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AUTOMATIC PROCESSING OF RADAR IMAGES FOR ELECTRONIC RIVER CHART GENERATION IN ECDIS FORMAT

Nicolae Paraschiv , Ciprian Vlasceanu

Control Engineering and Computers Department,"Petroleum – Gas" University of
Ploiesti, Bd. Bucuresti, Nr. 39, 2000, Ploiesti, Romania,
Tel +40244173171, Fax +40244175847

Abstract: Presenting the navigation environment in electronic format – ECDIS – triggers a major change of the classic method of cartography and raises up the need to approach a way of producing the charts in vector-like format. The present paper is intended to describe a way of processing information (provided by a RADAR system and a GPS receiver), using Kalman filter algorithms and the elements form graph theory, to provide a rough form of an electronic chart. This can be completed afterwards by adding further information so that the chart can become totally compatible with ECDIS standard and can be used in automatic or aided inland navigation.

Keywords: inland navigation, electronic vector-like charts, ECDIS, RADAR, GPS precision, image processing, Kalman filter, graph based algorithm.

1. OVERVIEW OF AN INTEGRATED SYSTEM FOR INLAND NAVIGATION

The applicative research in the field of Inland Navigation has become perfectly possible and necessary at the same time due to the modern informatics systems evolution and their involvement in automatic and aided navigation. Their fundamental role is to increase the safety of river navigation, to protect the personnel involved in the navigation process and the navigational environment by greatly reducing the accident risks on the inland waterways. This is an important issue especially in the case of transportation of products with a high potential of polluting the environment, in which case no supplementary effort can be considered useless.

Along with the increasing of traffic safety on the inland waterways, the use of the automatic and aided navigation systems can offer substantial benefits for the companies involved in the river transportation. Consulting the updated electronic charts which contain the current values for the water level, the companies can obtain an optimal loading of their ships maximizing the quantity of their load and minimizing the risk of being stuck because of low water level. The electronic chart also provides the ideal path that can be followed in order to reduce the fuel consumption.

1.1. Objectives of an automatic / aided navigation system

As we mentioned, an automatic or aided inland navigation system has as its main purpose increase of traffic safety with regards to the human resources involved in the process (navigators and passengers) and the environment protection. As an automation entity, the river navigation system must be able to guide the ship automatically in regular conditions of traffic in an autonomous manner (without any use of external devices). The object of automation – the ship – offers as control variables modification of the rotational speed of its engines and the position of its

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rudder, the same means that the human navigators are using to steer the ship. The research literature (Fossen, 1998) is quite rich in mathematical models of the small ships, complicated enough to make automatic controlling of the ship quite a difficult problem. The behavior of the ship depends not only on its shape and mass but also on its load mass, the speed and type of the wind, water currents etc. The current research status in the automatic inland navigation field (Zimmermann, 1999) had reached the point where automatic control means following a path considered as an ideal navigation line only by modifying the rudder angle.

Like with any other navigation system, a priori knowledge about the environment is necessary in order to build an automatic river navigation system. Moreover, considering the international interest in standardization of river navigation environment representation (IHO S52, S57), it turns out that there's a need of establishing a procedure for building the so called Electronic Navigation Charts as a representation of the environment on electronic media. Furthermore, considering that the navigation environment is continuously modifying in many areas, there's also the need of permanently updating the charts (Gern, *et al.*, 1998). In conclusion, a proper navigation system should also offer the user means for modification of the electronically stored environment features.

Such a system that answers the above mentioned requests is installed on the "SEMNAL 1" ship, property of Low Danube River Adminitration from Galati, Romania, system which has been used by the authors for testing the algorithm presented in this paper.

1.2. Short Description of the Integrated River Navigation System

To achieve the above-mentioned autonomy of the navigation process, the system contains one or more GPS receivers (figure 1) that help determining the position and the heading of the ship (its deviation from the N-S direction) with an accuracy of 3 meters and 0.3 degrees respectively. When the electronic chart contains correct information about the environment, there can also be done a matching between the RADAR image and the electronic chart in order to increase the position accuracy (Gilles, 1991).

Principally the GPS system contains a four GPS antennas frame that receive the satellite signals. The receiver is able to provide information not only about the current position of the ship but also about its speed and attitude (heading, pitch and roll).

The RADAR system is part of the standard configuration of the inland ships and it offers information about the current profile of the surrounding environment in form of "free" and "occupied" zones on a circled area of approximately 6 Km diameter. The RADAR signal is hardware processed by a dedicated ISA interface to allow its acquisition by a control equipment – PC in standard configuration.

