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PROGRESS AND DEVELOPMENTS OF OCEAN WEATHER ROUTEING

(VOORTGANG EN ONTWIKKELING BIJ HET ROUTEREN VAN ZEESCHEPEN)

by

DR. C. DE WIT
(Department of General Sciences. Delft University of Technology)

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VOORWOORD

Bij de huidige ontwikkelingen in de scheepvaart blijkt het van belang te zijn een goed kwalitatief en zo mogelijk kwantitatief inzicht te hebben in de faktoren die een optimaal verloop van het reistrajekt in de hand kunnen werken.

Snelheidsverstoringen ten gevolge van wind en zeegang en de daaruit volgende respons van het schip kunnen een gepland optimaal af te leggen trajekt zeer ongunstig beïnvloeden. Naast mogelijke schade aan schip en lading zijn ook de hogere exploitatiekosten, de langer durende reistijd en de verminderde kans op een juiste prognose van de tijd van aankomst, aspekten die tegenwoordig zeker vermeden moeten worden.

Tesamen met in het schip ingebouwde goede zeegangs- en windeigenschappen zal echter ook optimaal routeren een belangrijke rol kunnen vervullen om de genoemde negatieve aspekten te voorkomen.

In 1970 werd omtrent het laatstgenoemd onderwerp gepubliceerd het rapport no. 142 S ,,Optimal meteorological ship routeing". Naar dit rapport mag worden verwezen voor een nadere verklaring van in bijgaand rapport gehanteerde begrippen zoals vaartindicatrix, de konstruktie van tijd-fronten, het bepalen van het kortst durend trajekt, e.d.

De toepassing van optimaal routeren in de praktijk van het scheepsbedrijf ondervindt echter nog betrekkelijk veel moeilijkheden. Dit is hoogst waarschijnlijk te wijten aan te weinig betrouwbare prognoses van het zee- en weertype in een bepaald gebied over een periode langer dan twee dagen, ten gevolge van zeer snelle weersveranderingen. Daarenboven zijn echter andere faktoren van invloed die minder duidelijk te formuleren zijn. Toen de ,,Holland Amerika Lijn B.V." haar gerouteerde schip ss. ,,Atlantic Crown" in april 1972 beschikbaar stelde voor de meting van zeegangseigenschappen, zie rapport no. 158 S ,,Full scale measurements and predicted seakeeping performance of the containership ,,Atlantic Crown", was dit een goede kans voor een kombinatie met onderzoek gericht op de reeds gesignaleerde moeilijkheden. Temeer daar voorafgaand aan de metingen aan boord van het schip een uitgebreid laboratorium- en theoretisch onderzoek was uitgevoerd betreffende het gedrag van dit schip in wind en zeegang uit verschillende richtingen. Dit houdt in, dat ook gegevens voor de vaartindicatrix beter dan voor andere gevallen bekend waren.

De resultaten zijn samengevat in bijgaand rapport no. 201 S ,,Progress and developments of ocean weather routeing". Aan de hand van voorbeelden wordt onder meer aangetoond dat ook met een vereenvoudigde procedure voor het routeren van het kortst durend trajekt goede resultaten zijn te behalen.

De vereenvoudiging houdt in dat met een betrouwbaar vaartindicatrix diagram van het betreffende schip als uitgangspunt slechts rekening wordt gehouden met een weerprognose 2 dagen vooruit voor het gebied dat in dat tijdsbetek kan worden bereikt. Voor het resterend deel van het af te leggen trajekt wordt een kalme zee aangenomen. De konstruktie van tijdfronten en de bepaling van het kortst durend trajekt wordt elke dag één à twee

PREFACE

With todays development in shipping it is of importance to have a good insight with respect to quality and quantity of those factors which can improve the optimal ship's track. Speed disturbances caused by wind and seaway and the ship's response going with these phenomena may have an unfavourable effect on the planned ship's optimal track. Besides possible damage to ship and cargo, the higher operation costs, the longer lasting voyage time and the reduced probability for the prognosis of the expected time of arrival are aspects that have to be avoided today.

Together with the design incorporated good wind and seakeeping characteristics, the optimal ship routeing may play an important role in order to avoid the unfavourable aspects mentioned.

With regard to the subject mentioned last a report has been published in 1970, no. 142 S "Optimal meteorological ship routeing". To this report may be referred for a further explanation of conceptions used, such as speed indicatrix, constructing time fronts, determination of the least time track, etc.

The application of optimal routeing in practice is been hampered by many difficulties. Most probable one of them is the unfavourable reliability of the weather forecast for certain areas over a period longer than two days, caused by the relatively fast weather changes. However, on top of that there are other factors which are less clearly to formulate. When the "Holland Amerika Lijn B.V." placed her routed ship s.s. "Atlantic Crown" at our disposal to perform seakeeping measurements in April 1972, see report no. 185 S "Full scale measurements and predicted seakeeping performance of the containership "Atlantic Crown", this proved to be a good opportunity to make a combination with a research project directed to the difficulties mentioned. Moreover because prior to the said measurement aboard the ship, an extensive laboratory- and theoretical investigation has been performed regarding the behaviour of the subject ship in wind and waves from different directions. From this investigation could be derived all the necessary information for the speed indicatrix diagrams for a far better extend than for other cases.

The results are compiled in this report no. 201 S "Progress and developments of ocean weather routeing". Among others with examples is shown that with a simplified procedure for least time track routeing good results could be obtained. The simplification comprises that based on a reliable speed indicatrix diagram of the subject ship only a two days period weather forecast is needed for that area that can be reached within two days. For the remainder of the track to be covered a calm sea is assumed. Constructing the time fronts and determination of the least time track can be repeated once or twice a day by the officer of the watch when new weather information comes in. This procedure holds if reliable weather forecasts for a two days period are available and that the ship's officers can be actively engaged in ship routeing.

This report gives also some contemplations regarding practical maal herhaald door de officier van de wacht. Deze procedure gaar er tevens van uit dat betrouwbare voorspellingen van wind- en zeetoestand twee dagen vooruit regelmatig beschikbaar zijn en dat de scheepsofficieren aktief betrokken kunnen zijn in het routeren.

In het rapport zijn bovendien enige beschouwingen gewijd aan praktische suggesties voor het routeren aan boord van schepen. Deze suggesties betreffen zowel de algemene organisatie als een noodzakelijk geachte verdieping van het inzicht van de met de navigatie belaste scheepsofficieren.

Uit het gerapporteerde onderzoek blijkt nog eens duidelijk dat de resultaten van scheepvaartresearch slechts praktisch bruikbaar zijn indien de diverse researchonderwerpen zo goed mogelijk gecoördineerd en geïntegreerd zijn.

In de loop van de volgende jaren zal het inzicht in maatregelen voor verbetering van de zeegangs- en windeigenschappen van schepen verder moeten toenemen terwijl mogelijkheden voor een meer betrouwbare weerprognose op langere termijn dan twee dagen zeer waarschijnlijk ook dringend gewenst zijn.

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suggestions in order to improve routeing aboard ships. These suggestions are either of an organizational nature and/or of a presumed need for a better understanding by the ship's officers.

The investigation reported proves clearly that the results of shipping research are only applicable in practice if the different research subjects are coordinated and integrated to the most possible extend.

The understanding of measures for improvements in wind- and seakeeping characteristics of ships should be enlarged in the course of the coming years. Further it may be expected that more reliable weather forecasts for periods longer than two days forward are urgently desired.

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CONTENTS

LIST OF SYMBOLS

A	Starting point
B	Point of destination
C_0	Initial estimate of least time track (l.t.t.)
C	True least time track
D	Kernel of bad weather region
ETA	Expected time of arrival
H	Hamiltonian
P	Arbitrary point of G (ship's position)
S_1, S_2	Time fronts
T_s	Propulsion power
c_w	Waves propagation speed
h_w	Significant height of sea waves
p	Costate variable
p°	Initial value of the costate variable
t	Time
t_0	Starting time
t_1	Time of arrival
u	Desired propulsion speed
v_s	Ship's speed
v_a	Wind's speed
x	State variable
y	Swaying displacement of the ship's gravity centre
$\dot{y}$	Swaying velocity of the ship's gravity centre
z	Heaving displacement of the ship's gravity centre
$\dot{z}$	Heaving velocity of the ship's gravity centre
ϑ	Pitch angle
$\dot{\vartheta}$	Pitch angle velocity
λ	A non negative penalty factor
φ	Roll angle
$\dot{\varphi}$	Roll angle velocity
ψ_s	Desired power
ψ_a	Wind direction
ψ_w	Sea waves directions

PROGRESS AND DEVELOPMENT OF OCEAN WEATHER ROUTEING

by

Dr. C. DE WIT

Summary

The main purpose of this report is to make an analysis and to suggest possible solutions of the various problems, that have arisen since the beginning of organized ocean weather routeing of merchant ships.

The first chapter contains an investigation of two partial problems, inherent to meteorological least time routeing. The first of these problems is the uncertainty in weather forecasts for more than three days ahead. From some examples the conclusion is drawn, that the best policy seems to be to assume fully calm weather and sea conditions in the area, where the ship is going to be three or more days in advance. The second problem, being the collection of ship's performance data, seems to have both naval-technical and human aspects. An improvement of the present situation can be found in intensifying the mutual contacts between the ship's navigating officers, the meteorologists and the naval architects, who take an interest in ships' dynamics. A more detailed organization is recommended for the observation of the various ship's outputs as a response to disturbing inputs, caused by weather and sea waves.

Chapter 2 contains a contemplation of the advantages of least time routeing. Beside the time saving aspect, the importance is indicated of the fact, that slightly modified least time routeing can be of great importance in assisting to minimize the risk of bad weather damage. Other optimization criteria are treated and investigated and the conclusion is drawn, that least time routeing, combined with careful navigation, has about the same effect as least fuel or least cost routeing, while the former type has the great advantage of being far better understandable to the ships' officers involved.

In the third chapter a global description is given of the various working methods of 3 public routeing services. Although the Royal Dutch Weather Bureau's routeing office comes out as the best organization, when it comes to giving routeing advices, the suggestion is made to transfer a considerable part of the work to the ship's navigating officers. An increasing commitment of these men with the entire routeing procedure might very well have a favourable psychological effect and might thus contribute to obtaining better over-all-results.

0 Introduction

Since the beginning of organized ocean weather routeing around 1960, initiated in the Netherlands as a joint venture of the Holland America Line (H.A.L.) and the Royal Dutch Meteorological Institute (K.N.M.I.), other European countries, like Great Britain, Western Germany, Denmark and Russia have been following this example.

In the frame of technological and economical developments of merchant marine traffic some questions arise as to the applicability of weather routeing in this rapidly changing situation.

It is the aim of this report to investigate the possibilities of weather routeing in modernized society and to indicate possible adaptations of the routeing procedure in view of the changed circumstances.

