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Optimal ship routing via HF radar mapping of mesoscale eddies in the South China Sea

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Abstract

The determination of optimum sailing routes for merchant ships is strongly dependent on timely, synoptic environmental information. In this paper we explore the potential of HF radar to augment existing data sources, especially with regard to mesoscale eddies, using as a setting, the South China Sea

1. Introduction

In accordance with established guidelines, most merchant shipping follows well-defined routes, though a degree of flexibility allows vessels to deviate around storm areas or other hazards and to take advantage of large-scale currents. Such deviations are often guided by commercial ship routing services that collect and analyze real-time meteorological and oceanographic data to generate sailing plans that aim to trade off transit time, fuel consumption and risk, taking account of factors such as vessel characteristics and loading.

While the expertise of these services is not in question, the accuracy of their modelling is inevitably limited by the type, quantity and quality of the environmental data on which it is based, and the verisimilitude of the models that assimilate this information. Data sources include ARGO floats, ship reports, satellite measurements of sea surface temperature (SST), scatterometer measurements and altimeter traces. Some more advanced services assimilate observations with a coupled wave-current system where the currents are provided by an Ocean General Circulation Model Data (e.g. NEMO [1]) while the wave statistics are obtained from a wave model (e.g. WaveWatch III [2]) with wind forcing from a global meteorological model that assimilates ground-based observations and satellite products (e.g. ECMWF ERS 1,2 [3]).

The accuracy of the resulting nowcasts and forecasts is limited by the spatial and temporal sampling density of the assimilated data which, in many parts of the world's oceans, is insufficient to resolve the structure of energetic but localized meteorological disturbances, fronts, sharp gradients in ocean surface conditions and transient phenomena such as convective cells, all of which can pose a significant threat to shipping. In addition, the fidelity of environmental parameter estimates depends on the specific oceanic observables that are accessible to measurement.

An alternative data source that can provide accurate, high-resolution measurements of waves, currents and winds is HF radar, either in the form of coast-based radars using surface wave propagation to monitor the sea surface at ranges up to 400 km, or land-based radars using skywave propagation to observe conditions at ranges up to several thousand kilometers [4]. In each case there are geophysical phenomena that, if present, can impact on the availability and quality of the data, and thence of the subsequent retrievals of ocean surface parameters, though astute radar management and advances in physics-based signal processing have greatly reduced the severity of these limitations [5].

Importantly, by virtue of its precise Doppler measurement capabilities, HF radar can measure the vector surface current, in contrast with satellite-derived altimetric and/or SST data, which cannot yield current velocity directly. Instead, satellite-derived mesoscale current magnitudes are inferred from surface elevation anomaly maps through the application of hydrodynamic models that approximate the dynamics of the water body. Figure 1, reproduced from [6], shows an altimeter-derived surface height anomaly map for a region in the western Pacific; the derived surface current vectors are superimposed. Note, however, that multiple satellite transits are required to generate such maps, which can take at least a day, so the interpretation of a given map as a 'snapshot' is open to debate. This, in fact, is another strong reason to consider HF radar.

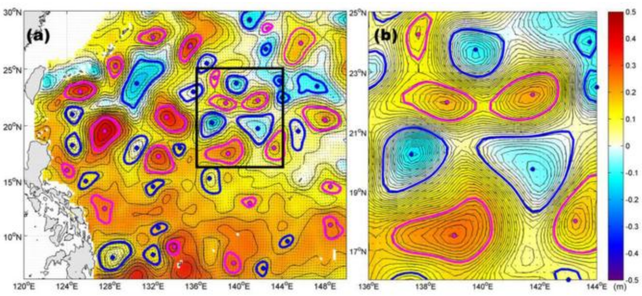

Figure 1. Synoptic-scale map of large eddies in the western Pacific, showing derived currents superimposed on the sea surface elevation anomaly [6].

In this paper we examine the contribution that HF radar can make to optimum ship routing via its ability to generate synoptic and persistent maps of mesoscale and sub-mesoscale eddies. To set our study in a realistic context, we have selected the South China Sea, in part because of its critical role in global maritime trade but also because of the proliferation of HF radars, skywave and surface wave, that illuminate part or all of this vital waterway.