The most important component of the river navigation system (aided or automatic) is the electronic chart that stores the "stage" on which the ship "acts" (Gern, *et al.*, 1998). The international concerns in unifying the representation of the inland navigation ways and channels with the purpose of increasing the portability of the electronic maps lead to an extension of the ECDIS standard (Electronic Chart Display and Information System) named Inland ECDIS (IHO S52, S57). The standard describes the issues that a navigation system must conform in order to be a real help for the navigators and supply substantial improvements of the traffic safety. We will discuss more about the ECDIS standard in the next chapter.

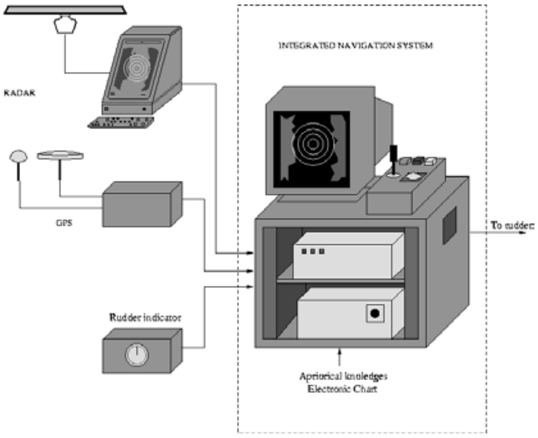

Fig. 1. An Integrated Inland Navigation System

1.3. Data recording of the sensors information for electronic charts production.

A navigation system must be able to reproduce its activity during a certain period of time. This feature is extremely important in the case of river navigation systems especially when accidents take place and it is necessary to determine the exact conditions of the traffic and the behavior of the ship during the accident. Regarding the present topic, storage of data provided by sensors (GPS and RADAR) leads to gathering information about the environmental navigation configuration, an offline processing of the data being possible in order to extract the necessary information.

The system described above allows data storage for activity replaying and it also offers the possibility of storing RADAR images along with the position and heading in text files in RSF format (Radar Sequence Format). Each of the RADAR image is assigned the position and heading of the ship provided by the GPS receiver so the image can be referenced in the global positioning system WGS84 (World Geodetic System 1984).

A RADAR image consists of more RADAR "rays" (1024 in our case) that have their origin in the center of the image and cover a 3 Km distance. Each ray contains the environment reflection of the signal emitted by the RADAR antenna. The reflections are represented by "obstacles" that appear in the way of RADAR waves, in the direction of each ray (figure 2). The waves are emitted and received for each ray while the RADAR antenna rotates around a fixed location (the center of the RADAR image) and after a full 360 degrees rotation it results an environmental representation in the form of obstacles and free zones. For our topic it is important to mention that the riverbanks are viewed as obstacles whose contours will be extracted for building electronic river charts. This is a major speedup of the process for determining the riverbank profile comparing with the other usual methods.

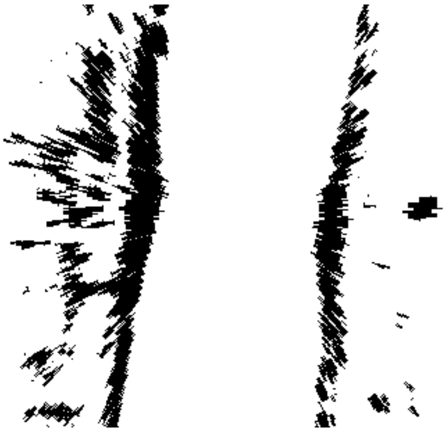

Fig. 2. A RADAR Image

2. ELECTRONIC CHARTS FOR INLAND NAVIGATION. ECDIS STANDARD

Electronic chart means that the information contained in a paper chart is now stored on an electronic media and this usually require the use of a computer or any other console based displaying device. The simplest way of transferring the information from paper charts into electronic format is by scanning them, the result being a raster based representation of the environment. But this method does not bring any improvement to the mariner's work, since the mechanism of getting the necessary information is exactly the same as in the case of paper nautical charts: the user has to interpret the pixels in order to recognize them as belonging to an object. Another drawback is that the information is displayed all at a time (or in few levels of detailing, but still in a pixel based structure) and it cannot be filtered in accordance with the navigator's needs.

