



## DEVELOPMENT OF A SHIP WEATHER-ROUTING ALGORITHM FOR SPECIFIC APPLICATION IN NORTH INDIAN OCEAN REGION

Debabrata Sen<sup>1</sup> and Chinmaya P Padhy<sup>2</sup>

<sup>1</sup>Department of Ocean Engineering & Naval Architecture  
Indian Institute of Technology Kharagpur, India  
E-mail: [deb@naval.iitkgp.ernet.in](mailto:deb@naval.iitkgp.ernet.in)

<sup>2</sup>Product Engineering Services, Wipro  
Technologies, Kolkata, India  
E-mail: [chinmaya.padhy@wipro.com](mailto:chinmaya.padhy@wipro.com)

### ABSTRACT

*This paper presents development of a ship weather routing algorithm for determining minimum-time route. The optimization is based on a form of Dijkstra's algorithm. The developed algorithm is investigated using various realistic wave data for the North Indian Ocean region obtained from the 3<sup>rd</sup> generation WAM model. Illustrative minimum-time sea routes on the Arabian sea and the Bay of Bengal have been determined and presented. All relevant practical and realistic constraints such as presence of land boundaries, consideration of non-navigable water, effects of wind and current, voluntary speed reduction etc. can be incorporated within the framework of the algorithm.*

**Keywords:** Ship-routing, added resistance, wave-modeling

### 1. INTRODUCTION

Ship routing is defined as a procedure to determine an optimal track for ocean voyages based on forecasts of weather, sea conditions, and a ship's individual characteristics for a particular transit. It is concerned with the choice of the most suitable strategic trajectory or route and the corresponding control options from the voyage origin to destination so that a desired objective function or performance index is optimized. There are a number of different approaches to calculate the shortest path/route between two nodes representing the start and destination ports. For a given problem, the implementation of this path finding algorithm may have to be executed several times due to the varying ocean wave conditions during the passage of the ship. It is therefore important to choose an algorithm that is as efficient as possible. Within specified limits of weather and sea conditions, the term 'optimum' may be defined to mean maximum safety and crew comfort, minimum fuel consumption, minimum time underway, or any combination of these factors.

The problem of obtaining an optimal trajectory of ship has attracted attention of many researchers in the past. This includes Hanssen and James [10] who demonstrated an optimum ship route under stationary weather conditions, Haltiner et al. [9] who developed a routing algorithm using variational methods assuming ship speed under maximum power to be independent of time, Faulkner [4] who developed models based on numerical methods for optimal

trajectory, Zoppoli [19] who formulated the minimal time algorithm as a N-stage discrete process subjected to stochastic and dynamic conditions, and Chen [2] who developed an adaptive open-loop feedback optimization procedure. Other works include Mitchell and Papadimitriou [12] who investigated shortest path through a weighted planar sub-division, and Hagiwara [7] [8] who proposed the isochrone method for the solution of the minimum-time route (MTR) problem. More recent work on the ship routing problem can be found in Perakis and Papadakis [16], Chen and Lacey [3], Ulusoy [18] and Montes [13]. Although most of these works focus on the optimization algorithm using advance mathematical models, their use for developing an operational algorithm for practical application are not often demonstrated and thus their actual application remains somewhat unclear.

From the above it can be seen that although ship weather routing is a fairly old problem, due to its commercial value, the exact operational algorithm is rarely available in open literature. In this paper, taking advantage of these modern developments in wave modeling, an optimum track ship routing algorithm for ships operating in the Indian Ocean region is described by using a network graph for the Indian Ocean. A binary heap version of modified Dijkstra's algorithm has been used to determine the optimum route given an input from atmospheric/wave model and basic ship response functions. The algorithm is then applied for determining optimal routes for voyages in the North Indian Ocean region.

## 2. THE ROUTING ALGORITHM

### 2.1 Wave Climate

The most important environmental factors relating to ship's safety and performance on the high seas are surface winds and waves. For the wave climate, the final input that is needed for evaluating the vessel behavior is the spectral representation of the waves.

