Spatiotemporal uncertainty of movement data in unstructured geographic areas: Approaches to generate possibility spaces from ship movements

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Abstract

Path planning in unstructured geographic areas usually cannot rely on an existing graph of potential route segments, but has to operate on polygonal spaces. Furthermore, it does depend on the underlying structure (e.g. terrain, weather, water conditions), which constrain the movement. When it comes to a reconstruction of historical ship voyages, exact trajectories or detailed navigation data are often lacking, and thus an accurate itinerary is difficult to reconstruct due to inaccurate or incomplete documentation. What is often given, however, are ship logs, which contain information about harbors, events on the route or general navigation information.

The aim of this work is to determine potential navigation spaces that are based on the calculation of a geographical area that attempts to encompass all valid path options, based on given information and general assumptions also taking common navigational practices in historical seafaring into account. This knowledge is encoded in terms of different weighting schemes for a generalized shortest path approach. The idea uses the concept of *possibility spaces*, which was introduced in a previous publication (Fuest et al., 2025) and focused on the visualization of these uncertain spaces.

1. Introduction and motivation

Path planning in unstructured geographic environments is challenging, as it is usually not possible to rely on predefined networks or graphs of feasible routes, but instead it must operate on continuous spatial domains shaped by environmental conditions such as terrain, weather, or hydrodynamic influences (LaValle, 2006; Thrun, 2002). This challenge becomes particularly pronounced in the context of reconstructing historical ship voyages. Historical sources, including travel reports, logbooks, and letters, often provide only fragmented or imprecise information about past journeys. While such documents frequently record key events or stopping points of a ship, their locations are typically associated with considerable spatial and temporal uncertainty. Moreover, the actual course taken between these events usually remains undocumented or cannot be unambiguously inferred from the available sources.

Despite these limitations, a comprehensive reconstruction and visual representation of historical routes, explicitly accounting for their inherent uncertainties, is crucial in terms of many issues relating to the maritime sector. Such representations enable a wide range of analyses that would otherwise be difficult or impossible, particularly in cases where sources are incomplete, ambiguous, or even contradictory (Gregory & Ell, 2007; Knowles & Hillier, 2008). For instance, they facilitate the identification of potential encounters between ships, the analysis of maritime traffic patterns, or the detection of corridors with increased navigational activity.

However, conventional path planning approaches, such as computing a single shortest or least-cost path between known events, are ill-suited for this purpose, as they impose a false sense of precision on inherently uncertain data (Khaksar et al., 2015). Even the consideration of a limited set of alternative routes fails to adequately capture the full range of plausible trajectories, as many feasible paths remain unrepresented. To address this limitation, it is more appropriate to model spaces that encompasses all routes that could realistically have been traversed within a given temporal and environmental context. Such a representation provides a more trustful reflection of the uncertainty embedded in historical data.

Building on the concept of possibility spaces introduced by Fuest et al. (2025), this paper presents methods for the computation and visualization of such spaces in the context of historical maritime navigation. Using a real-world case study of a historical voyage, it is investigated how different weighting schemes for path calculation influence the spatial extent and structure of the resulting possibility spaces. Through a series of experiments, it is demonstrated how these methodological choices affect the range of possible route options, which provides interesting insights into how different factors may have influenced navigation in historical times.

2. State of the art

2.1 Digital humanities in the context of historical ship voyages

Digital Humanities (DH) function as an interdisciplinary framework that synthesizes computational methodologies with traditional humanistic inquiry, and has become particularly influential in the study of historical maritime navigation and ship routes. Within this context, DH enables the systematic reconstruction and analysis of historical voyages by integrating heterogeneous archival sources, such as logbooks, travel accounts, and administrative reports, into computationally tractable formats. By employing advanced data processing techniques and algorithmic modeling, the field facilitates a transition from predominantly qualitative interpretations toward empirically grounded, reproducible analyses (Berry, 2012; Schreibman et al., 2016).