1 Some notes on the feasibility of minimum-time ship routeing

In several countries the problem of finding the least time track of a ship across an ocean has been studied. As a result of these studies numerical procedures and techniques have been developed and tested, so that there is now a practical possibility to compute a least time track – denoted as "l.t.t." – with the aid of a normal size digital computer.

However, the practical application of these computing procedures runs across two severe difficulties, being the weather forecast's uncertainties and the serious doubts of ship's operators about a ship's performance in sea waves. These difficulties will be treated and considered in the following paragraphs of this chapter.

1.1 *Weather forecast uncertainties*

The most apparent difficulty in estimating a ship's l.t.t. is the fact that a rapidly changing weather situation makes it almost impossible and at least hazardous to say anything of significance about the weather and sea situation in an area, where the ship can be expected to be two or more days later. This uncertainty has two main implications.

The first one is that the originally estimated l.t.t. may in its later part differ considerably from the track, that is decided upon later on, when more reliable short term weather and sea predictions come in. The nature of this implication is not too serious, providing that the initial l.t.t.-estimate is carefully adapted day by day, taking account of changes in the weather and sea conditions to be expected.

A more serious implication of this uncertainty is that it may seriously affect the selection of the initial course. In order to explain this, let us consider the following situation, shown in figure 1.

Constructing the consecutive timefronts for a l.t.t.

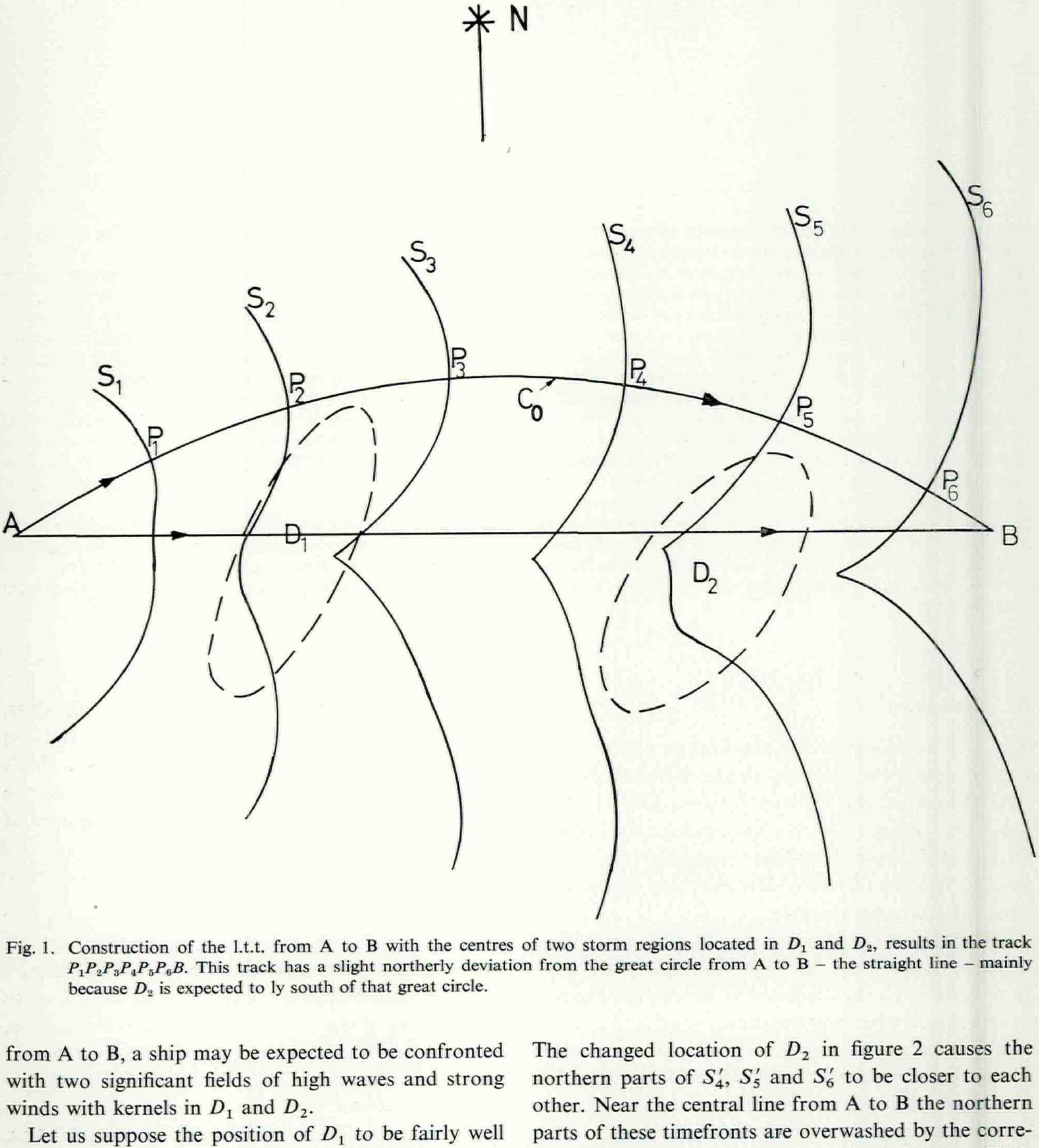


Fig. 1. Construction of the l.t.t. from A to B with the centres of two storm regions located in D_1 and D_2, results in the track $P_1P_2P_3P_4P_5P_6B$. This track has a slight northerly deviation from the great circle from A to B – the straight line – mainly because D_2 is expected to ly south of that great circle.

from A to B, a ship may be expected to be confronted with two significant fields of high waves and strong winds with kernels in D_1 and D_2.

Let us suppose the position of D_1 to be fairly well estimated, while D_2 may be subject to considerable uncertainties.

In the situation of figure 1 the initial l.t.t.-estimate – denoted as C_0 – will pass north of both D_1 and D_2.

However, if D_2 would have been located some 200 miles north of its originally estimated position, the l.t.t. would have led the ship south of the wave fields (see figure 2).

The reason for this abrupt change in the initial course is, that in first approximation, the northern part of the sixth day's timefront S_6 is closer to B than the southern part (see figure 1).

The changed location of D_2 in figure 2 causes the northern parts of S_4', S_5' and S_6' to be closer to each other. Near the central line from A to B the northern parts of these timefronts are overwashed by the corresponding southern parts in the revised situation. With the southern part of S_6' coming closer to B it is obvious that the true or absolute time-extremal runs south of D_1 and D_2.

From a practical point of view it would not be fair to compare the initial estimate C_0 with the true l.t.t., indicated as C. Once the initial course from A is selected, the ship will follow the initial estimate C_0 until a point where the corrected information about the position of D_2 becomes relevant. Let this point be P_3. The adapted track from then on can be found by constructing timefronts from P_3 as a new start. Figure

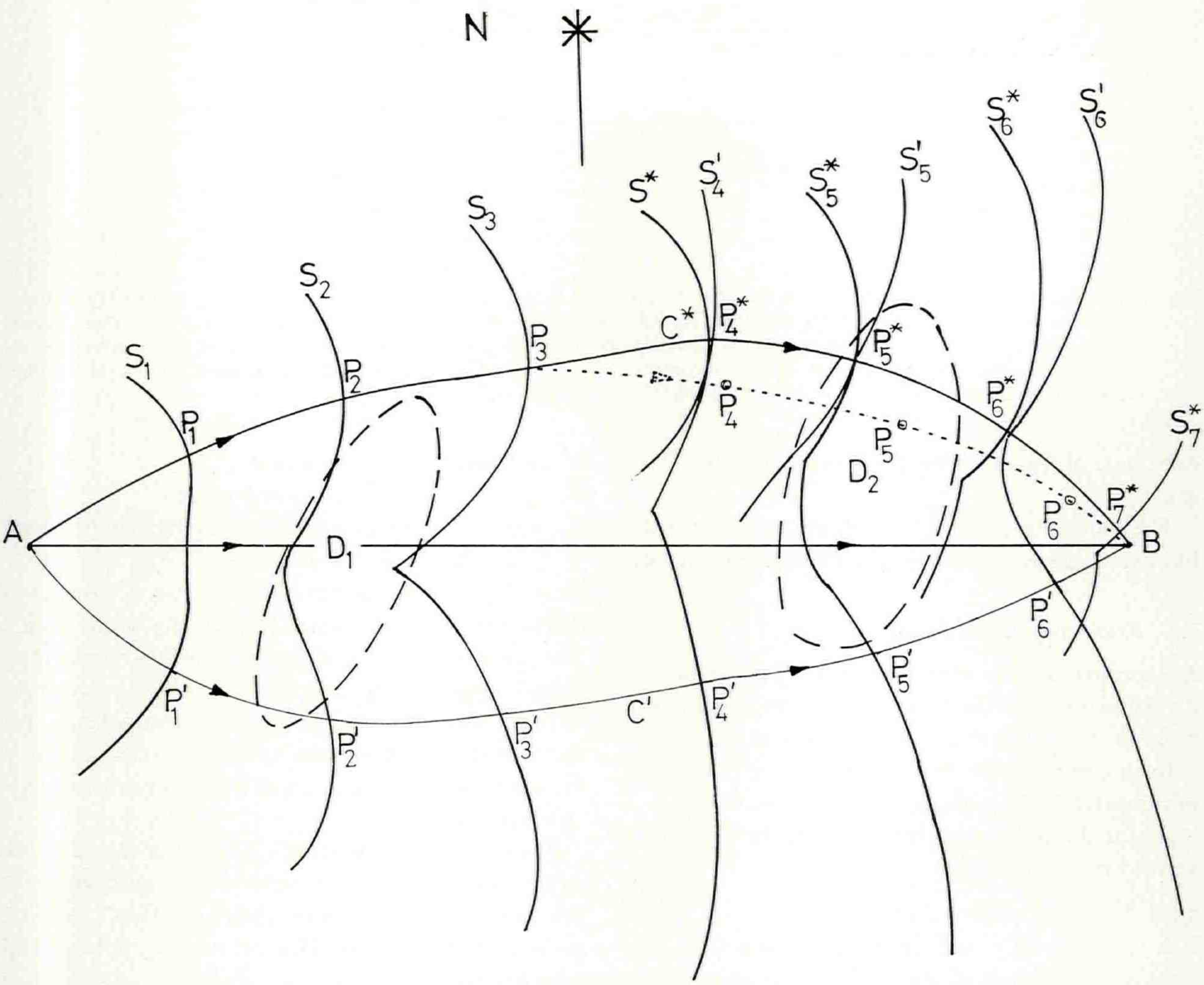


Fig. 2. This figure can be seen as a sequel to Fig. 1. Once the ship has selected the northern route, the second storm region appears to have a slightly more northerly position. From P_3 we now construct a sub-l.t.t. to B with the corresponding sub-timefronts S_4*, S_5* etc. The adapted track now becomes $A \ldots P_3P_4^* \ldots B$. The southern track C' from A via P'_1, P'_2 etc. to B is the true l.t.t. After completing the voyage, this track can be constructed by hindcasting the entire sequence of situations.