Significant advances have been made over the past few decades in both quality and quantity of satellite-generated wave data as well as in the ocean-wave prediction models. Presently up-to 3<sup>rd</sup> generation wave-prediction models are available producing high-quality wave-specification of significant wave height, typical representative time periods (zero-upcrossing or peak period) and the dominant wave direction when driven by high quality wind fields. These models can also produce the wave energy spectrum, both long crested and directional.

To determine ship behavior in a realistic wave field, the usual procedure is to use a theoretical wave spectrum. The mathematical formulations of these normalized uni-directional (i.e. long-crested or two-dimensional) wave energy spectra are based on one or two parameters: the significant wave height, and/or average wave periods.

In the present work, as is usual for ship applications, we apply the ITTC spectrum based on the 3<sup>rd</sup> generation WAM generated data on significant wave height and representative periods. This means over the applicable ocean region WAM produces the mentioned wave parameters which are then used with the relevant theoretical ITTC formula to generate the wave energy spectrum.

### 2.2 Ship Response in Waves and Added Resistance

The method to determine ship behaviour in irregular waves defined by means of a wave spectrum, using the response parameters in regular waves or so-called RAO (Response Amplitude Operator) is well known and is available in any standard text on naval architecture (e.g. Lewis [11]). What is most important here is the determination of the relevant RAO's. In this respect, as far as the fundamental six-modes of motions are concerned, we use the well-known Salvesen-Faltinsen-Tuck version of the strip theory for these computations (Salvesen et al. [17]). As for added resistance, which is a second order force, there are several formulae for its determination in terms of the heave and pitch forces response parameters, see e.g. Bhattacharya [1], Faltinsen [5]. Here we use the formula of Gerritsma and Buekelman [6].

### 2.3 Ship Track (Route) Optimization

Without loss of generality, the objective which needs to be optimized for the track optimization problem can usually be related to a reduction in speed under the following heads:

- Involuntary speed reduction
- Voluntary speed reduction

Involuntary speed reduction is due to the increased resistance in a seaway while voluntary speed reduction is the deliberate reduction in speed by the ship's captain in order to ensure that the ship's wave-induced responses are within acceptable safety limits, since it is found that in general a reduction in speed (and also heading to some extent) improves sea-keeping (i.e. reduces motions). For example, there may be a maximum limit to the bow slamming, or a maximum acceptable roll angle etc.

#### 2.3.1 The Track-optimization algorithm

Although many optimization methods have been developed for the ship routing problem, a survey of these works shows that most of these methods are somewhat limited by their inability to handle the part associated with involuntary speed reduction. The optimization algorithm to be used should be general enough so that it can handle a variety of multiple objective criteria. In general, the optimal-path problem is a problem of interest in many fields of study, e.g. traffic engineering. A literature search on general path-optimization algorithm reveals that one of the available and easy to implement optimization technique in this context is the Dijkstra's algorithm, which tries to minimize the distance between any two node points in a given mesh/grid. The distance can also be replaced by any 'weight' function. In the case of the ship routing problem, the weights can be viewed as an 'objective' or 'achievement' function, which can be obtained by combining weather information along with sea-keeping characteristics of the hull. It was thus felt that this algorithm could be successfully applied for the present ship-routing problem.

Dijkstra's algorithm finds the shortest path from a point in a graph to a destination. It finds routes by cost precedence. The algorithm begins at a specific node and extends outwards. It can be used to calculate the shortest path between any two vertices in a weighted graph, where each edge has non-negative edge weight. Although most applications of shortest path involve graphs with positive edge weights, modified algorithms are also available where such a constraint on weights is not necessary. For our case, the weight will never be negative (it can at best be very small), and therefore the original form of Dijkstra's algorithm appears adequate.

Based on this algorithm, a code has been developed, where in a given mesh (grid) with associated weights, if a start and end (destination) nodes are defined, then the algorithm finds the 'optimal' path joining these two nodes through grid points such that the total weight is minimized.