A particularly sophisticated application of DH lies in the spatial reconstruction of historical ship movements through the digitization and annotation of archival records. Researchers extract spatiotemporal information, such as coordinates, bearings, wind conditions, and recorded events from logbooks and related documents, transforming them into structured geospatial datasets (Gregory & Ell, 2007). This data is subsequently processed within Geographic Information Systems (GIS), allowing for the generation of digital trajectories that visualize maritime routes and enable the analysis of patterns of mobility, trade, and colonial expansion across global oceans.

In the context of historical ship routes, DH approaches also address challenges related to data uncertainty, variant toponyms, and incomplete records by incorporating probabilistic modeling and semantic annotation techniques. This not only enhances the interpretability of reconstructed routes but also allows for the integration of additional data layers, such as environmental conditions or associated historical events.

2.2 Path planning in unstructured geographic areas

Path planning in unstructured environments is challenging, because, unlike in structured areas, there are often no clearly defined paths, which a vehicle could follow. In literature, existing approaches are typically divided into two main categories: hierarchical planning methods and end-to-end learning approaches (Wang et al., 2024).

Hierarchical approaches follow a classical navigation pipeline comprising perception, mapping, terrain traversability analysis (TTA), cost modeling, and global and local path planning. Traversability analysis plays a key role here, as it assesses the navigability of a terrain based on geometric (e.g. gradient, roughness) and physical properties and integrates this information into cost functions (E. Carvalho et al., 2025; Fabres Dalmonech et al., 2026). On this basis, classical planning methods are employed, including graph-based methods (e.g. Dijkstra, A*) or optimization-based approaches. Modern extensions integrate additional aspects such as safety, energy or comfort costs, as well as explicit risk models (e.g. traversal risk graphs), to generate robust and safe trajectories (Lee et al., 2025).

In contrast, there are learning-based methods, in particular deep learning and reinforcement learning, which enable sensor data to be directly mapped onto actions or trajectories (Wu et al., 2026). These methods are particularly well-suited to highly dynamic and difficult-to-model environments, but still pose challenges in terms of training effort, interpretability and generalization.

Path planning in unstructured environments can apply to various types of infrastructure-scarce terrestrial environments such as deserts or forests, as well as to water surfaces. For path planning on water surfaces additional challenges arise from dynamic environmental influences such as wind, waves and currents (Öztürk et al., 2022). Traditional methods such as A* or Dijkstra are also used in the maritime context, but are often extended by evolutionary algorithms (e.g. genetic algorithms) or numerical optimization methods to take into account additional criteria such as energy efficiency, safety and path smoothness (Hashali et al., 2024). A key distinguishing feature from terrestrial path planning is the need to explicitly integrate environmental influences into the model in order to generate realistic and feasible paths. Another important area of research concerns multi-agent systems. Here, multi-objective optimization methods are used to simultaneously account for competing objectives such as collision avoidance or energy consumption.

A review of the navigational practices of historical sailing ships shows that routes were typically chosen to allow for orientation using coastal landmarks. At the same time, areas in immediate proximity to the coastline were generally avoided in order to reduce the risk of hazards such as shallow water areas, strong currents, or submerged obstacles. While navigation across the open sea could offer greater efficiency, it also entailed significant risks due to the absence of reliable reference points and increased exposure to weather conditions. Consequently, route selection in historical seafaring was commonly characterized by a dynamic balance between proximity to the coast and the relative safety of offshore navigation (Harland & Myers, 1984; Litvine et al., 2024).

3. Historical context and case study

Historical research into maritime voyages draws on a wide range of diverse sources, each offering specific insights into maritime mobility, colonial interactions and everyday life on board. The most important types of sources include official logbooks and reports to military or state institutions, personal travel accounts and letters from crew members, contemporary newspaper articles, and material artefacts in the form of museum objects (Gregory & Ell, 2007). While logbooks and Admiralty reports frequently contain standardized, administrative information on routes, weather conditions and events, personal records offer subjective insights into perceptions, interpretations and motives for action. Newspaper reports, in turn, convey a public-facing, often politically colored account, while objects in museum collections can be interpreted as material evidence of colonial encounters (Gosden & Knowles, 2020; Thomas, 2009).