2 shows the result. The adapted track becomes $P_3P_4^*P_5^*P_6^*P_7^*$B. It does not deviate much from the "relative" l.t.t. from A to B, which is meant to be a time extremal, compared to other tracks from A to B that pass north of D_1 and D_2.

An aspect that makes this adapting procedure recommendable is that it leads the ship away from bad weather regions as well as possible, so that it contributes to the avoidance of damage to ship and cargo.

With this example in mind, but emphatically remembering, that it is no more than just another example, we can now try to formulate an answer to the main question in this respect: "What is the best assumption regarding the weather and sea state in the over-two-days-ahead area?"

In the treated example we see that a total neglection of the estimated presence of D_2 would have led to the selection of a southern initial course. However this is no more than a sample-based conclusion without any general value.

A significant argument for assuming a perfectly calm sea in the uncertain area could be the following one.

In time-varying situations any estimation of the future conditions, no matter how sophisticated, has too much of a chance of being wrong and thus it has too great a probability of leading to a wrong selection of the initial course. Since such a sophisticated estimation would probably involve a rather complicated computing procedure, the assumption of a perfectly calm sea and atmosphere in the unpredictible region has the practical advantage of being simple, while there is no indication, that this assumption would generally lead to larger errors than any other pre-predicting procedure.

The answer to the question, formulated above, could thus be: "In areas with rapidly changing weather and sea conditions the best policy is to assume a completely

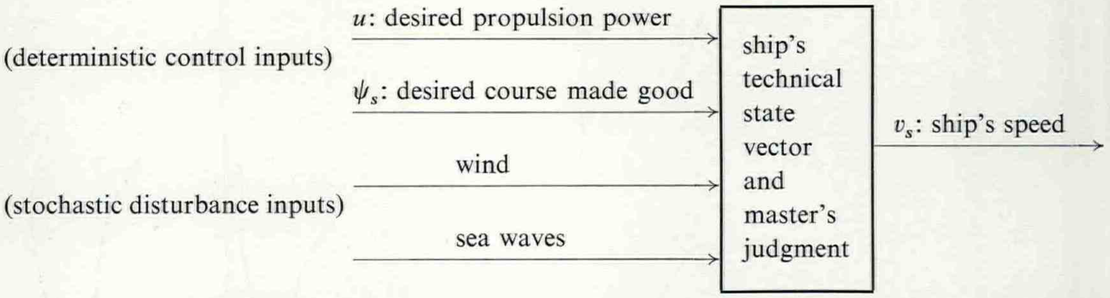


Fig. 3. This figure is meant to illustrate, that an arbitrary ship with a given total weight, a given cargo and fuel distribution and a given set of control parameters, transfers the total of input signals into a stationary speed as the output. Of these inputs, the desired propulsion force and the desired course, to be made good with respect to the ground, are deterministic control inputs. The other two inputs are stochastic disturbances. The values of the control parameters depend, among other things, upon the judgement and choice of the master and the chief engineer.

calm state of sea and atmosphere in the over-two-days-ahead area".

The initially estimated l.t.t. should be adapted day by day, taking account of freshly obtained information.

1.2 *Ship's performance data*

Meteorological ship routeing cannot be done without the knowledge of the behaviour of the routed ship, when being propelled in a wind-generated sea.

In this respect, the ship can be regarded as a dynamical system, schematically shown in figure 3.

As for the technical components of the ship's state vector one can think of:

v_s: ship's forward speed
$z, \dot{z}, y, \dot{y}$: heaving and swaying displacements and velocities of the ship's gravity centre
$\vartheta, \dot{\vartheta}, \varphi, \dot{\varphi}$: pitch and roll angles and the corresponding angular velocities.

The input to this system can be split up in two parts. The first part is formed by the propulsion signal (u) and the desired ship's course (ψ_s).

The propulsion signal causes the engine to exert a propelling force on the ship.

The course signal ψ_s is corrected for

i. drift on account of expected wind influence as well as for
ii. magnetic or gyroscopic errors of the ship's compass.

The corrected course signal is then fed to the ship's compass or ordered to the human helmsman as the desired compass course.

Neglecting time lags, it can be stated that

i. the propulsion signal is one of the contribuants to the ship's velocity v_s, while
ii. the ship's course can be taken to be constantly equal to its reference value ψ_s.

The disturbance-part of the input is of a stochastic nature.

It has the following components:

ψ_a, v_a: wind's direction and speed,
ψ_w, h_w, c_w: sea waves' direction, height and propagation speed.

(ψ_a and ψ_w are usually taken in the sense of "direction where the wind and waves respectively come from". The stochastic nature of these quantities means that, strictly speaking, their probability density functions have to be known. As for the wind components, the distribution can be taken to be Gaussian about a mean value with a rather small and practically negligeable variance.

The wave components are subject to various difficulties. In the first place we have the uncertainties in the mean values of h_w and c_w, given the wind's velocity, its fetch and duration or rather its geographical and time history.

As a result of extensive studies and investigations, done by Pierson, Moscovitch and others, a prediction of significant wave heights and velocities can be trusted with a probability of at most 90%. This 90%-guarantee for the prediction to come true can only be given in the, not too frequently occurring case of one single field of wind waves, built up from zero initial conditions by a practically constant wind. In practice, things can turn out to be much more complicated. Most of the time the sea consists of a system of wind-generated sea waves, superimposed with a decaying system of swell waves from another direction. Situations like that occur quite frequently on the North Atlantic as a result of the passage of a cold front. Before the frontal passage winds and waves are coming in from SW to W, but the cold front passage causes the wind to veer to NW, usually accompanied by an increase in wind speed. Figure 4 may serve to explain this.

In cases like this, the entire situation is rather chaotic. In particular, the directional distribution of the wind waves is extremely hard to predict.

As for the computation of a ship's response to this input, important progress in experimental research has

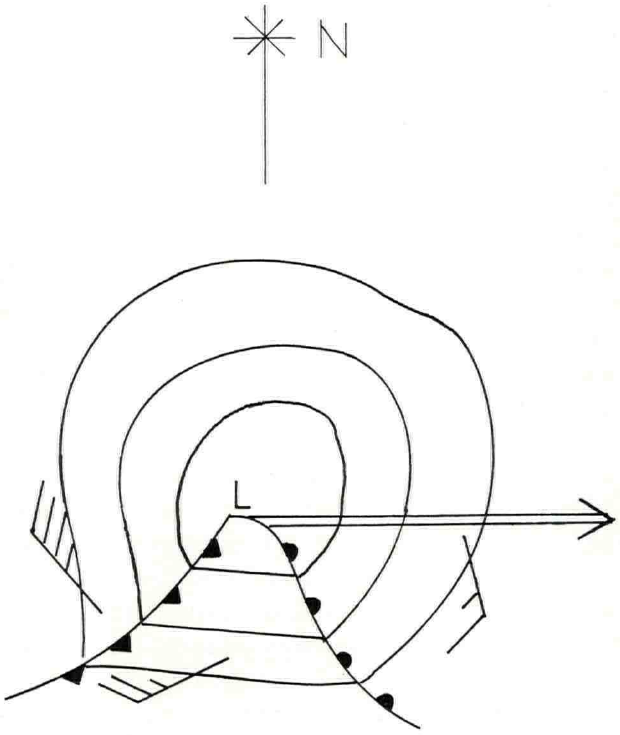


Fig. 4. When a well developed depression moves across the ocean from West to East with an average speed of some 35 knots, the ocean surface south of the centre's track is initially under the influence of southerly to southwesterly winds, building up a field of wind waves that move from SW to NE. The passage of the cold front causes the wind to veer to NW rather abruptly. This "new" wind then builds up a new wave field, while the former waves gradually decay into long period swell.

been made at various institutes of naval architecture.

One of the results of these investigations is, that for wind and waves coming in from -40° to $+40^\circ$ relative to the ship's heading there is a possibility of making a fairly reliable estimate of the ship's velocity for a given propulsion input signal u. For wind and sea coming in from directions between the beam and the stern the situation is much less favourable. For example, a phenomenon like heavy low frequency rolling occurring on modern fast sailing container carriers, is at this moment still in a stage of being qualitatively analysable but by no means quantitatively computable.

In addition to this, a ship's state vector contains more than merely physical variables. There is also the aspect of the captain's judgment. The following lines may serve to enlighten this.

Hydrodynamicists have succeeded in making predictions about the occurrence of phenomenae like bottom and bow flare slamming and shipping green water. Besides affecting the ship's speed, these phenomenae are subject to a captain's judgement to be more or less undesirable. Otherwise stated, a captain's decision to see a certain chance of slamming etc. as a restraint could imply the necessity to reduce the propulsion input signal.

In view of the before mentioned difficulties to obtain good and useful ship's performance data, a few recommendations will now be made for activities, that have the object of contributing to an improvement of the present situation.

It is the author's opinion, that an improvement can be found in involving the ships' officers more actively in the attempts to collect ships' performance data. After all, these men are responsible for the safety of ship and cargo and this safety depends almost exclusively on their decisions. This involvement could be effected in various ways.

For one thing, the officers' training and education could be adapted by organizing special courses in meteo-routeing at the nautical colleges and by adjoining this subject to the basic educational program of these institutes. In these courses and lessons much attention should be devoted to new topics, like the generation and decaying of sea waves, ship's dynamics in irregular waves and the solution of the time-optimal routeing problem. As for ship's dynamics, it should be made plausible how the various motions, like pitching, rolling and heaving are generated and how they affect the ship's forward resistance. The causes of unwanted phenomenae, like slamming, shipping green water and long period rolling should be treated as thorough as possible.

Once the officer has a good understanding of these things, he is able to give a sensible contribution to the solution of the problem of finding out as much as possible about a ship's performance. This contribution could consist of various activities like:

i. observations of wind waves and swell, estimations of significant wave heights, direction and speed of wave propagation as well as estimation of the variances of these quantities,
ii. measurement of the apparent wind speed and direction and
iii. observations and measurements of the components of the ship's dynamics as a response to these inputs.

Important features to be measured could be continuous registrations of pitch, roll and heave during sufficiently long periods of time. Another important quantity to be observed could be the phase lag of the pitching motion with respect to the incoming waves. This quantity could be derived from observations of the stem's motion with respect to the sea surface.

Other activities to contribute to the knowledge of the ship's dynamics could be:

iv. the observation of the ship's speed by means of continuous registrations of the ship's log and
v. observation of the frequency and intensity of the occurrence of slamming and shipping green water.