### 2.3.2 Determination of the 'Weights'

In order to apply Dijkstra's algorithm for the ship routing problem, an area of the sea-surface encompassing the possible route of the ship needs to be discretized by means of a grid formed by latitude and longitude lines. The nodes or vertices can be taken as a central point in the grid or alternatively the intersection of each latitude and longitude line can be considered as a node. Typically the weather information (significant wave height and characteristic wave period) will be available from satellite generated data and advance wave modeling methods like WAM at each grid. As in WAM output, these values are assumed constant over the corresponding grid.

The next and most important task is now to determine an appropriate 'weight' function for each grid or node by combining the wave conditions (significant wave height and direction) with ship response parameters. Once these 'weights' are known at each node/grid, the problem is now transformed to a state where Dijkstra's algorithm can be applied to find the 'optimal' path for minimum (or maximum) 'weight'.

The weights  $w_{i,j}$  between the path lines joining adjacent nodes  $i, j$  will depend on the parameter that need to be optimized. There can be several possible parameters such as minimum travel time, minimum fuel consumption, safe and comfortable travel etc. In the present work, we will consider the optimum ship routing for minimum travel time and discuss the methods to determine the weight function based on involuntary speed reduction. For this we first need to determine the reduction in speed due to the added drag.

The speed of the self propelled ship in calm water is given by the so-called self propulsion point. This is the speed at which the thrust  $T$ , after taking into account the thrust deduction factor  $t$ , i.e.  $T(1-t)$  equals the calm or still water resistance  $R_{SW}$ . The speed at which the ship will travel for the total resistance  $R_T$  including the additional resistance from all other environmental sources (wave, wind, current) will similarly be at the speed where  $R_T$  equates  $T(1-t)$ . This is schematically shown in figure 1 where  $V$  and  $V_R$  are the calm water and reduced speed. For a ship in operation, for the given engine

setting  $V$  is known. Therefore the objective will be to determine  $V_R$  given its calm water speed  $V$  at a given engine setting (i.e. revolution per unit time  $N$ ).

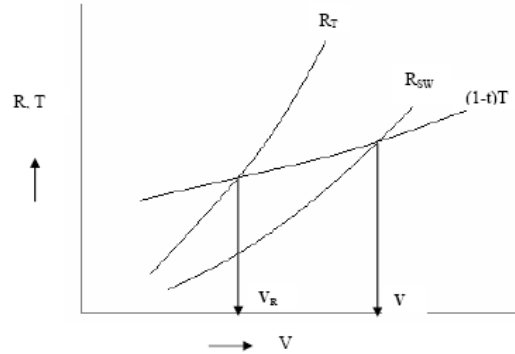


Figure 1. Illustration for self-propulsion point

The thrust  $T$  produced by a propeller depends on its propulsion characteristics and is usually represented by means of  $K_T - K_Q - J$  curves, where

$K_T = T / (rN^2D^4)$  is the thrust coefficient,  $K_Q = Q / (rN^2D^5)$  is the torque coefficient, and  $J = V_a / (ND)$  is the advance coefficient. Here  $Q$  is torque,  $D$  is propeller diameter and  $V_a$  is the velocity of advance, which is the velocity of water past the propeller.  $V_a$  is related to ship speed by the relation  $V_a = (1-w)V$  where  $w$  is the wake fraction for the hull.

For a given ship in operation at a given engine setting, the parameters  $N, D, t, w$  are fixed. Thus  $J$  is a direct function of  $V$ . Therefore effective thrust  $T(1-t) = K_T r N^2 D^4 (1-t)$  as a function of  $V$  can be plotted if the propulsion characteristics, i.e.  $K_T - K_Q - J$  is available. The ship speed will then be given by the intersection of the effective thrust line and the resistance line, as shown in figure 1.

