the experimental test are depicted in Fig.9.



(a) (b)

Fig. 9. Course representation for the two sets of experimental data: (a) collected with an America's Cup Class (ACC), (b) collected on an amateur sailboat.

Both of the test boats are equipped with an electronic circuit that provides all the sailboat information with NMEA protocol. In both of the tests, the sensors mounted on the vessel are been preliminary calibrated. The measurement chain is closed by a computer that has two important tasks:

- save the information collected during the navigation;
- compute the real-time algorithm to provide the polar maps.

The results of the algorithm for the two set of data are summarized in Fig. 10.

Finally, we can export the results of the algorithm in the classical polar representation. This graph represents the best performance that the sailboat reached during the navigation and provide a good benchmark for the sailor to improve the sail trim as well as the route. The comparison depicted in Fig.11 highlights that the proposed method finds the best performance of a sailboat. In particular, we can observe two different situation:

- when the boat reaches the best performance, the RTPD has almost the same values of the VPP polar map and in some situations the RTPD improve the accuracy of the best sailboat speed;

- since that the RTPD always represents the real maximum speed reached by the sailboat during the navigation, in some case the real boat speed underestimates the polar diagram derived by the VPP. This situation is due to the incorrectly sail trim and it could be modify when the boat reaches a speed that improve the performance under that condition.

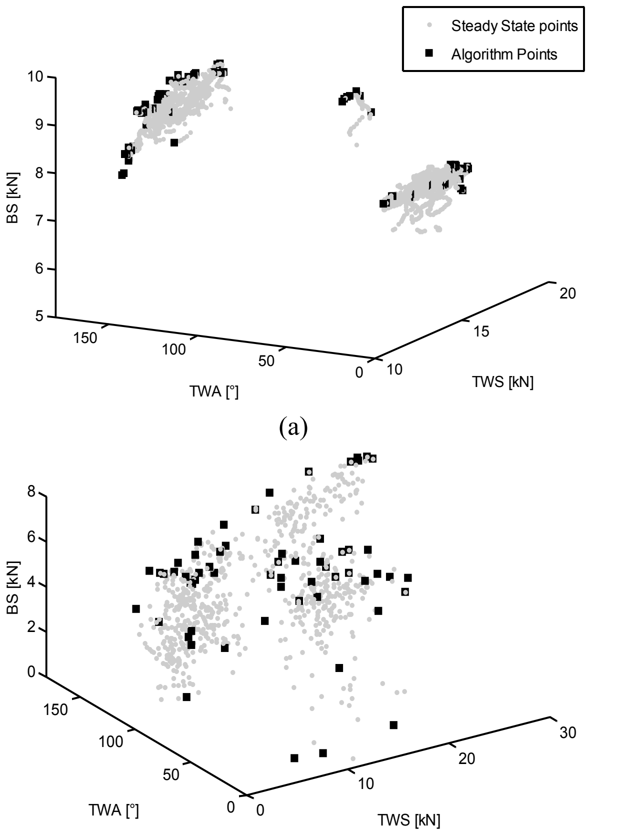


Fig. 10. RTPD estimated for the two sets of experimental data: (a) concerned an America's Cup Class (ACC), (b) concerned an amateur sailboat.

VI. CONCLUSION

In this paper the problem of estimation of the best performance of a sailboat is tackled in a real-time framework. A new algorithm is introduced to real-time data capture and updating of the best performance of a sail ship. The presented method improves the polar diagrams accuracy and provides a real-time feedback of how far the boat speed is from the target. Furthermore, the algorithm can be extended for the estimation of the boat performances respect also to the sea conditions and simply adapted for the VMG estimation.

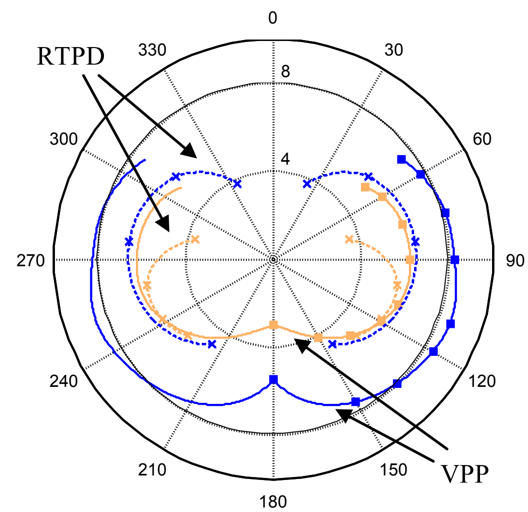


Fig. 11. 2D comparison of the result provided by the VPP and by the real-time performance estimator for 6kn (orange lines) and 14kn (blue lines) values of TWS.

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