In connection with (iv) it must be remarked, that ship's log observations are worthless if the log is not tested at every possible occasion. The best way to do this is to take Decca or visible-bearing fixes in sufficiently deep coastal waters with 15 to 20 minutes intervals. The distance runs between the fixes should be corrected for expected tidal stream shifts.

All these observations and measurements would have to be compiled, preferably in combination with numerical data and other knowledge, obtained from ship model basin tests. The final object would be to obtain reliable speed indicatrices of a ship for wave-heights of 0 to 10 meters with 0.5 m-intervals.

In this respect it may be of interest to mention an organized series of measurements of wind and sea waves on board a merchant vessel, combined with the simultaneous registrations of the components of the ship's response. These full scale measurements were prepared and executed by a technical team of staff members of the Shipbuilding Laboratory of the Delft University of Technology. The results were laid down in Report No. 185 S of the Netherlands Ship Research Centre, "Full Scale Measurements and Predicted Sea-keeping Performance of the containership Atlantic Crown" by Beukelman and Buitenhek [7].

It was the main purpose of this project to compare the actually measured increase in required power on account of wind and sea with values, calculated on the basis of a new method, which was based on the principle of energy balance.

The agreement between the actual power registrations and the power calculations was quite satisfactory for the higher frequencies, but the calculations turned out to be less reliable in the lower frequencies.

Concludingly it can be stated that this method has opened the possibility to obtain a fair estimation of the "$-40°$ to $+40°$ off the bow"-part of the ship's speed indicatrix for significant wave heights between 0 and 6 meters.

Coming back to the various recommended activities, the question remains, which shore authority would be the best one to serve as a central guide and co-ordinator for this work. It seems, that the entire organization of the compilation of ship's performance data is a large scale activity, the results of which are of primary importance to shipping companies and their personnel. This work seems to be an appropriate task to be assigned to an institute for navigational research and development.

2 Advantages of minimum time ship routeing

2.1 *Economic considerations*

A first advantage of following a least time track or a track that comes close to it, is the fuel cost saving, rather than the time gain itself. While the relatively small time gain in most cases is lost as a result of difficulties in making mooring and loading arrangements, the fuel cost savings turn out to be an interesting figure.

The Koninklijk Nederlands Meteorologisch Instituut (K.N.M.I.) has been hindcasting the advised routes ever since the operational start in 1962. Comparing the tracks, that were actually followed by the routed ships, with the pilot chart routes that would have been followed without the routeing assistance of a weather bureau, indicated an average time gain for routed ships of two hours for a 2500 miles North Atlantic crossing. For a second category container carrier with a service speed of 25 knots this means a fuel saving of 15 tons of oil, representing a value of approximately Dfl 1000.— (at present equivalent to $ 400.—). The normal dues for a set of routeing advices are Dfl 350.— for one ocean crossing.

Another advantage of meteo-routeing is the far better reliability of a given expected time of arrival, denoted as ETA. This better reliability was concluded from practical experience even in the early days, when weather routeing was still in its experimental stage.

Although a money equivalence to this better ETA is hard to evaluate, it seems recommendable to supply some figures.

For container and lighter-aboard-ship carriers an estimation error in the ETA of one hour represents an average cost increase of $ 300.— on account of unexplored stevedoring facilities. This evaluation is based on the experience that the ETA has a 90% chance of being too early. Furthermore, the fact that a one hour ETA-error has no effect at all from 11 h p.m. to 6 h a.m. was taken into account.

For ports with a considerable vertical tidal range like Le Havre or Southampton a good ETA is obviously essential. Considering container carriers, the loading and unloading facilities are generally limited to harbours or peers with no more than two berths. The difficulties arising from a mutual change in loading and unloading turns of two vessels can certainly be prevented to an important extend by the production of a more reliable ETA.

The reason for this greater reliability of the ETA for least-time-routed ships is the considerably low frequency of the occurrence of severely bad weather for these vessels. This can be explained by the following argument.

From what has been explained in 1.2 it clearly follows that, globally speaking, the predictability of a ship's performance decreases with increasing wave heights and wind speeds.

Where it is obvious that a good predictability of a ship's forward speed gives reason for a good predictability of its time of arrival, it can be said that a high probability of the ETA is promoted by least-time routeing in as much as this policy helps the ship to avoid areas of strong winds and high waves.

This last point will be further discussed and developed in paragraph 2.2.

As a last but certainly not least advantage of weather routeing it may be remarked that it results in a considerable decrease of a ship's bad-weather-holding time. The consequence of this is, that cases of damage to ship and/or cargo on account of experienced bad weather occur much less frequently.

Summarizing it can be concluded that a well organized weather routeing service for merchant ships forms an indispensable link in the entire dynamic system of intercontinental cargo sea traffic. It keeps this system running with a minimal chance of being stagnated or brutely disturbed by calamities.

2.2 *Theoretical investigations of a modified-least-time criterium*

In trying to make a comparison between the least-time problem and problems of crossing an ocean with other optimization criteria, it seems appropriate to reconsider the original problem statement.

A ship is to make an ocean crossing from A to B, a geodetical distance of at least 2000 nautical miles. The following things are assumed to be known:

i. The starting time from A, denoted by t_0.
ii. Meteorological and oceanographical circumstances, as far as they are relevant for the ship's navigation, for a sufficiently long span of time.
iii. The "reduced service speed" in a given field of wind and waves.

The following lines are meant to explain the concept of "reduced service speed". A ship is usually designed and constructed to sail at a certain service speed. The propulsion power, needed to maintain this speed in a calm and practically windless sea, then has a certain value T_s. Generally, this value T_s is some 80–85% of the maximal power, that can be delivered by the ship's propulsion engines.

The reduced service speed can now be seen as the ship's stationary speed, that can be attained in a given wind and wave field, when exciting a propulsion power T_s.

Turning back to the intention of taking a ship from A to B, we can try to make a comparison between the results of the following two policies, marked by P_1 and P_2.

P_1: The ship's master uses the standard service propulsion power T_s up to a speed loss of 80%. In case this treshold value is exceeded, he plans to apply as much propelling power as is needed to keep the ship controllable. This policy is supposed to be maintained regardless of the occurrence of slamming, shipping green water or heavy long period rolling.

P_2: A more careful ship's master is assumed to select his boundary of propelling power on the basis of a set of constraining wishes, i.e. he wishes to reduce the probability of the occurrence of slamming etc. to a certain percentage, like 5% for slamming, 10% for shipping green water and 1% for heavy long period rolling.

Let us now reconsider the P_1-policy. In this case, the master could select the time last from A to B to be minimized. Since he is determined not to reduce his propulsion power, unless the ship meets extremely high waves, the least time track will probably lead his ship through regions of rather bad weather.

Instead of merely minimizing the arrival time t_1, which is equivalent to minimizing the integral

$$\int_{t_0}^{t_1} 1 \cdot \mathrm{d}t$$

the captain might alter his object of optimization, by putting a certain time-penalty on meeting waves of a certain height. The function, to be integrated while sailing from A to B, which equals 1 in the minimum-time-case, could thus be altered into

$$1 + \lambda h_w(x, t)$$

In this expression, $h_w(x, t)$ is the significant wave height, that is met in the point x of the ocean between A and B, when being there at time t. The positive value of λ is an expression of the penalty, that one wishes to put on meeting waves. The object to be minimized, while sailing from A to B, would thus become

$$I = \int_{t_0}^{t_1} (1 + \lambda h_w(x(t), t))\,\mathrm{d}t \qquad (2.2.1)$$

In order to explain, that the value of this integral depends on the selected track, let us consider two extreme cases, illustrated by figure 5.

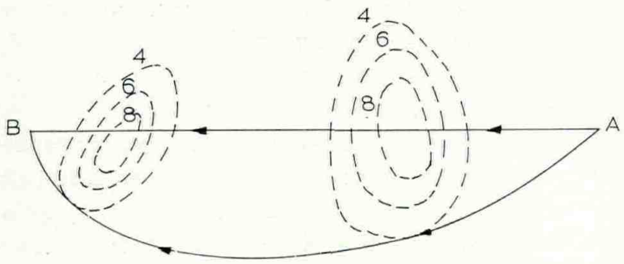


Fig. 5. Comparison of $I=\int_{t_0}^{t_1}(1+\lambda h_w)\mathrm{d}t$ along C_1 and C_2. Take $\lambda=0.1\ \mathrm{m}^{-1}$. This means that the penalty for the ship to be in waves of 1 m during 1 hour is 0.1 hour. Let the track C_1 take 120 hours and let the average wave height along C_1 be 4 m. Then $I_1=120(1+0.4)=168$ hours. Let C_2 take 130 hours with an average height of 2.5 m. This makes $I_2=130(1+0.25)=162.5$ hours.

C_1: The ship is led straight through from A to B along a great circle.

C_2: The ship is carefully manoeuvred around regions of severe bad weather.

In the first case, the arrival time $t_1^{(1)}$ will undoubtedly be earlier than in the second case, where it amounts to $t_1^{(2)}$. The first track however does not avoid bad weather, while on the contrary the second one accentuates this avoidance. So, with a certain value of λ in mind, the outcome of I in the first case might very well be greater than in the second case. (See the subscripts of fig. 5).

Otherwise stated, the selection of the course as a function of time $\psi_s(t)$ for $t\in[t_0, t_1)$, so that the ship is led from A to B, determines the value of I. It now makes sense to state, that this integral I depends on the selected course function. Mathematically speaking, we say that I is a functional of the course function ψ_s.