2. The Marine Environment of the South China Sea

In a broad sense, the local environmental parameters of the SCS (South China Sea) that are relevant to our study include the surface wind, the directional wave spectrum, the large-scale current and tide, and the mesoscale flow associated with eddies. All these impact on ship performance; we shall mention several of these in Section IV where their inclusion in a multivariable Pareto optimization scheme is outlined, but for now we focus on the eddies.

Statistical analysis of 18 years of measurements has been reported in [7]. It reveals that, in this region, systems tend to be roughly elliptical in shape, with major axis length of ~ 100 km and minor axis ~ 60 km. Structural features of the resultant current field, such as the width of filamentary flows between vortices, often have length scales of 3 – 30 km, while eddy circumferential current velocities tend to lie in the range 0.5 -1.5 ms^{-1}, reaching 2.3 ms^{-1} (4.5 knots) in extreme cases. The eddies drift at speeds of up to 10 km per day, with lifetimes of 20 – 60 days. A representative snapshot of the surface elevation anomaly in the SCS is shown in Figure 2 taken from [8]; several eddies are marked, some departing from elliptical form. Often this distortion precedes breakup, with consequent rapid local changes in flow.

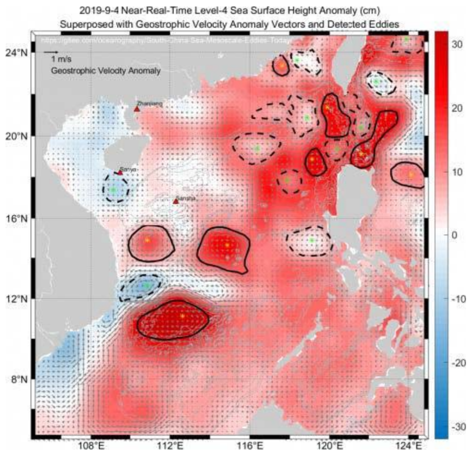

Figure 2. A map of the sea surface height anomaly in the SCS with the geostrophic anomaly vectors shown. Note the elongated eddies in the northern region [8].

To illustrate the variation of the eddy field structure from day to day, we have extracted maps of current vectors for three consecutive days, as shown in Figure 3 where the currents are superimposed on sea surface temperature.

The principal impact of eddies on ship movements is the addition of the eddy circumferential velocity with the ship speed through water (STW) vector to yield the speed over ground (SOG) resultant vector. For a bulk carrier, with an average STW of 11 knots, the difference in SOG between an adverse eddy component and a favorable one can easily exceed 2 knots, which corresponds to a steaming time penalty of perhaps 2 hours transiting a single medium-sized eddy, at a cost of tens of thousands of dollars.

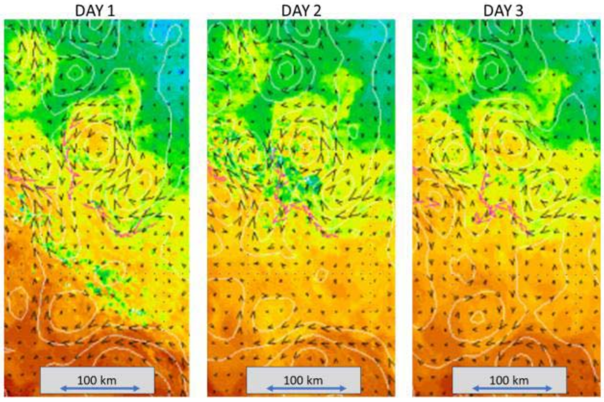

Figure 3. Day-to-day variation of the surface current field

3. Ship Traffic in the South China Sea

Over one third of all global marine traffic passes through the SCS, the overwhelming majority of it (as measured by tonnage) connecting China, Japan and the Republic of Korea to their suppliers and markets. In addition to this through traffic, the SCS supports the world's most numerous concentration of fishing boats; these harvest some 12% pf the total global fishing catch, so any discussion of traffic management and route optimization must take account of this 'background' of small vessels.

The situation can best be illustrated by maps showing the locations of vessels reporting via the Automatic Identification Scheme (AIS) at a specific time. To show them all on a single synoptic map is impractical, so, in Figure 4 we show the distribution as presented by Marine Traffic's display for the entire SCS [9], and then, in Figure 5, zoom in to the box indicated in Figure 4 to reveal other vessels not plotted in the larger frame.