A section of a real historical voyage serves as a case study in this research, which is part of the DiViAS Project (Luhmann et al., 2026). The voyage concerns the reconstruction of the route taken by the gunboat *Albatross*, which was launched in 1871 and served in various capacities during its service – from gunboat to cruiser and survey vessel (Hildebrand et al., 1980). With a crew of around 103 men, the ship was deployed in various regions of the world, including South America, the Caribbean and, in particular, Oceania, where it was stationed between 1884 and 1888. Under the command of Friedrich Graf von Baudissin (1852–1921), who commanded the *Albatross* from November 1885 to December 1886, so-called ‘punitive actions’ were carried out against local populations as part of the exercise of colonial power (Bundesarchiv, 1885). These included, among other things, violent measures such as the demand for tributes, arrests and the destruction of settlements (Hiery, 1995). The events are not only documented in written sources but are also reflected in collections of artefacts, which are now housed, for example, in the State Museum of Nature and Man in Oldenburg, Germany.

The journey considered in this work covers part of the Bismarck Sea in the Pacific Ocean, within the territory of present-day Papua New Guinea, and took place in February and March 1886. The journey covered two geographically separated areas, which were more frequently visited by the *Albatross* as part of its voyages in colonial contexts: a northern area in the north-west of what is now the island of New Ireland, and further south an area in the north-east of what is now the island of New Britain.

To validate the methods developed in this paper, the scope was limited to the northern section of this route, as it offers the most interesting geographical conditions in terms of the methodology for calculating possibility spaces: The area includes a large number of islands which form a natural barrier and therefore had to be circumnavigated.

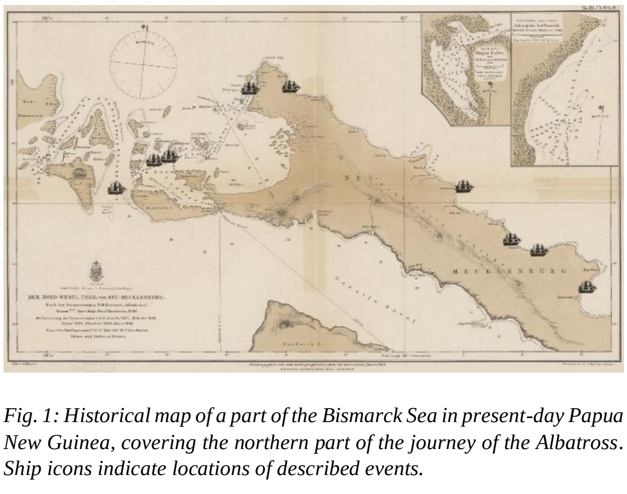


Fig. 1: Historical map of a part of the Bismarck Sea in present-day Papua New Guinea, covering the northern part of the journey of the Albatross. Ship icons indicate locations of described events.

Figure 1 shows a historical map dating from 1889 that depicts the area including the northern section of the route (Bundesarchiv, 1889). Ship icons are used to illustrate the locations of events that were described in the source material of the journey. The maximum speed specified for the Albatross class of vessel is 10.5 knots (19 km/h). The cruising speed can be taken as half the maximum speed, which corresponds to approximately 10 km/h.

The different events that occurred during the journey are modelled as point objects, while it is also possible to model events as line objects in case a movement is described. Each event has various attributes derived from the textual description in the source material such as the location name, time and geometry information, or information about objects and involved persons.

The source material contains various types of uncertainties, relating in particular to spatio-temporal uncertainties that stem from imprecise descriptions. These can be attributed primarily to spatial or temporal prepositions and postpositions, such as ‘off the coast’, ‘near the bay’ or ‘towards evening’. In this work, however, the focus is in particular on the spatio-temporal uncertainty regarding the path chosen between the locations of two successive events. Reconstructing such paths is particularly challenging, since the sources provide very few clues as to the exact trajectory. Additional challenges are the historical toponymy, such as varying spellings or different indigenous and colonial naming systems. Here, historical maps can serve as a supplementary source to validate and contextualize spatial information.

Therefore, in this study, the calculation of possibility spaces is performed using information extracted from the historical map as a basis. To prepare the navigable space, geometries marked on the historical map such as landmasses or shallow water areas have been digitized as vector data.