As for wind and sea conditions, the simplifying assumption is made that wind waves are in an equilibrium state with respect to the wave-generating wind forces. Among other things this assumption implies that $\psi_w=\psi_a$, while c_w has a one-to-one relation with h_w (see 1.2 for notations). Thus the only two, place and time dependent, parameters that have to be taken into account are the significant waveheight and the central direction from where the waves come:

$$h_w(x,t) \quad \text{and} \quad \psi_w(x,t)$$

The ship's reduced service speed can now be seen as a numerically known function of these quantities and of the ship's course $\psi_s(t)$, which acts as a control in the dynamical system:

$$\dot{x}(t)=f(h_w(x,t),\psi_w(x,t),\psi_s(t)) \qquad (2.2.2)$$

According to the theory of optimal control (see [1]) the necessary conditions which the state variables x_1 and x_2 and the costate variables p_1 and p_2 have to satisfy for an optimal solution, are:

$$\dot{x}_i(t)=f_i(h_w(..),\psi_w(..),\psi_s(.)) \qquad (i=1,2) \quad (2.2.3)$$

$$\dot{p}_i(t)=-\sum_{i=1}^{2}\frac{\partial f_j}{\partial x_i}(\ldots)p_j(t)+\lambda\frac{\partial h_w}{\partial x_i}(..)$$

$$(i=1,2) \qquad (2.2.4)$$

For given values of x_1, x_2, p_1, p_2 and t the course $\psi_s(t)$ has to be so selected as to maximize the Hamiltonian, which in this case reads:

$$H(x,p,\psi_s,t)=\sum_{i=1}^{2}p_if_i(h_w(x,t),\psi_w(x,t),\psi_s)-$$

$$-1-\lambda h_w(x,t) \qquad (2.2.5)$$

Remarks:

i. In the last expression the costate vector (p_1, p_2) is denoted by p. Furthermore the time arguments of the variables x, p and ψ_s have been omitted for the sake of brevity.

ii. In the general optimal control problem:
"Find a control function $\{u(t)\}$, $t_0\leqslant t<t_1$, so that the dynamic system

$$\dot{x}_i(t)=f_i(x(t),u(t),t),\ i=1(1)n,$$

is transferred from the given initial state $x_0=x(t_0)$ to the final state $x_f=x(t_f)$ with a minimal value of

$$I=\int_{t_0}^{t_1}L(x(t),u(t),t)\,\mathrm{d}t$$

the costate variables $p_1,\ldots,p_n$ can be seen as Lagrange multipliers, having the function to guarantee that, whenever the optimal control $u_0(t)$ is selected, the dynamics $\dot{x}_i(t)$ are equal to $f_i(.,.,.)$.

Denoting the locations of A and B as $x^a=(x_1^a, x_2^a)$ and $x^b=(x_1^b, x_2^b)$ respectively, the differential equations (2.2.3 and 2.2.4) have to satisfy the starting conditions

$$x_i(t_0)=x_i^a \quad \text{for} \quad i=1,2 \qquad (2.2.6)$$

while for some, yet undetermined time t_1 we must have

$$x_i(t_1)=x_i^b \quad \text{for} \quad i=1,2 \qquad (2.2.7)$$

Comparing these conditions to those in the least-time case, which corresponds to $\lambda=0$, the only difference apparently lies in (2.2.4), the last two terms in the Hamiltonian

$$\text{“}-1-\lambda h_w(x,t)\text{”}$$

being irrelevant for the maximization of $H(\ldots)$.

The extra term $\lambda(\partial h_w/\partial x_i)$ in (2.2.4) results in a scalar increase of p in areas, where the waveheights $h_w(\ldots)$ have a tendency to increase with increasing x_i. This can be shown to result in a selection of ψ_s – by maximizing (2.2.5) – so as to avoid such an area.

This somewhat modified least-time problem could be solved numerically in a way, analogous to the numerical solution of the pure least-time problem, as indicated and extensively worked out by Faulkner (see [2]).

In order to give a brief explanation of the solution procedure, let us consider the systems (2.2.3) and (2.2.4) keeping in mind that (2.2.5) determines $\psi_s(t)$, if $x(t)$ and $p(t)$ both are given. The system of differential equations could only be integrated if the initial value of the costate vector $p^0 = p(t_0)$ would be known. Denoting $p^0 = (p_1^0, p_2^0)$, the entire problem amounts to finding the unknown numbers p_1^0 and p_2^0.

Considering these two numbers as parameters, the solutions of (2.2.3), (2.2.4) and (2.2.5) can be seen as functions of t, p_1^0 and p_2^0:

$$x_i(t) = X_i(t, p_1^0, p_2^0) \qquad (i = 1, 2) \tag{2.2.8}$$

$$p_i(t) = P_i(t, p_1^0, p_2^0) \qquad (i = 1, 2) \tag{2.2.9}$$

It can be remarked that in general the functions X_i cannot be determined analytically, but a sufficiently accurate numerical integrating procedure could deliver any wanted set of function values for assumed values of p_1^0 and p_2^0.

Beside the initial values of p_1 and p_2, the arrival time t_1 is also unknown. This last fact means that the final value of the Hamiltonian has to be zero.

The unknown quantities t_1, p_1^0 and p_2^0 now follow from

$$X_1(t_1, p_1^0, p_2^0) = x_1^b \tag{2.2.10a}$$

$$X_2(t_1, p_1^0, p_2^0) = x_2^b \tag{2.2.10b}$$

$$\sum_{i=1}^{2} p_i(t_1) f_i(h_w(x^b, t_1), \psi_w(x^b, t_1), \psi_s(t_1)) -$$

$$-1 - h_w(x^b, t_1) = 0 \tag{2.2.10c}$$

(Remember that $p_i(t_1) = P_i(t_1, p_1^0, p_2^0)$)

Once the initial values of p_1 and p_2 are known, the corresponding curve $[x(t)]$ can be reconstructed or possibly taken from the computer's memory.

There are, however, two severe objections to this approach. As a first objection it must be remarked that the conditions (2.2.3), (2.2.4) and (2.2.5) are necessary but in no way sufficient to distinguish an extremal track – minimizing (2.2.1) – from an arbitrary other track from A to B. Like the least-time case, this problem is essentially non-linear, so there is a good chance that there is more than one state-space-solution, to be determined by the values of p_1^0 and p_2^0 that follow from the nonlinear system (2.2.10).

Referring to the results of classical variation calculus, (see [3]) we have to be on guard for two things not to happen.

The first thing, that should be prevented, is that the constructed track has points, that are “conjugate” to the starting point A. Briefly stated, a conjugate point can be defined as a point, where the state-space solution is stationary with respect to a change of p_1^0 and p_2^0. In our specific case this would amount to the fact that the determinant of the Jacobian matrix

$$\left\{\frac{\partial X_i}{\partial p_j^0}\right\}_{(i,j=1,2)}$$

becomes zero.

The mathematical test to make sure, that a conjugate point does not occur, is called the Jacobi-condition.

In our case this condition reads that the determinant of the Jacobian matrix

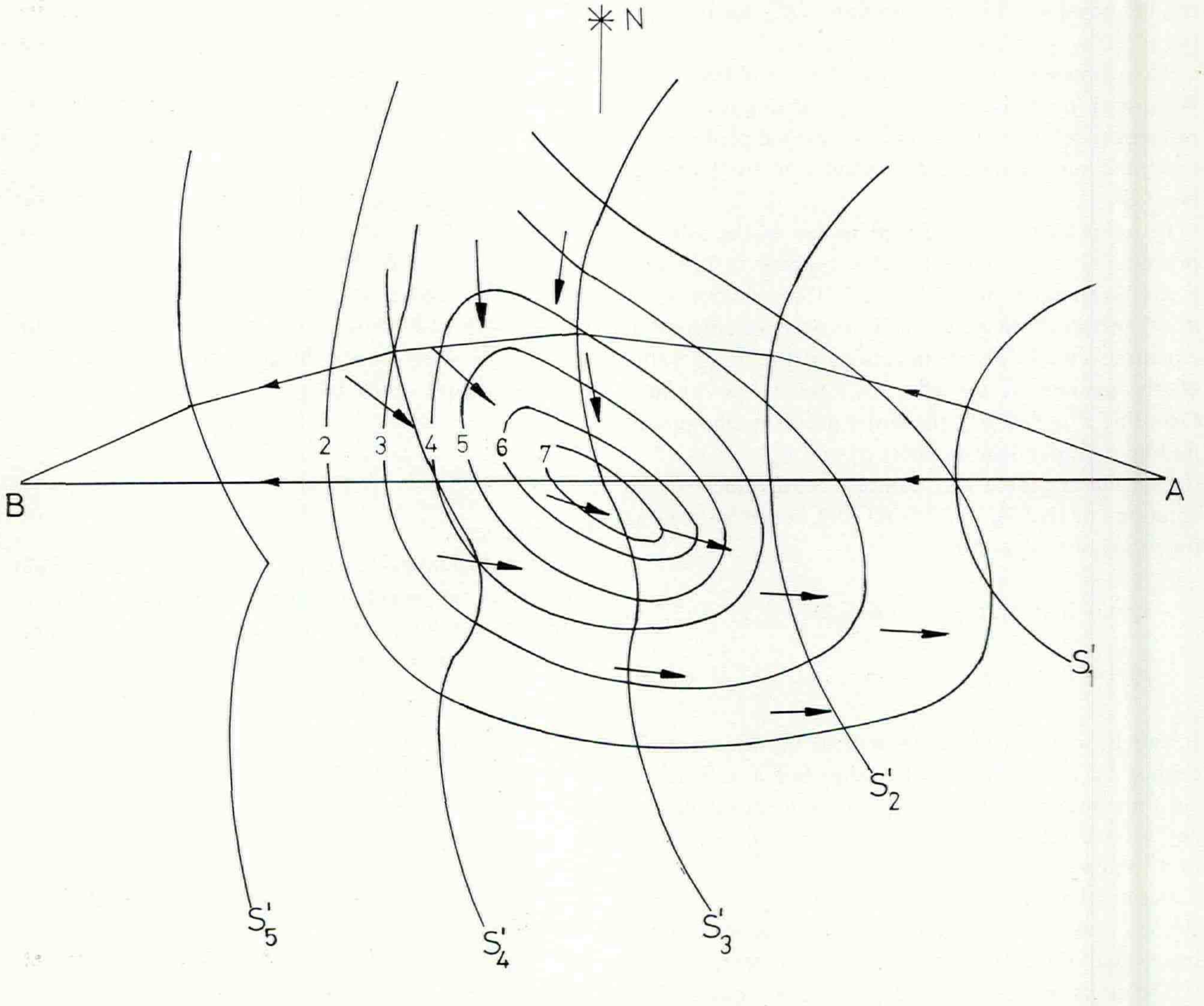
$$\begin{pmatrix} \dfrac{\partial X_1}{\partial p_1^0} & \dfrac{\partial X_1}{\partial p_2^0} \\[2ex] \dfrac{\partial X_2}{\partial p_1^0} & \dfrac{\partial X_2}{\partial p_2^0} \end{pmatrix}$$

should never be zero, at least not before arriving at the endpoint B.

As to the second thing, that should not occur, let us assume for a moment, that we found a solution of (2.2.3), (2.2.4) and (2.2.5) taking the state vector x from x^a to x^b and satisfying the Jacobi-condition all the way. Then we still have to realize that this curve is only guaranteed to be a local extremal. In a more global sense, there is no way to tell, whether or not there is another solution with a yet smaller value of the functional $I(\psi_s)$. The only way to investigate this would clearly be to make an overall search for extremals, seeing that the Jacobi-condition is satisfied and to select the specimen that satisfy the final-state conditions (2.2.7). The curve of this finite collection with the smallest value of $I(\psi_s)$ would be the solution of the problem.

Coming to the second objection to this rather tedious procedure, it is clear that this goes way beyond the field of common sense for daily practice. Like it was remarked before, the ship's officers are strictly responsible for the safety of ship and cargo, so they should have a fair knowledge and understanding of what goes on. Seen in that light, the above described procedure seems hardly recommendable.