Figure 4. Synoptic map showing the distribution of ship traffic in the SCS and surrounding seas, as generated by Marine Traffic [9]. Note the rectangular box to the south of Vietnam.

Figure 5. Additional ship traffic revealed by zooming onto the box marked in Figure 4.

4. HF Radar Coverage and Resolution in the South China Sea

The SCS is under observation by scores of HF radars, including skywave systems, surface wave radars, and, it is fairly safe to assume, hybrid configurations including shipborne receiving systems or other combinations. For our present purpose, we confine attention to conventional configurations.

Figure 6 shows the nominal coverage of around eighty HF radars, most of them HFSWR systems. The achievable range for current measurement varies from one system design to another, but it seems evident from the map that only skywave radars provide coverage of the main shipping routes along the south-west to north-east axis. Almost the radars shown are presently operation, the exception being the proposed US radar under construction in Palau. The associated coverage is shown by the blue dashed lines.

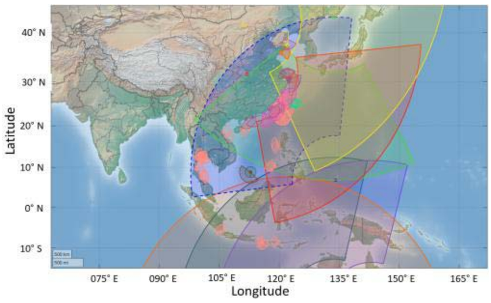

Figure 6. Nominal coverage of HF radars over the South China Sea and neighboring waters.

We hasten to note that access to outputs from these radars is problematic in the extreme, but that is not our concern here, where we focus on the potential applicability of the technology, not its present-day implementation.

There are several practical considerations to address. First, we need to compare the size of HF radar resolution cells with the length scales of the mesoscale eddies, and also the traffic spacings. To do this, we have in Figure 7 superimposed representative radar resolution cells on the high resolution traffic map of Figure 5.

The yellow panel shows the representative size of a resolution cell for a hypothetical HFSWR which we have located in Vietnam for purely illustrative purposes. The blue panel shows what one might expect for the Palau skywave radar, should it proceed to completion. Of course, the size of a resolution cell changes with radar frequency, which may vary over two octaves in some cases, but the point we make is that, under favorable conditions, these HF radars are able to resolve features of order 10 – 20 km in size, which is sufficient to map the spatial structure of the eddy field. As for the ability of HF radars to distinguish vessels in close proximity, we point to their exceptional Doppler resolution, so even when two ships fall within the same spatial cell, they can be resolved if their components of velocity along the radar viewing axis differ by as little as one knot. The yellow panel shows the representative size of a resolution cell for a hypothetical HFSWR which we

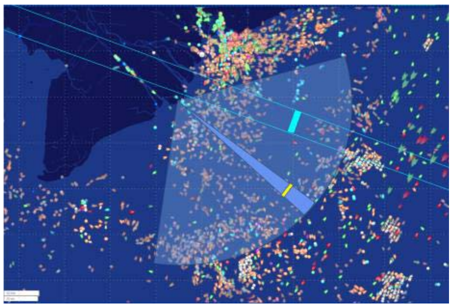

Figure 7. Coverage as in Figure 5, with representative radar resolution cells shown. Light blue denotes HF skywave radar, yellow HFSWR.

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A second issue arises from the fact that skywave radar involves a propagation path that is in some respects unknown, so the transformation from radar coordinates of range and bearing into geographical coordinates of latitude and longitude can introduce appreciable errors in absolute position, up to tens of kilometers. However, for the problem at hand, namely guiding a cooperating vessel through its prevailing environment, absolute position is largely immaterial; what matters is relative position between the ship and the features of the eddy current system it confronts. As the propagation paths are very similar for the two skywave measurements, prospective absolute errors of 10 – 20 km become relative errors of 1 – 2 kilometers.