4. Workflow and data model

Further analysis requires the systematic processing of the sources. This initially involves transcribing handwritten texts into a modern, machine-readable format. Building on this, automated methods using language models are employed for annotation and information extraction. The aim is to identify and classify relevant entities such as places, dates, people and objects. The data structured in this way is then stored in a geodatabase, which serves as the basis for further analysis and visualization. In this way, it becomes possible to explore historical ship movements and associated events not only narratively, but also spatially and analytically.

The proposed approach for modeling historical movement data is fundamentally based on an event-centric data strategy, primarily drawing upon the CIDOC CRM (International Committee on Documentation - Conceptual Reference Model) ontology (Bekiari et al., 2024). Central to this model is the formal representation of entities such as “E5 Event” and “E4 Period” to capture the spatio-temporal dynamics of maritime movements. Logbook entries serve as the primary data source, aiming for a granularity of at least one event per day. These discrete events are interconnected through segments, which function as the structural routing elements ensuring topological and temporal continuity.

The data model's hierarchical structure is designed to be both strictly relational and highly differentiated. At the macro level, the project serves as the primary container, subdivided into specific routes. These routes may further consist of parallel subroutes or secondary routes (e.g. shore leaves) and individual segments. The terminal nodes of this hierarchy are the spatio-temporally anchored events. To account for the inherent vagueness of historical sources, the model implements mechanisms for storing alternative coordinates and place names. The representation of possibility spaces is realized through geometric constructs such as buffers (for point-based locations) and polygons (for areas and segments), classified by specific uncertainty categories.

Technically, the implementation currently relies on a relational database management system, specifically PostgreSQL/PostGIS, with the potential integration of DuckDB for future analytical requirements. A distinctive feature of this architecture is the mapping of actors (persons, vehicles, objects) within a structure characterized as a kind of “relational triple store”. Within this framework, complex relationships between groups and objects are stored with explicit spatial and temporal references, linked directly to the corresponding route segments.

In terms of future development, the model aims for “FAIR data provision” (Wilkinson et al., 2016) and integration into the “Linked Open Data (LOD)” (Wildermann, 2024) ecosystem. By transitioning the relational data base into a Knowledge Graph and enabling queries through GeoSPARQL (Car et al., 2024), a high level of interoperability will be achieved. This facilitates the semantic linking of (colonial) objects with specific shipping routes and provides the computational foundation for advanced network analyses within the context of global history.

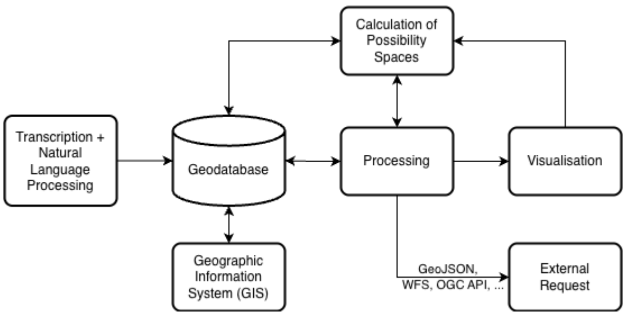


Fig. 2: Schematic workflow from the transcription of textual sources to the cartographic visualization.

5. Methodology: Path Planning

Often, travel reports do not provide sufficient information about the path chosen between two consecutive events in a way that it would allow to reconstruct its geometry. In order to obtain meaningful *possibility spaces* for these paths, it is important to first of all define the navigable space and also take into account additional factors that may influence a possible route. In this way, higher certainty can be achieved in estimating the route, thereby reducing the spatial extent of the *possibility space* to be created. In the context of historical ship routes, the most important elements are land areas or other obstacles that can be ruled out as part of a route. Additional information such as water depths, wrecks, currents, wind direction, wind speeds and known historical shipping lanes can provide further important clues about possible paths. This information can be used to define the cost for calculating possible routes in a path planning task.