A proper alternative is the vector-based representation that in this case means that the electronic chart is composed by well-defined objects with their geometry being described by polygons in a coordinate system. With this kind of information storage new features can be added to a navigation system, not only in matters of displaying – building different detailing levels and choosing what should or should not be displayed being straightforward tasks now – but also regarding the mechanisms for providing information (Gern, *et al.*, 1999). For example the objects included in the chart may contain additional information which can be displayed only on the user's request, or – with a right chart update mechanism – the mariner is able to early inform himself about the current environment's situation in certain difficult areas (like high dynamics in water level changing), facilitating in this way the route planning procedure. Of course we should also mention that an object-based representation of the environment with a right mechanism of acquiring information about the status of the environment is also a good basis for automatic river navigation research. All these, and much more are fulfilled by ECDIS.

ECDIS means Electronic Chart Display and Information System – a standard that was originally meant for marine navigation and than extended to inland navigation. As the name says, ECDIS is a system that provides ways not only for displaying but also for information, e new feature that is greatly appreciated by the navigators, especially when it comes to navigation efficiency and safety.

The specifications that make an electronic chart displaying system to be an ECDIS have been formulated by the International Maritime Organization (IMO) within a performance standard. Basically, the standard describes the right functionality of an ECDIS so that it constitutes a proper replacement for the paper nautical charts and the National Maritime Administrations have agreed to consider ECDIS as an adequate equivalent to the charts required by Regulation V, Chapter 20 of the 1974 SOLAS Convention. Along with the performance standard, IMO also specifies technical standards developed by the International Hydrographic Organization (IHO) related to the physical data format (IHO Special Publication 57 which refers to data format, production of electronic navigational chart data and an updating profile) and the content and display of an ECDIS (IHO Special Publication 52 – describes the means for color, symbol displaying and chart updating). In association with all these, the International Electrotechnical Commission (IEC) has established performance tests and checks which assure that a system is an IMO – compliant ECDIS one (IEC Publication 61174).

As an example we will emphasize some of the features of an ECDIS for a portion of the Danube River in the figure 3.

The upper side of the picture in figure 3 represents an overall view of the area in which one can observe the kilometer marks, the traffic signs and some city areas along the riverbanks. On lower side there is a zoom of the dotted area in which, besides the already mentioned elements one can see new elements like the hectometer marks or the waterway axis. Also with an interactive method, the user can obtain additional information about a certain area. In our example a pick report from the position indicated with an arrow shows that the object is a shoreline construction, it is radar conspicuous or that it is partly submerged when the water level exceeds a certain limit.

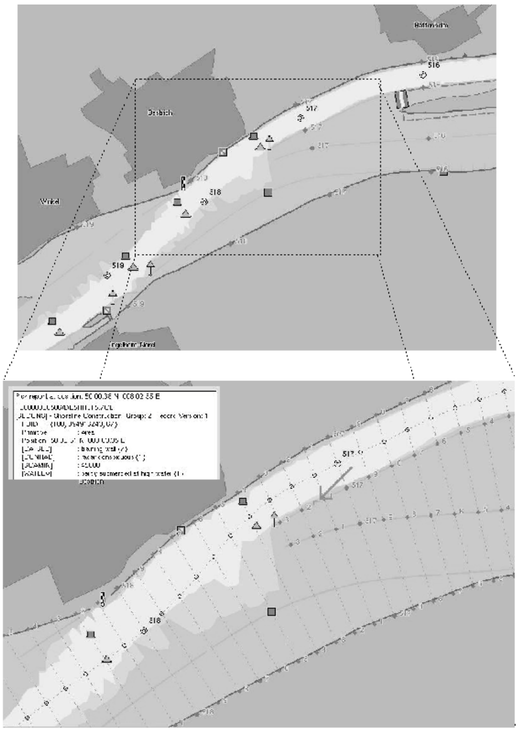

Fig. 3. ECDIS Features

Besides operating with S57 complying data and presentation of objects and their characteristics according to presentation library S52, there are a lot of other functions that en ECDIS must offer, like antigrounding function, warning of obstructions to shipping, display updating and various types of chart operation like entering fixed position, sounding or measuring of distances, etc.

In conclusion, an ECDIS is not only an adequate replacement for the paper nautical chart but also a system that provides information about the compound objects, information which can be called up any time, without any delay, in comparison with the old manual procedures for searching the data in catalogues or any other special publications.

But in order to have an ECDIS, first one must gather together all the information regarding the navigational environment. There are different methods in doing so, one of them being RADAR image processing which we will describe further in this paper. For rivers who still have their natural banks such a solution is extremely useful for continuous correction of the charts, as it can also be a base method for constructing ECDIS charts from the scratch.