This procedure is the way to determine the speed given the total resistance. However, for the present purpose of ship routing application, it has the following difficulties. It needs to be recognized that the speed has to be determined between each adjacent grids for all possible path lines connecting the grids. This will a very large number, and this number will increase rapidly if the navigational domain is large (i.e. the possible area of the sea within which the route is expected to lie, e.g. for large ocean crossings). The other issue is that for each path line, the value of  $R_T$  will be different depending on the prevailing environmental conditions even if  $R_{SW}$  is constant. Thus for each possible path line, one has to

determine the curves  $(1-t)T$  and  $R_T$  against speed, and then determine the intersection of these two lines to find  $V_R$ . This procedure, besides needing the propulsion characteristics in terms of  $K_T - K_Q - J$  curves, is therefore extremely time and computer intensive, and may not be feasible for the present application. We therefore need to consider some simplified and approximate methods to determine  $w_{ij}$ , which is fast and yet gives the weights within practically acceptable limits of accuracy.

The reduction in speed due to environmental factor is expected to be not very large, at least for most part of the voyage. As a result, it may be reasonable to assume that over the applicable speed range (i.e. over the range  $V_R$  to  $V$ ), the propulsion characteristics remain same. This means, the effective power  $P_E$  is assumed constant. In calm water,  $P_E$  is given by  $R_{SW}(V)V$ , but in the presence of waves, winds and current, the effective power will be given by  $R_T(V_R)V_R = (R_{SW}(V_R) + R_{add}(V_R))V_R$ . Here  $R_{add}$  is the resistance due to winds, waves and current. This is illustrated in figure 2. In order to determine the reduced speed from this, we note that the calm water resistance can be expressed in the form  $aV^2$  where  $a = 0.5\rho SC_{SW}$ . As regards the additional drag, if an assumption is made that the power required for this component at speed  $V_R$  is same as the power required at speed  $V$ , i.e.  $AB = CD$  in figure 2, then we get,

$$aV_R^2V_R + R_{add}(V)V = aV^2V \quad (1)$$

From above, we can get the reduced speed as:

$$V_R = \left( V^3 - \frac{R_{add}(V)V}{a} \right)^{1/3} \quad (2)$$

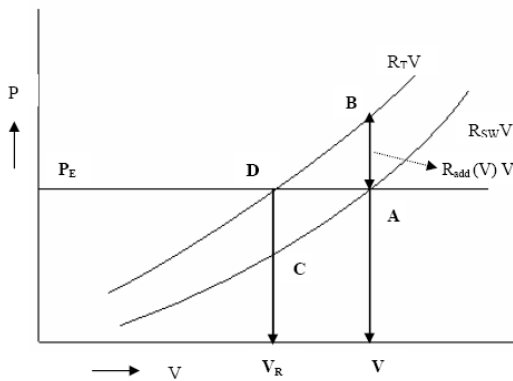


Figure 2. Procedure to obtain reduced speed for constant effective power

To make further simplification, we now made an ad-hoc assumption that the effective thrust, i.e.  $(1-t)T$  does not vary much over the range  $V_R$  to  $V$ ,

and therefore we can take it as constant as far as determination of reduced speed  $V_R$  is concerned. We note that the procedure to determine the total added resistance are all based on approximate theoretical and/or semi-empirical formulations, and therefore there is quite some uncertainty in these values. Additionally, there will also be some uncertainty in the forecast weather information like wave data and wind data. Further, it also needs to be noted that prevailing weather conditions are all assumed constant over a grid, which itself is an averaging process introducing some inaccuracy. It also needs to be noted that the error introduced in assuming thrust to remain constant will have similar order of error for all possible paths, and therefore the determined optimal path will still remain optimal or near optimal. Thus determination of the reduced speed based on the assumption that effective thrust is constant over the small range of speed around the prevailing calm water speed may be acceptable for practical calculations.