5.1 Determination of underlying navigation structure

One option to determine the underlying navigation structure is to transfer the navigable space into a routing graph, e.g., using medial axis transform of the extended polygonal objects (Elias, 2007). The disadvantage is, that the medial axis might be very far from a realistic route – especially in the context of open sea navigation. Another option is to use a **grid-based approach**, where the water area is converted into a regular grid, with each cell being assigned a cost value. The route is then calculated using shortest-path methods over this grid. The result is a continuous path, with the geometric accuracy depending on the grid resolution: a finer grid provides more detailed results and a smoother route, but is more computationally intensive. A further option is to use an **irregular grid in terms of a triangulation**, with objects and obstacles represented as points connected by hard boundary edges. The additional insertion of Steiner points in the navigable area (here the water area) serves to improve the quality and to achieve a higher level of detail in the mesh. This is achieved by a conforming Delaunay triangulation, in which the triangles form a planar embedded network, where the edges can then be used as a routing graph, as shown in Figure 3.

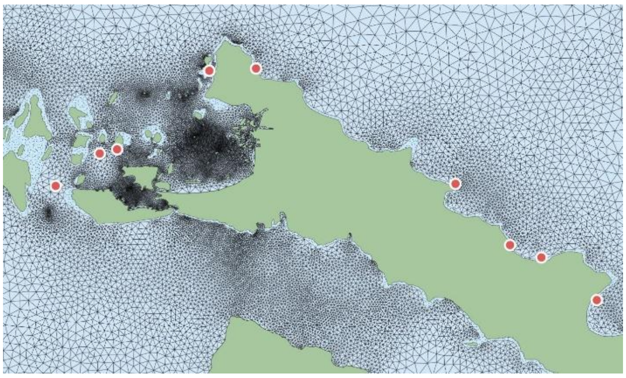


Fig. 3: Conforming Delauney triangulation applied to the water surface in the case study area. Red dots indicate locations of events.

To define the geographic extent of the navigable space, an automated workflow was established that builds a water-domain triangulation from input data: Based on a points shapefile consisting of locations of events as input, a buffered bounding box is created around the point locations. In the following, both land and shallow-water areas are removed to define a valid water area geometry. Using the Gmsh Python API, a water area geometry is constructed (including holes where needed, e.g., to represent islands), while embedding the input points as mandatory mesh vertices, and generating a conforming 2D Delaunay mesh, i.e. a mesh, which has a maximum edge length and is adapted to the given geometry in order to generate good-shaped triangles. After meshing, unique triangle edges are extracted, converted to line features, and then exported as a shapefile for further processing.

The costs for the routing calculation will be assigned using the geometric length of the edges combined with the underlying information of constraints (e.g. distance to land, water depths, currents).

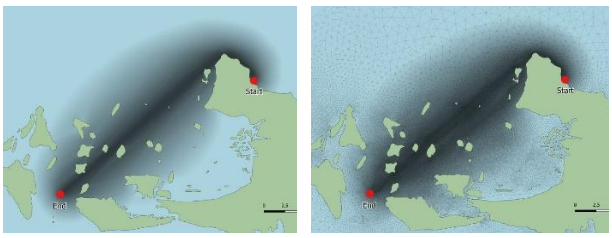
5.2 Path calculation

To determine the possible paths, for each location (pixel in grid or node in triangulation) the shortest path between start point and target through this location is calculated. This is done by summing up the distances from starting point to all points and from end point to all points using the single source-shortest-path algorithm based on Dijkstra. This results in total distances for each location between the three locations. The distribution of distances in all locations can be interpreted as possibility space of routing points: location with shorter distances have a higher possibility than those with longer distances.

These values later allow to limit the locations to those, which are reachable, e.g., in max. 120% of the shortest distance between start and end point. Another option is to use the uncertainty in travel time as a constraint: if, e.g. the shortest path was 100km, the maximum speed was 20km/h, and the travel time was 7.5h, then a deviation of 150% would be allowed.

The calculations can be done on a grid or on the triangulation. The calculation on the triangulation is much more efficient. The advantage of the grid is that it can directly be visualized, as every location has a “distance value”. On the contrary, the triangulation has these values only on the grid points. Still, it is easily possible to visualize the triangles using a mean value of the distance values of the corresponding three triangle points.