Let us now consider the case, where a master would select the P_2-policy, meaning that he is willing to accept a smaller speed in regions with high waves with the object of avoiding severely disturbing ship's motions and other extreme events. With these artificial speed reductions it can be shown, that the selection of the voyage's duration as a minimization criterion will generally lead to a track, that automatically avoids bad



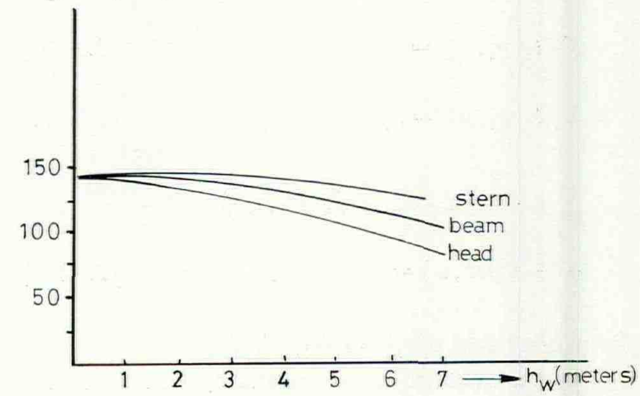


Fig. 6a and 6b. Figure 6a shows the construction of the l.t.t. from A to B with an unmodified speed indicatrix, derived from the waveheight-speed graphs, as shown in figure 6b. This l.t.t. leads the ship through rather high waves, because speed reduction due to of slamming and/or shipping green water is disregarded.

weather regions just as well as with the P_1-policy.

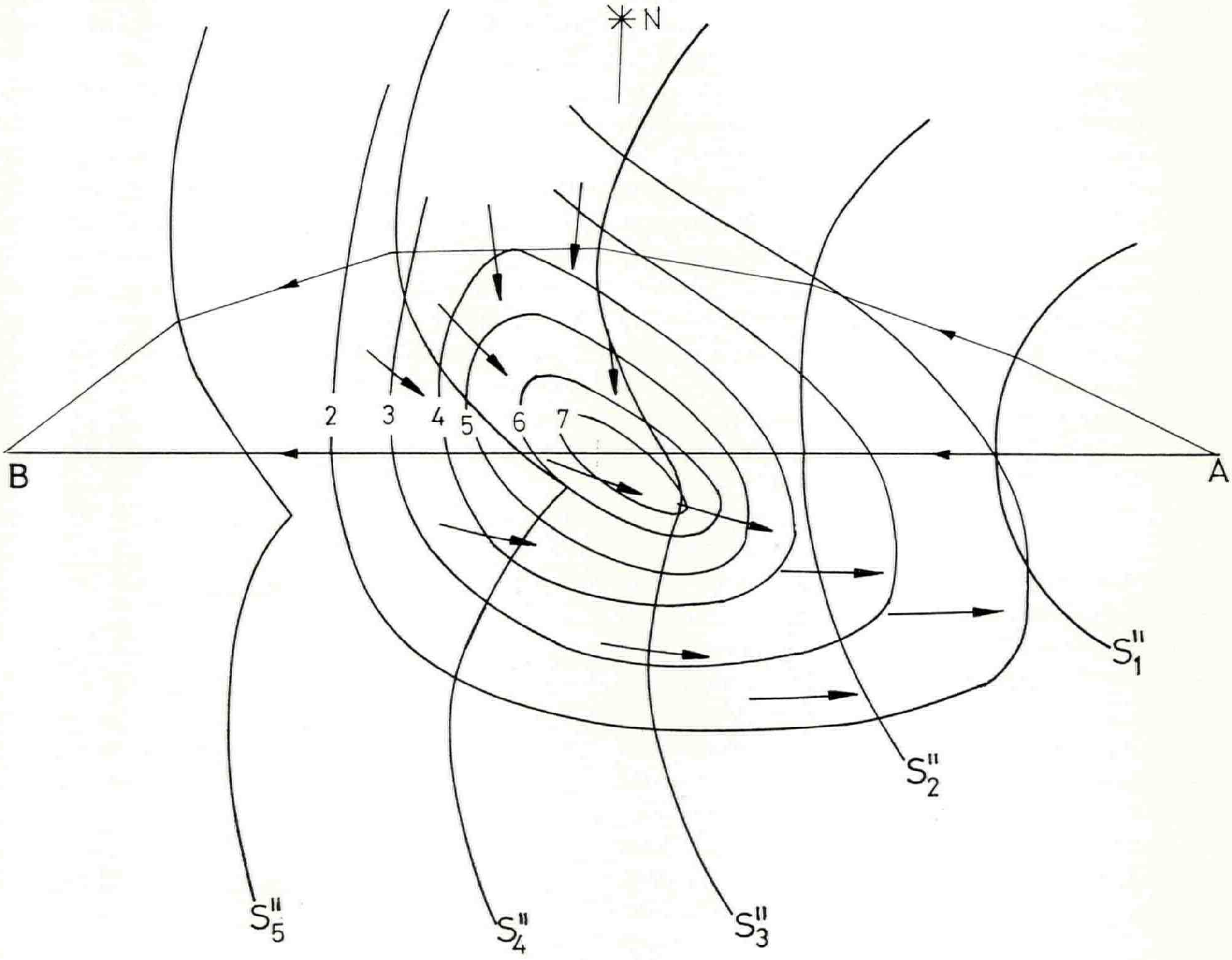
In order to explain this, let us consider an elementary example, shown in figures 6a, 6b and 7a, 7b.

A ship is to sail from A to B. Near the middle of the great circle, connecting these two points, there is a rather deep, well developed and stationary depression with a corresponding wavefield.

We shall now construct two l.t.t.'s for the same ship with the difference that the first track (see figures 6a and 6b) is constructed for an unrestricted ship's performance and no penalty for passing through regions with high waves, while the second l.t.t. is constructed for the case, where the master would adopt the P_2-policy.

In the first case the speed-waveheight graphs for waves coming in from astern, abeam and ahead are shown in figure 6b.

The timefronts S_1', S_2' etc. were constructed for



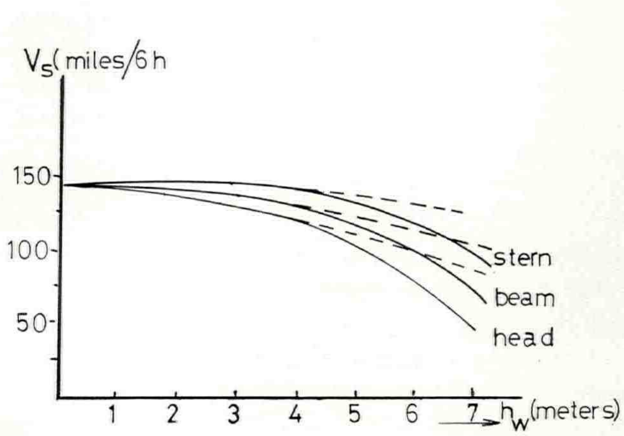


Fig. 7a and 7b. Figure 7a shows the same wavefield between A and B as depicted in figure 6a. In this case, however, the l.t.t. from A to B is constructed with the aid of modified waveheight-speed graphs, shown in figure 7b. As a result of these modifications the ship would be delayed more in regions with waves of over 4 m height, so the l.t.t. makes a somewhat larger bow around the storm area than in the former case of figs. 6a and 6b.

timesteps of 6 hours, in which the ship can cover a distance of 144 miles in a calm sea. In the region north of AB the ship makes more progress due to the fact, that the waves generally come in from directions between 40° and 90° from the stem. The l.t.t. in this case is a curve from A to B with a slight northern deviation from the great circle.

In the second case the speedgraphs, shown in figure 7b, coincide with the graphs in figure 6b for waveheights up to 4 metres. Beyond that boundary the speed is voluntarily reduced to avoid slamming etc. In this case the timefronts S_1'', S_2'' etc. in figure 7a become, with the same sea conditions as in figure 6a, considerably more dented near the wavefield's centre. With better possibilities to maintain normal speed in the outskirts, these central parts of the timefronts are gradually overwashed by the outer parts. The resulting l.t.t. leads through a more quiet area in this case, with waves lower than 4 metres. The time loss, caused by this P_2-policy, is not striking, compared to P_1 – approximately half an hour over a total time of 35 hours – but the selected track is a better guarantee for the avoidance of bad weather.

Concluding this paragraph it seems most recommendable to adopt the P_2-policy. The P_1-method with a modified optimization criterion can only be carried out with the aid of a digital or perhaps a hybrid (i.e. combined analogue and digital) computer. Beside probable financial objections, the adoption of such a syncopated policy would have an unfavourable influence on the navigating officers' feelings of being gradually overruled by automation and it might thus have a bad effect on the quality of their performances.

The P_2-policy has, on the contrary, the advantage of being much simpler. Assuming calm weather in the over-two-days-ahead area (see chapter 1), the construction of the adaptations of the initially advised route, when better short term weather information is available, is very well possible without the aid of a computer. This would also have a very attractive human aspect. The involvement of ships' officers in collecting ship's performance data and the assignment to adapt an initially advised l.t.t. would make these men feel more useful and motivated, because their own observations and their judgments would play an essential part in the navigating procedure.

2.3 *Minimization of the fuel consumption*

In this paragraph the possibility of sailing from A to B – like stated in paragraph 2.2 – with minimal fuel costs will be considered briefly and merely theoretically.

It must be remarked, that with this optimization criterion, the arrival time t_1 has to be a fixed and known quantity. The reason for this is that the amount of fuel costs per covered mile is a monotonously increasing function of the engine's propulsion power. With a free arrival time, an ocean crossing with minimal fuel costs would therefore become a track, covered with a ridiculously low speed. Theoretically, the speed would become zero and t_1 would become infinite.

From an operational point of view, a previously known arrival time is rather attractive, as it helps stevedores and shipbrokers in making arrangements for an efficient loading and unloading schedule. On the other hand it may be difficult to determine a feasible and at the same time realistic arrival time some six or seven days ahead, there being a fair chance that the actual weather and sea conditions differ from what was expected at first hand.

Possibly earlier data on the trip's duration of that ship in the same season could be used to determine an arrival time, that has a 95% probability of being feasible.