Based on the above assumption, the reduced speed will be as depicted in figure 3. If we write

$$R_{add}(V) / R_{SW}(V) = k \quad (3)$$

then

$$R_T(V) = R_{SW}(V) + R_{add}(V) = R_{SW}(V)(1+k) \quad (4)$$

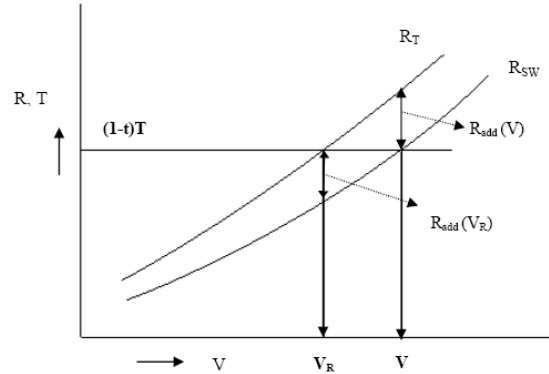


Figure 3. Procedure to get reduced speed assuming constant thrust

If a database is created by computing  $R_T(V)$  against  $V$  for different values of  $k$ , then for any given  $k$ , one can determine the corresponding speed  $V$ . Hence by a process of interpolation, for a given additional resistance value, one can determine the reduced speed  $V_R$ , as shown in figure 3. This procedure is however based on expressing the additional resistance as  $kR_{SW}$ . This means, the additional resistance due to environmental factors are all a function of calm water resistance regardless of speed, which means it has the implicit assumption that the speed dependence of  $R_{add}$  is same as that of  $R_{SW}$ .

Instead of this, it may be more reasonable to assume that  $R_{add}(V_R) = R_{add}(V)$ , as illustrated in figure 2. In such a case, if we have  $R_{sw}$  expressed as  $aV^2$ , we can directly get the reduced speed as:

$$V_R = \left( V^2 - \frac{R_{add}(V)}{a} \right)^{1/2} \quad (5)$$

Both the approximate procedures given by (2) and (5) will require determination of the additional resistance  $R_{add}$  arising from wind, waves and currents for each possible path line between adjacent grids using the prevailing environmental conditions at that location, but for the given calm water ship speed  $V$ .

Once the reduced speed for each possible path line joining nodes  $i$  and  $j$  is determined, i.e.  $V_{R,i,j}$  is found, it is straightforward to determine the weight functions as the time  $t_{i,j}$  taken to cover the distance between the nodes  $i$  and  $j$  given by  $L_{i,j}$ :

$$w_{i,j} \equiv t_{i,j} = \frac{L_{i,j}}{V_{R,i,j}} \quad (6)$$

Thus, by optimizing (minimizing)  $w_{i,j}$  for the complete path, the minimum time travel route for the ship can be found. Here the route optimization due only for involuntary speed reduction, that is, due to additional drag arising from environmental factors have been considered. It may be noted that in case of calm water,  $w_{(i,j)}$  reduces to  $t_0(i,j) = L_{i,j} / V$ , which is the travel time taken at constant calm water resistance, and the minimum-time route becomes the shortest route.

In the present work, both (2) and (5) are used, and it is found that the difference in the predicted path from these two is marginal. Therefore finally the approximate formula (5) is retained, as it is found to be the most convenient and easy to apply.

### 3. RESULTS AND DISCUSSION

A large number of results have been previously published for demonstrating the working of the algorithm, and its correctness in achieving the minimal time route (e.g. Padhy et al. [14] [15]), and thus these are not repeated here. Here we apply the algorithm to determine minimum-time optimal route for two ships termed Ship1 and Ship 2 for routes lying in the North Indian Ocean region, for which realistic wave data are generated using the 3<sup>rd</sup> generation WAM. The wave model is run using the NCMRWF (National Centre for Medium Range Wave Forecast, at Delhi) wind field data. Ship 1 is a relatively small vessel of length 60m, breadth 11m and draft 2.9m, while ship 2 is of length 160.93m, breadth 23.1m and draft 9.07m.

Figure 4 show the route between Damman and Mumbai, and the return route of Mumbai-Damman for ship 1, while for the same routes for ship 2, results are shown in figure 5. From these results and from comparison of the routes between the two ships (not shown here for brevity), it is clear that the routes depend on the ship type, and also on their direction with respect to the waves.