Figure 4 shows the result of an allowed deviation of 120% (calculated on a grid and on a triangulation), where darker colors indicate shorter distances and – in turn – higher possibilities of being part of a route from start to end. Both visualizations give an adequate impression of the distribution of potential routes – with the grid giving a slightly more detailed visualization.



Grid Triangulation

Fig. 4: Routes with 120% longer distance, no specific weighting scheme, calculated on a grid (left) and on a triangulation (right): darker values indicate shorter path distances.

5.3 Variation of weighting schemes

In the visualizations in Figure 4, no specific weighting (besides distances) is used, thus it prioritizes routes close to the coast and rather direct between start and endpoint.

Other weighting schemes can be designed to include additional knowledge. A straightforward function takes the distance to land masses and shallow water into account, which can be calculated by a distance transform (see Figure 5).

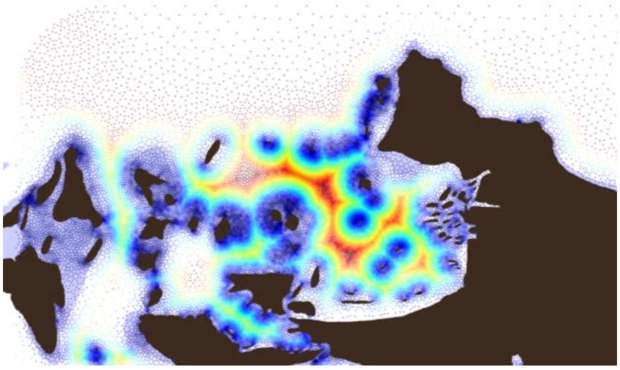


Fig. 5: Distance function: distance from land and shallow water; jet color scale: blue = small distances, red = large distances.

Based on this, different cost functions for the shortest-path-calculation can be determined: For example, to keep a certain distance to the coast and feely allow navigation in the open sea. This is achieved by applying the following function to the distance function in order to achieve a cost-function (see Figure 6). The function determines the costs (between 0 and 1) of traversing a node or edge. The values and especially the ramps of the curve determine which distances are preferrable, and how strong the decline is.

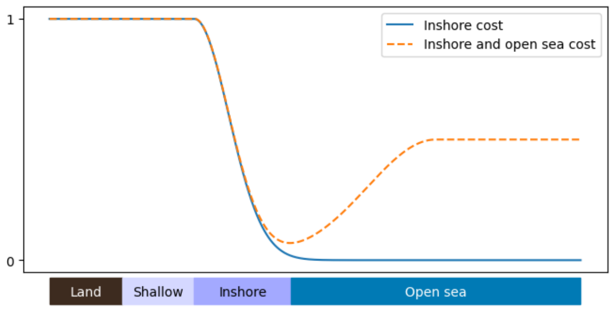


Fig. 6. Function to determine cost functions: blue: shifting routes from shore; orange: also preventing to move too far to the open sea.

When reconstructing the paths of historical ship movements, it is important to take into account the navigational practices in historical seafaring. Therefore, variants could include the effect that captains of historical sailing ships typically have avoided obstacles such as landmasses and shallow water areas, and at the same time navigated closer to the coast for a better orientation.

The effect of adapting the weighting scheme considering historical navigational practices is illustrated in Figure 7 (calculated on the triangulation). As compared to the case that prefers the shortest path, without specific weighting scheme (7A), Figure 7B uses a weighting scheme that intends to avoid obstacles (using “inshore costs” from Figure 6). It is visible that now the routes are less straight and seemingly pushed away from the land masses. Also, considerably large distances from the shortest routes are feasible – also towards the open sea.

Another interesting variant is to additionally include the effect of navigating closer to the coast for a better orientation. This can be controlled by higher costs to travel on open sea (“inshore and open sea costs”). The effect can be achieved by increasing the weight at a certain distance from land. The result is shown in in Figure 7C. It is clearly visible that the possibility space comprising all valid path options is now more narrowed down to the connection between start and end point.