In order to solve this problem, the ship's speed would have to be known as a two-components-vector function, depending on the significant waveheight and wave direction, on the course as well as on the engine's propulsion power. Denoting this latter quantity by $u(t)$, we have

$$\dot{x}(t) = f(h_w(x(t),t), \psi_w(x(t),t), \psi_s(t), u(t)) \qquad (2.3.1)$$

With the object of minimizing

$$I = \int_{t_0}^{t_1} u(t)\,\mathrm{d}t \qquad (2.3.2)$$

the state and costate differential equations, which have to be solved, are (with omission of place and time arguments):

$$\dot{x}_i = f_i(h_w, \psi_w, \psi_s, u) \qquad (i = 1, 2) \qquad (2.3.3)$$

$$\dot{p}_i = -\sum_{j=1}^{2} \frac{\partial f_j}{\partial x_i} p_j \qquad (i = 1, 2) \qquad (2.3.4)$$

For each t, the optimal course (ψ_s) and the optimal propulsion power (u_0) follow from the maximum principle:

$$\underset{(\psi_s, u)}{\text{maximize}}\, H(x, p, \psi_s, u) = \sum_{i=1}^{2} p_i f_i - u \qquad (2.3.5)$$

Maximizing $H(\ldots)$ with respect to ψ_s and u means solving ψ_s and u from

$$\frac{\partial H}{\partial \psi_s} = 0 \quad \text{and} \quad \frac{\partial H}{\partial u} = 0 \qquad (2.3.6)$$

For the solutions ψ_{s0} and u_0 of these equations, the conditions

$$\frac{\partial^2 H}{\partial \psi_s^2} > 0 \quad \text{and} \quad u \leqslant u_{\max} \tag{2.3.7}$$

have to be satisfied.

The case that

$$\frac{\partial^2 H}{\partial \psi_s^2}$$

is not positive corresponds to a course ψ_{s0} in a non-convex sector of the ship's velocity indicatrix. (See fig. 8).

The ship then has to take one of the bordering courses ψ_{s1} or ψ_{s2} of that non-convex sector, whichever one gives the largest value of $H(\ldots)$.

As for the optimal value of u we can do by saying that, whenever u_0 would turn out to be greater than its maximal value $u_{\max}$, we should take $u_0 = u_{\max}$.

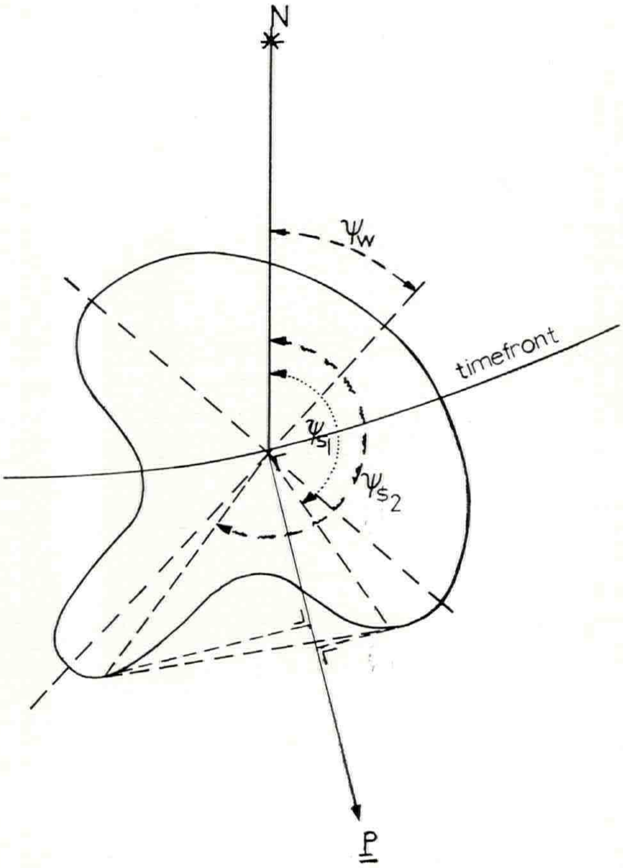


Fig. 8. This figure shows an example of a non-convex speed indicatrix. The non-convexity is caused by the fact, that long period rolling with waves coming in from between abeam and astern is considered too much of a threat to the safety of ship and cargo. With a timefront's normal directed between ψ_{s1} and ψ_{s2}, the optimal course is either one of these two courses, depending on which course vector has the largest projection onto that normal. In the depicted case ψ_{s1} is the optimal course.

Once the optimal values for $\psi_s(t)$ and $u(t)$ have been determined, the system of dynamic equations (2.3.3) and (2.3.4) can be integrated with the initial conditions

$$x_i(t_0) = x_i^a \quad \text{for} \quad i = 1,2$$

The unknown initial values $p_1(t_0)$ and $p_2(t_0)$ can be taken along as parameters, denoted as p_1^0 and p_2^0. The state-solutions of (2.2.3) now become functions of t, p_1^0 and p_2^0:

$$x_i(t) = X_i(t, p_1^0, p_2^0), \qquad i = 1,2$$

The initial values of the costate variables can now be computed from the end conditions:

$$X_i(t_1, p_1^0, p_2^0) = x_i^b, \qquad i = 1,2$$

(remember that t_1 was a given number in this case).

Seen from a mathematical point of view, the problem seems solvable. However, the same considerations as were mentioned in paragraph 2.2 also hold here. This means that the Jacobi-condition has to be checked upon and that an overall search of possibilities has to be made in order to make sure that the solution is globally optimal.

Because of weatherforecast uncertainties, this procedure would have to be repeated day by day as an adaptation to the changed circumstances and newly obtained formation.

As a result of a severe deviation from the initially estimated circumstances, the initially fixed arrival time t_1 may turn out to be non-feasible, once the ship is on her way. The best thing to do then would be to switch, from then on, from least fuel to least time routeing.

3 Routeing services

3.1 *Procedures of present weather routeing services*

This paragraph contains an outline of the working methods of public routeing services in the Netherlands, in West Germany and in Great Britain.

The Netherlands

In the Netherlands the weather routeing bureau is a subdivision of the Koninklijk Nederlands Meteorologisch Instituut (K.N.M.I.) at De Bilt. Its procedure has the following operating characteristics.

All sea-shore communications go through regular wireless telegraph channels. For the routeing service a special manual [6] has been composed and issued, containing all the necessary data for coding and decoding the various messages from ship to K.N.M.I. and vice-versa.

Shortly before the ship is to start an ocean crossing, the master requests the K.N.M.I. to have his ship routed. Along with this request he informs the routeing office about the ship's draught and her thwarships metacentric height.

The permanent or quasi-permanent ship's performance data are known at the routeing office and the master is of course welcome to supplement them with other information of an either temporary or permanent nature.

Once the ship has left port, a first routeing advice for the ocean crossing is transmitted from the K.N.M.I. Whenever the routeing office considers it necessary, this first message can be supplemented with other messages.

The three main features of these coded telegrams are:

i. Advised Route
ii. Routeing Tactics
iii. Wave forecasts.

The advised route may be either a direct standard route or a composite route.

The "Routeing Tactics" can be seen as a brief explanation of the reasons for the advised route. This part of the message gives the location(s) of wave field(s) that the ship is to pass on the advised route. Also the corresponding wavefields' types are given with the way, in which it can be best avoided. Examples, taken from [6], are shown in figure 9. The waveforecast-part gives an estimation of the waveheights and directions, to be expected in the coming 36 hours.

The initial routeing advice can be followed by other advices, whenever a change in the expected weather and/or sea conditions makes it relevant to do so. If the original advised route is maintained, it can be followed by additional waveforecasts for the remaining part of the advised route.

The ship's master is expected to inform the K.N.M.I. about his ship's daily (local) noon positions.
Whenever a master should decide to deviate from the advised route by altering course and/or speed, he is expected to inform the routeing bureau about this by means of special-form telegrams, also described in [6].

Apart from the routeing communications, the master is also expected to furnish the K.N.M.I. with the observed weather and sea conditions at least every 12 hours.

Beside the information, obtained via the "Routeing Tactics" and "Waveforecasts", most ships can get meteo-information from various shore weather stations.

The two main forms in which this information reaches the ship are:

i. weather reports and forecasts in plain language,
ii. weather and seawave maps, printed on the ship's facsimile receiver.

West Germany

The Westgerman Maritime Weather Bureau (Deutsche Seewetteramt) in Hamburg also issues routeing recommendations to ships, that are to make a North Atlantic crossing, leaving from Hamburg, Bremen or Emden. For these ships the first problem is to select the initial course, meaning that a decision has to be made whether the ship is to sail around Scotland or via the North Sea and the English Channel. The advice about this alternative is given by the Seewetteramt on the basis of global information about the situations in the corresponding parts of the North Atlantic.

A few hours before the ship's departure the master receives a telex or wireless message, in which the Seewetteramt gives him this global routeing advice and informs him about the presence and global location

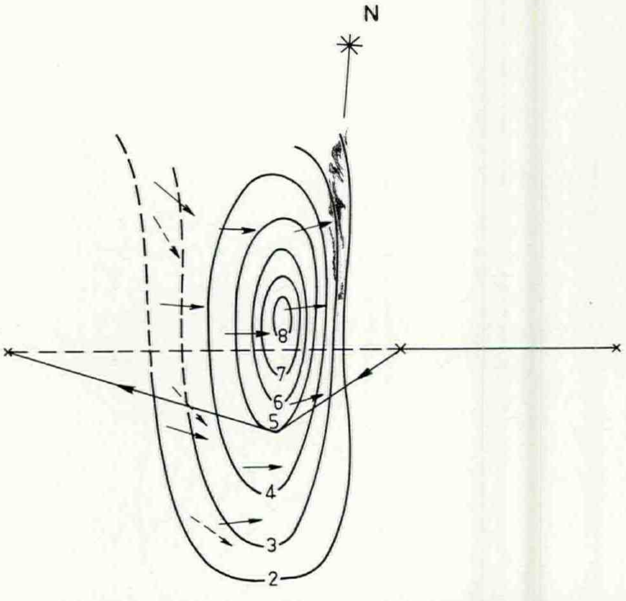


Fig. 9a. When a high westerly wavefield develops so quickly that the westbound ship has insufficient time to make a deviation, or if the 4 m waveheight contour (usually swell) extends so far to the south that a deviation would be uneconomically large, an attempt is made to keep the ship outside the highest part of the wavefield.

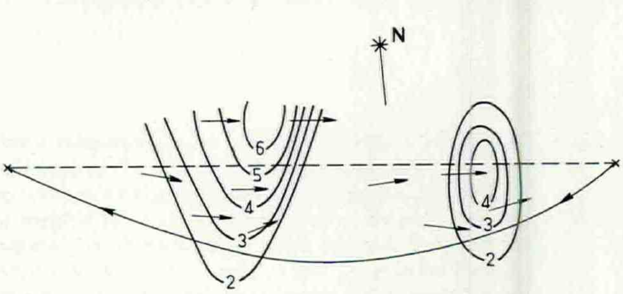


Fig. 9b. Westbound, the ship runs south of all passing successive westerly wavefields.

of good and bad weather areas, to be met by the ship on either one of the two routes. The following lines give an example of such a message.