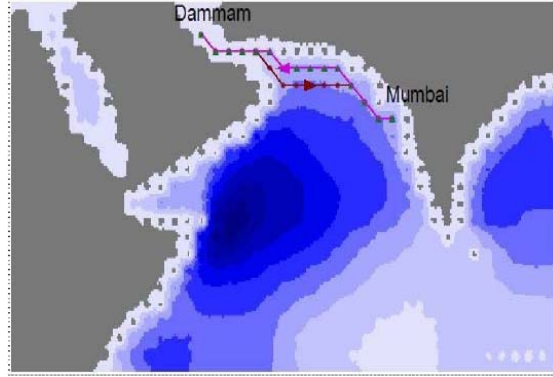


Figure 4. Route between Damman - Mumbai and Mumbai - Damman by Ship1

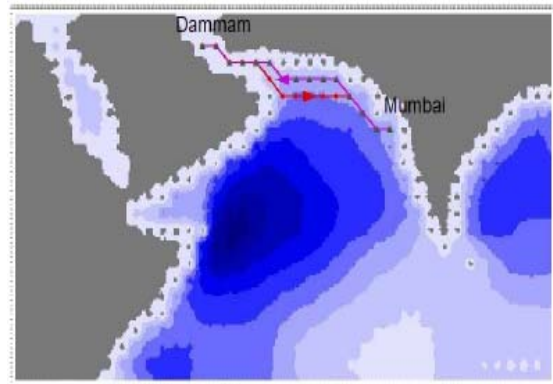


Figure 5. Route between Damman - Mumbai and Mumbai - Damman by Ship2

In order to demonstrate the ability of the algorithm to generate route circumnavigating a land mass, in figure 6 we show the route from Mumbai on the west coast of India to Visakhapatmen on the east coast of India. The result is for ship 1. The algorithm here simply assigns very large wave heights to those grids which are land masses. As can be seen, the algorithm could produce a route going around the land mass. However, there is a problem with this track: this route goes through the Palk Strait, the water between India and Sri Lanka. This Strait is not open for navigation, and therefore ships are not allowed to go through it. Such constraints are also easily handled by the algorithm, by simply 'blocking' selected areas of ocean. This is achieved by simply taking such areas as part of land mass. Thus isolated areas on open ocean which are not open to navigation can be treated as islands by simply assigning very

large wave heights associated with those grids (see figure 9 below)

Figure 7 and 8 show the result from the algorithm where the monthly average wave-data is used. Although the algorithm is run for all 12 months, here for brevity we show results for only two months, January and July, the former being a winter month with relatively calm sea and the latter being a monsoon month with high sea conditions. Note that here Palk Strait is treated as navigable water. As can be clearly seen, the routes generated are quite different. Such studies are therefore for great use for planning routes based on time of the year of the voyage.

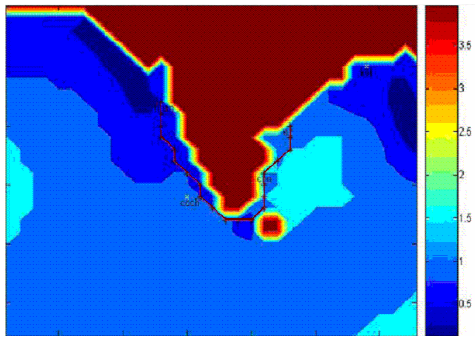


Figure 6. Route between Mumbai-Visakhapatnam

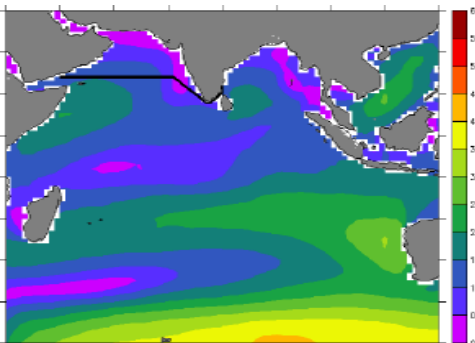


Figure 7. Route between Adan - Chennai based on WAM climatological wave data for January