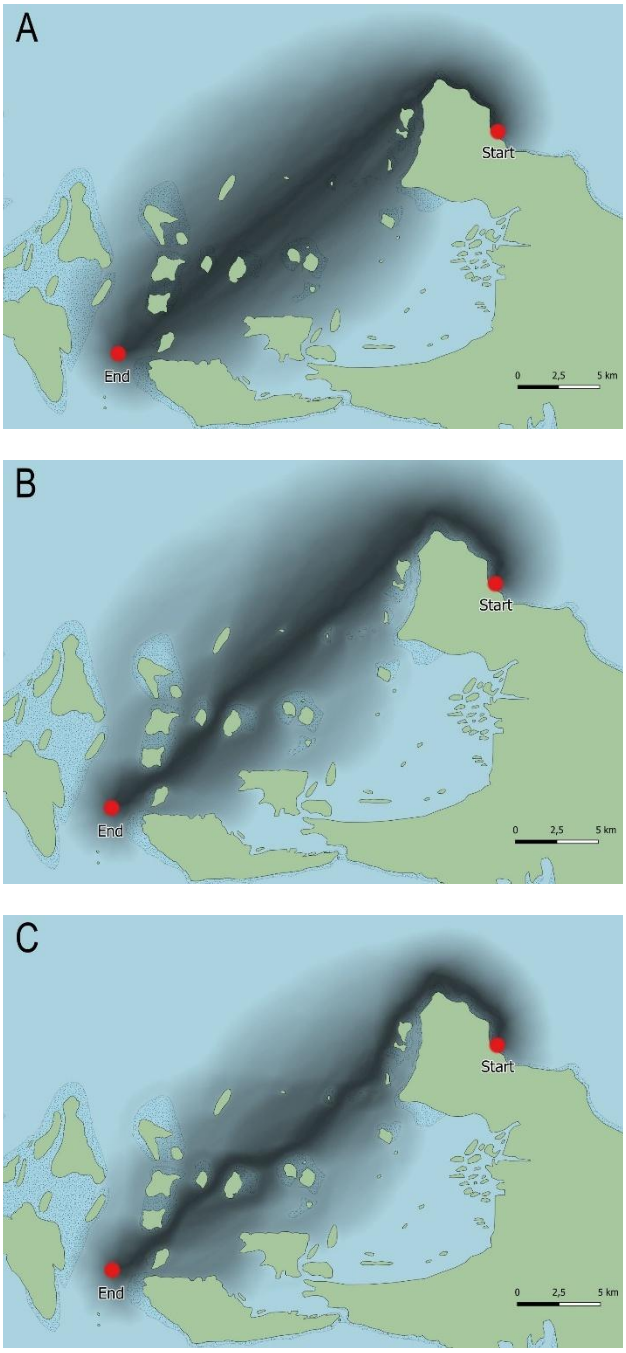


Fig. 7: Possibility space between the locations of two events: (A) no specific weighting scheme, (B) avoiding land masses, (C) avoiding land masses and open sea.

In summary, this leads to different control options, which are included via the weighting scheme, namely:

- discouraging navigation too close to the coast / too far in the open ocean
- additional “enhancers” or “inhibitors”, e.g., a heavy storm, which is to be avoided, or the presence of other ships which act either as attractor or distractor.

The latter can be achieved by adding additional “objects” into the cost function, e.g., a circular area representing a tornado, which would be assigned high weights in order to be avoided.

Besides the weighting, an overall parameter is the maximum allowed deviation from shortest route. This parameter can be set precisely, if the information is available – namely travel time and maximum speed; otherwise, it has to be estimated based on typical routes.

The results in terms of the potential routes can be stored in the data base, in terms of an alternative geometry. When the main goal is an (interactive) visualization and inspection, then they can also be only calculated on-the-fly.

The described method is applicable to any pair of input start and end point. Figure 8 shows the calculated possibility space for a near-coast route from the journey of the *Albatross*, based on a weighting that avoids land masses and open sea areas, exemplarily visualized on the historical base map (Bundesarchiv, 1889). We can see that the preferred paths run relatively close to the coast, without actually touching it, whilst areas out on the open sea tend to be avoided.