A third issue is the variable accuracy of Doppler measurement. Skywave propagation paths introduce Doppler shifts due to the motions of the ionosphere, and these bias the estimation of surface current velocity. Fortunately, there are many techniques that can be applied to separate the ionospheric Doppler from the eddy current Doppler, the most powerful being those that exploit echoes from fixed scatterers such as small islands and even submerged shoals. For much of the SCS, there are abundant candidates for this Doppler registration procedure, but even where this is not the case, observations over a period of hours can usually reduce the error to much less than 1 knot.

Yet another difficulty relates to the spatial transfer function of the skywave propagation channel. Often multiple paths exist between the radar and any given point on the ocean surface. Again, enormous effort has been devoted to the development of amelioration techniques to unravel the superposition (e.g. [6]) and extract the desired information.

While these complications can be annoying and occasionally challenging, HF skywave radars routinely deliver high quality measurements that meet the requirements for mesoscale eddy mapping, along with many more ambitious tasks relevant to ship routing. For example, detailed measurements of the directional wave spectrum can be retrieved, and interpreted in real time to detect the development of sea states with the potential to be hazardous to some classes of vessel, such as container ships. As another example, short-lived squalls and other severe transient weather have characteristic radar signatures.

5. Single Radar vs Dual Radars

It has been recognized since the earliest days of radio oceanography that to map the current velocity vector and not just one component – the projection onto the radar viewing axis – measurements from two different directions are needed, as illustrated in the simulation shown in Figure 8. However, in our case, it may be possible to derive enough information from a single radar to help determine the optimum sailing route, or at least a reasonable approximation to it. The reason for this is that we may presume the optimum course to be strongly dependent on the (integrated) current component aligned with the ship's heading. Therefore, a radar whose viewing axis lies along the nominal route is well situated for mapping the following and opposing current speeds and identifying the optimum course. For sub-optimum radar siting, the single component map is still useful when combined with even a crude model of the circulation, just as single HFSWR systems employ may employ the assumptions of divergence-free flow to derive a two-dimensional current map.

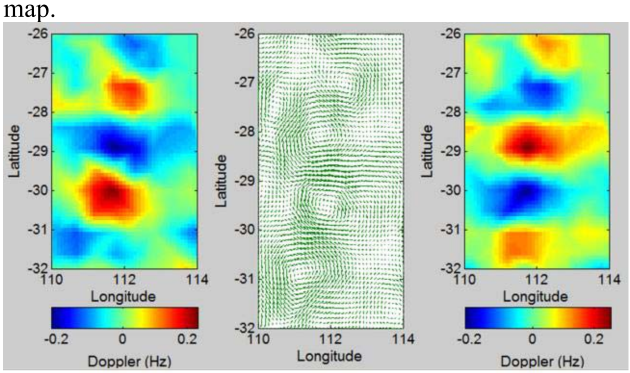

Figure 8. An altimeter-derived eddy vector current map recorded off western Australia, in the central panel, with predicted Doppler maps for two hypothetical skywave radars located to the west and east shown in the left and right panels.

6. Route Planning Techniques

If we now assume that a map of the eddy circulation is available, we are confronted with the optimization problem familiar to the route planning experts. Complicating the situation is the existence of a host of different optimization criteria – do we seek the shortest travel time, the most economical in terms of fuel usage, the route that is constrained to meet a particular arrival time, the need to take account of vessel sensitivity to wind and wave conditions, and so on. This multi-objective problem is well suited to the Pareto optimization approach, as used in [10] to optimize HF radar siting in the Strait of Malacca with two independent criteria.

The evaluation of optimum paths in the general discrete case is often formulated in the framework of graph theory. Several well-known methods have been developed for this setting, most famously the Dijkstra algorithm, where a set of nodes is defined and weights assigned to the edges. In our case, we are exploring a different approach, using the accelerated genetic algorithm of [11], together with a strategy for dynamic reassignment of nodes. Simulation results are expected soon.

7. Conclusion

The desirability of optimizing ship routes has led to an industry of professional route planners, but the data on which they base their recommendations falls short of what is possible. We argue in this paper that HF radar, especially HF skywave radar, has the potential to contribute significantly to improved planning by virtue of its ability to measure the currents associated with mesoscale eddies. Parenthetically, we note that HF radar can measure sea state and surface winds, though that has not been our focus here.

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