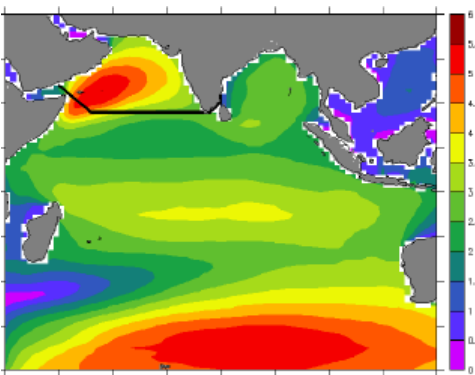


Figure 8. Route between Adan - Chennai based on WAM climatological wave data for July

One problem for this algorithm is that the route produces often shows a zig-zag saw-tooth type nature lacking smoothness, e.g. see figure 6. This is a result of generating the route by adding the nodes at the centre of the grids by straight lines. A 'smoothing-scheme' is therefore devised to handle this problem, and the results of applying this scheme is shown in figure 9. It can be seen that the generated track is now smooth.

The algorithm, as developed is also capable of handling presence of current and wind fields: these can be considered by simply taking the additional drags induced by these effects. Formulations are available for estimating current drag and wind loads. Figure 10 shows a minimum-time route in a wave and current field. In a similar way, the effect of wind drag can also be considered.

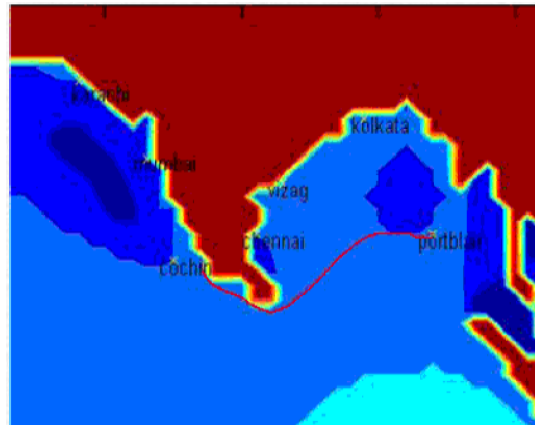


Figure 9. 'Smoothed' track between Cochin and Port Blair

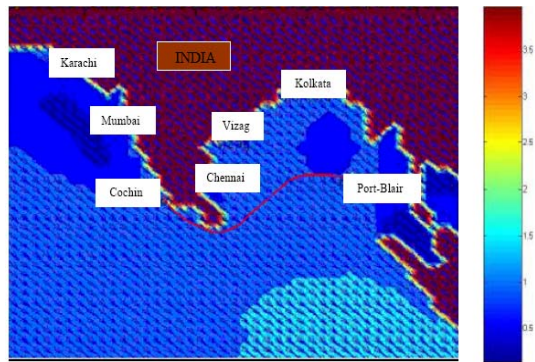


Figure 10. Optimum Cochin - Port Blair route with waves and current

#### 4. CONCLUDING REMARKS

In this work, an algorithm has been developed for ship weather routing application considering the prevailing weather (wind-wave-current) conditions and ship behavior in waves. The specific application in this work has been confined to routes lying in the

North Indian Ocean region, primarily because of the availability of information from ISRO satellites and from sites such as NCMRWF of India providing ocean wave related data over this region. The optimization procedure is based on a variant of Dijkstra's algorithm, which has been suitably modified for application to the ship-routing problem. The algorithm is general enough to consider a variety of optimization parameters since it is based on a concept of a weight function associated with the path that needs to be minimized/maximized. Therefore as long as such a weight function can be determined combining weather conditions and ship performances, the routing algorithm can in principle work. In this work, the optimization criterion is chosen to be the time of travel, so that the obtained path represents a minimum-time-travel route. For this, the procedure to determine the appropriate weight functions has been explained. It is found that the algorithm is versatile and robust enough to handle all constraints that are usually present in practical application of ship routing by ship operators.

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