3. RADAR IMAGE PROCESSING

In order to obtain an environmental representation in the form of an electronic chart in vector-like format we will use the information contained by the RSF files mentioned in paragraph 1.3. We will present in this third part a procedure for processing of RADAR images using elements from graph theory

3.1. Object Identification From RADAR Images

As we mentioned a RADAR image is presented as rays that contain the obstacles meet by the RADAR wave on each of the 1024 directions in a full rotation of the antenna. The received RADAR wave is digitized by the RADAR–PC interface with a frequency of approximately 500 kHz which results in a spatial digitization of the environment's configuration with a 3 meters step. In the RSF file, for an angle α from the origin of RADAR image, a ray contains the number of the start and end quantum of each obstacle meet by the RADAR wave in one direction, which represents the position of the real obstacle with an accuracy of 3 meters.

The first step of the algorithm described by this paper is the identification of objects in a single RADAR image. The identification is made by comparing the successive rays from the image(Blackman, 1986). If an obstacle from the ray k+1 is overlapped with an obstacle in the ray k then the two obstacles belong to the same object. If two or more obstacles from the ray k are overlapped with a single obstacle from the ray k+1, then the objects assigned with the obstacles from the ray k will be joined in a single object. Finally the last and the first rays are compared (the two rays being also one near each other) and the objects whose obstacles are overlapped are also joined. In the end we obtain a set of RADAR objects described by start and end quantum of the obstacles meet by the RADAR waves in the direction of each ray.

After an analysis of the contours of the objects obtained, the need for a "microsmoothing" procedure raised up. The procedure is shown in the figure 4 and one can notice that the successive ray's length are compared and truncated or extended in order to smooth the objects' contour: The distance between the dotted lines corresponds to the ray quantisation step – approximately 3 meters.

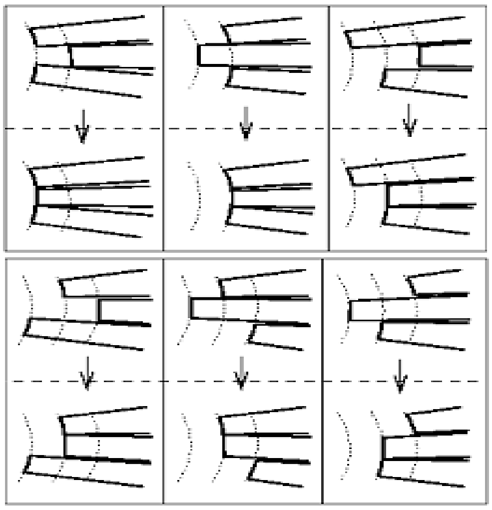

Fig. 4. Microsmoothing of RADAR Image

Any possible extensions of the object's areas are totally legitimate considering the distribution of probabilities of existence of an obstacle within a ray, whowen in figure 5.

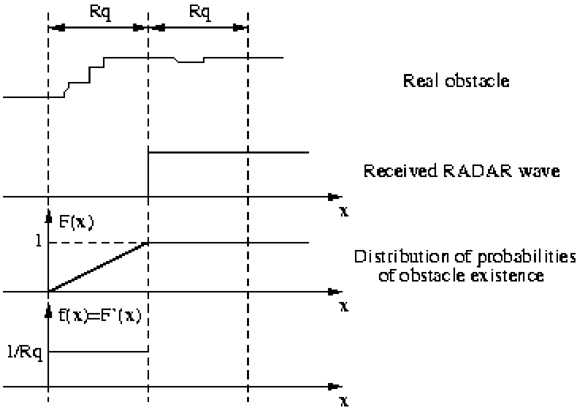

Fig. 5. The probability distribution F of the existence of an obstacle given by a start quantum, and its density f.

Also at this stage we use a filtering procedure of the RADAR image as a whole, by eliminating the objects with an area smaller than a certain limit. As each obstacle in a ray is expressed by the index of the start and end quantum, the area A of an object is computed with the formula:

$$A = \sum_{i=1}^{NO} \frac{\beta \cdot Rq}{2} (C_e^2 - C_s^2)$$

where:

- NO means the number of the obstacles contained by the object;
- β is the angle covered by a ray, in radians;
- Rq – the ray quantization step, in meters;
- C_e, C_s – the index of the end and start quantum respectively;

Choosing the minimum value of the remained object's areas depends on the configuration of navigation environment, especially of the shape of riverbanks on which this paper issues upon. As for the electronic chart production in ECDIS format for the Romanian part of the Danube we established that a limit of 6 to 10 square meters keep a high accuracy in determination of riverbank profiles which usually are represented by objects with an area bigger than 100 square meters.