Fig. 8: Further visualization example of a possibility space for a near-coast route. The weighting scheme avoids land masses and open sea areas.

6. Visualization of Possibility Spaces

Finally, the generated geometries can be communicated visually using cartographic symbolization, thereby distinguishing different levels of uncertainty based on their geographical location within the *possibility spaces*, for example by using graduations on a grey scale (with darker shades indicating higher likelihood of being part of the route) or a color scale (Fuest et al., 2025). Besides the uncertainty region derived with the process described above, additional cartographic elements can be included in order to enhance the immediate understanding of the visualization. One option is to use symbols, for example to indicate the travel direction or to highlight different route options. In the example of Figure 9, the least cost path and two other, randomly selected, path options are exemplarily highlighted using arrows. Since the least cost path marks the most likely route to be taken within the possibility space according to the used weighting scheme, the arrow symbols are presented as visually larger than those for the alternative route options. The visual presentation of the possibility space area together with different route options is intended to enhance the impression that the calculated possibility space includes a large variety of possible paths. Furthermore, also here, the historic base map is used to place the resulting possibility space within the historical context of the case study.

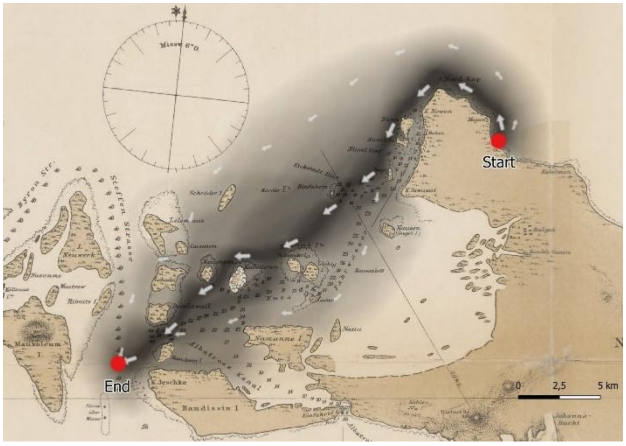


Fig. 9: Visualization proposal of the possibility space of a route between two places, including exemplary routes.

Selecting other representative rules is not trivial, as there are potentially as many routes as there are points in the underlying navigation structure. In order to automate the process of symbol placement, they could be placed on locations with the (relatively) highest values of the possibility space. Such a calculation could be directly done using a density-based approach, which has been used for the typification of building symbols in medium scale maps (Sester, 2005). An alternative is to use so-called Snakes (Klinger et al., 2011). The advantage of such a method is that it does not need an explicit determination (and selection) of a route.

7. Conclusion and outlook

In this paper, a method for generating *possibility spaces* in unstructured geographic areas is proposed, using the example of historical ship voyages.

The generation of possibility spaces is performed using two point objects as a start and end location of a route, based on a given underlying weighting scheme. This allows for a large flexibility and is not restricted to (historical) travels on sea, but can be extended to other movement situations in open spaces.

The work was primarily aiming at developing an algorithmic solution to create the possibility spaces; the next steps have to investigate its usability for historians with regard to different perspectives: on the one hand the efficiency of the graphical variables and on the other hand to use the tool for validating historical hypotheses by encoding them as additional constraints.

While the approach may give the impression that the geographic locations of events always can be determined precisely, in reality, however, these locations are often uncertain – just like the paths that connect different events. For this reason, possibility spaces must also be calculated for each event. As a result, routes have to be defined by areas rather than exact points as their starting and ending locations. In addition to spatial uncertainty, temporal uncertainty also needs to be taken into account.

From a methodological point of view, it is also interesting to investigate the number of topologically different routes, e.g. passing between islands or around them.

While the proposed method uses distance-based cost functions, the inclusion of further information from historical map sources such as water depths, known anchorages or marked preferred routes could further narrow down the extent of the possibility space. To be applicable as a generic tool for historians or museum scientists, typical values for the parameters have to be determined, e.g., appropriate functions to determine cost functions from the distance functions or intuitive tools to add other constraints such as winds or currents.

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