> "19.1.1967, MS "Margarethe Bolten", Emden – Los Angeles, Auslaufen abends.
>
> Wetterlage um 12.00 GMT:
>
> Sturmtief 980, 51° Nord, 20° West gegen Westirland laufend. Schwere Weststürme mit Wellenhöhen bis 9 m westlich vom Kanal. Weiteres Sturmtief 995 nördlich von Wetterschiff "D" ostverlagernd. Umfangreiches Hoch 1022 Ostgrönland mit breitem Keil 1015 Island festliegend. Daher wird eindeutig die längere Nordroute nach der Mona-Passage empfohlen.
>
> Streckenwetter: In der Nordsee achterliche Winde 4–6, westlich der Shetlands Ost bis Nordost 6–8. Auf der wettermäszig schlechten Südroute ist in den nächsten Tagen westlich vom Kanal mit stürmischen Westwinden und hohen Dünungen aus westlichen Richtungen zu rechnen."

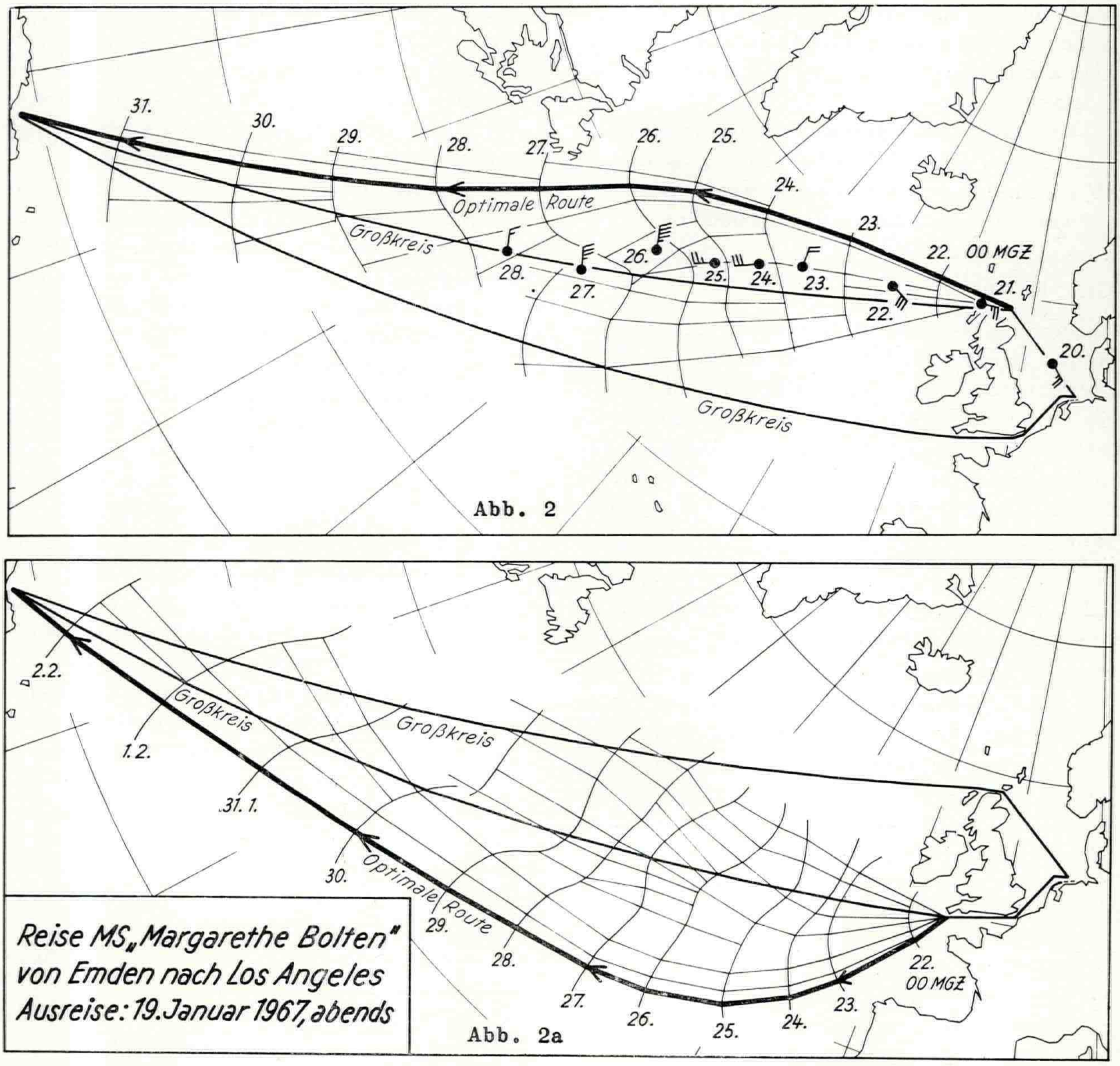


Fig. 10. This figure shows an example of the evaluation of the l.t.t. from a West-German port, like Hamburg, Bremen or Emden, to Mona-Passage. The evaluation is done by the West-German Sea Weather Bureau (Deutsche Seewetteramt). The upper figure (Abb. 2) gives the l.t.t. in case the ship's master has selected the northern route around Scotland, while the lower part (Abb. 2a) gives the l.t.t. for the same ship, if it would have sailed through the English Channel. Ship's masters can be advised by the Seewetteramt to take either one of the northern or southern route approximately 6 hours before the ship's departure. The l.t.t.'s evaluation has the object of learning the master and his officers, how good or bad their own selected route was. The navigating officers thus have the opportunity to enrich their experience and their insight into these matters.

In general, the Seewetteramt does not give any additional weather routeing advices during the voyage, unless the ship's master asks for it explicitly. On the other hand, this office does support the routed ship by transmitting daily weather and wave forecasts through facsimile channels. This way the master is enabled to base his decision on a fairly complete package of useful information.

In cases, where the course of events gave a fair reason to do so, the Westgerman routeing office makes up a hindcasting of the optimal weather route and compares it with the actually selected track. The ship's navigational officers have the possibility to discuss the tactics with the routeing office functionaries and thus have a good chance to improve their knowledge and judgment.

The Seewetteramt's weather routeing service yearly takes care of about 350 global routeing advices. In 40% of these cases a hindcasting is worked out.

Figure 10 shows a hindcasting example.

Great Britain

The working procedure of the routeing section of the British Meteorological Office in Bracknell is comparable to the situation in the Netherlands. On request, the mere routeing advices can be supplemented with information regarding the actual and future weather and wave situation. Unlike the Dutch and Westgerman services, this office does not explicitly offer any hindcasting services.

3.2 *Discussion and recommendations regarding the present situation in the Netherlands*

Comparing the operating procedures, described in the preceding paragraph, the Dutch routeing service seems to be going pretty much ahead when it comes to supplying the ships with information and navigational advices. It is also the only service that offers the possibility of a feedback during the voyage across the ocean. This feedback works in two ways, namely:

i. through the daily reports of the ship's position as well as the reports of the actually experienced weather and sea conditions and
ii. through an eventual report of a deviation from the advised route.

Although the daily position and weather reports do include two figures that represent the ship's course and speed made good, these figures stand for too wide intervals – 45° in course, 5 knots in speed – to be of any significance as a contribution to the ship's performance data. The communication by way of coded telegrams makes a somewhat immobile impression. The navigating officers are obliged to decode the routeing telegrams and in order to get a clear view of the conditions on and near the advised route, they are compelled to draw a mapping of the reported features into a sea chart. A comparison of the predicted circumtances with predictions, obtained from the fascimile receiver thus becomes a rather tedious and time consuming task. Besides, the K.N.M.I. does not give any information about the circumstances in a zone, parallel to the advised route. This might occasionally lead to unanswered questions and misunderstandings as to the motivations for the issued advice.

Summarizing it can be concluded that the Dutch routeing office offers a rather extensive package of information and advices, but the possibilities for a master to take autonomous decisions are certainly not optimal.

There seems to be one thing that practically all presently operating meteorological ship routeing offices have in common. Being practically always a subdivision of a meteorological institute, the component of studying and predicting a ship's behaviour in wind and seawaves is underdeveloped in most cases and sometimes it is even entirely missing.

In an attempt to indicate some possible improvements, the following recommendations are introduced:

i. The ship's master needs a good view on the global weather and sea situation at the start of an ocean crossing. This need could be provided with by furnishing the ship with a weather and wave map, showing winds and waves to be expected for the coming 36 hours in a zone along the advised route with a width of some 600 nautical miles. This first and rather extensive report could be best transmitted in a coded form, similar to the I.A.C.-Fleet weather reports. A broadcast via facsimile channels would probably be too expensive, regarding the fact that it would seldomly serve more than one ship.
ii. Once the ship is sailing along the advised route, the adaptation of this route to circumstances, the knowledge or expectation of which come up in a later stage of the voyage, can be primarily left to the navigating personnel of the sailing vessel.
On board most ships one can dispose of sufficient facilities to do the rest of the navigation autonomously. After the initial routeing advice the routeing office could suffice to stand by, supplying the ship with more routeing information whenever the master sends in a request.
iii. Re-evaluation of the true least time track and the corresponding timefronts could be done by the

K.N.M.I.-routeing office with the aid of the afterwards known weather and sea data.

Fruitful work in this field has been done at the K.N.M.I. by Bijlsma and Van Rietschoten, resulting – as far as today – in three reports, containing a problem analysis and a thoroughly tested computer program with favourable results [5].

iv. An important part of ship routeing consists of the human contacts about this matter between the various classes of people that are involved, like the ship's officers, the employees of the routeing office, scientific and technological authorities and ship-owners.

To be more concrete about these contacts, there should be more room and opportunity to discuss the experiences with the routed ships, among others regarding the received meteo-information and the observations of the ship's dynamics.

These experiences could be matched and/or combined with results, obtained from ships laboratory tests and might lead to adaptations and improvements of the so far adopted on-board-routeing-procedure.

These contacts could be best organised by a separate institute for navigational research and development.

As for the objects and tasks of this – yet to be established – routeing interface office, the following matters might be worthwhile considering.

The office could organize the collection and arrangement of observations and measurements regarding a ship's behaviour in sea waves. The improvements of the knowledge of the ship's behaviour and the recommandations regarding the routeing procedure can be seen as a pay-off to the ship's officers for their inputs.

The necessity of a continuous and intensive contact with the K.N.M.I.-routeing office is rather obvious, because this service is capable of judging, whether or not the meteo-information, that was obtained by the ship, was used in an optimal way.

Contacts with institutes of research of ship's dynamics can be very useful, because these institutes can be expected to give a good scientific and technological support to the development of ship routeing.

Nautical offices of shipping companies should also have full access to the mutual discussions in this respect. Besides being economically interested, their importance can be derived from the fact, that they are the only real authority, when it comes to recommendations and orders to ships' commanding officers with reference to the way, in which the ship is to be routed.

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