3.2. Graph Based Representation of the Navigation Environment

This section presents a method for approximation of the contours using nonoriented graphs (Gern, 2000). The procedure contains one stage of initialization of the graph and than a cyclic updating of it until the end of the information stream processed.

Front Contours Approximation

This algorithm intends to approximate the profiles of the riverbanks in the form of an electronic chart in vector-like format. In order to do this we will use the objects previously identified to extract only the so called "front contours" (figure 6). These are the part of the object's contours that are situated facing the center of the image[1].

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[1] We can obviously assume that the records have been made while the ship was navigating, so the contours facing the center of the RADAR images represent the riverbank profiles with a high probability.

Fig. 6. Front Contours Approximation

To be more specific, the indexes of the start quantum for each obstacle will form the front contours for each RADAR object. If an object contains "holes" (which means that more obstacles from the same ray are contained in one object) only the first quantum of the first obstacle will be considered as being part of the front contour.

At this step it is also used the information that GPS provided during the recording step by referencing the set of front contours in the WGS84 coordinate system, using the following approximation formulas:

$$Lat = L + \frac{d \cdot \cos(\alpha + \varphi)}{R},$$

$$Lon = l + \frac{d \cdot \sin(\alpha + \varphi)}{R};$$

where

- Lat and Lon are the latitude and the longitude of the contour point;
- L and l are the latitude and the longitude of the center of the RADAR image, given by GPS receiver;
- d is the distance from the center of the image to the node;
- α is the angle between the first ray and the ray containing the point from the front contour;
- φ is the ship's deviating angle from the S-N direction.

Each one of the front contours obtained so far will be approximated with vectors with a smaller number of vertexes to minimize the number of significant points in a front contour. The algorithm for approximation of the contours is described further on (figure 7).

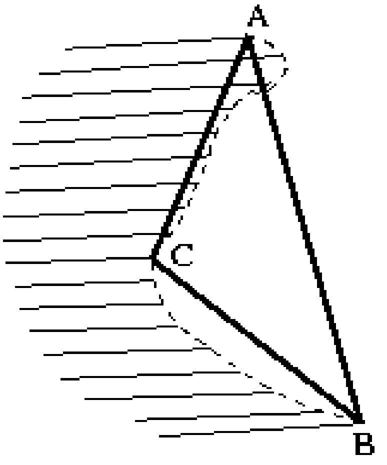

Fig. 7. RADAR contour approximation

1. start with a rough approximation by a single line AB;
2. choose from the contour, the furthermost point from the line AB, let it be C;
3. if the distance from C to line AB is within a certain limit, the current approximation of this portion of the contour is considered satisfactory;
4. otherwise the algorithm starts from step 2 for contours AC and CB.

Finally one obtains an approximation of the front contours in the form of a set of vectors that contains global coordinate pairs.

Current Graph Initialization

The initial graph that will be used forward in the algorithm is build using the set of front contours approximation obtained by processing the first RADAR image. This set of contours is transformed into a nonoriented graph in which every node gets assigned a Kalman filter that estimates the current position of the node (Gelb, 1979).

Considering the probability for the obstacle existence (figure 5) we can see that the error covariance $E[X^2]$ for the position of the obstacle (measured from the center of the RADAR image) is:

$$\left|E[X^2]\right| = \left|\int_{-\infty}^{\infty} x^2 f(x)dx\right| = \frac{Rq^2}{3}.$$

Given a RADAR heading ψ for the node (the angle between the first ray's direction and the direction of this node's ray), the error covariance matrix of the node's position expressed in latitude and longitude (we consider the transformation from RADAR coordinates into geodetic coordinates to be the current measurement of the node's position) is given by:

$$(1)\ M = \begin{pmatrix} Rq^2\cos^2\varphi & Rq^2\sin\varphi\cos\varphi \\ Rq^2\sin\varphi\cos\varphi & Rq^2\sin^2\varphi \end{pmatrix}$$

Naturally, for further computations M is transformed in radians in the WGS84 coordinate system.

The initial error covariance matrix E of the state estimation equals the error covariance matrix of the measurements, and the initial Kalman gain matrix is:

$$(2)\ K = E \cdot (E + M)^{-1} = \frac{1}{2} \cdot I_{2\times 2},$$

The first state estimated by the Kalman filter will be the first measurement obtained by transforming the RADAR coordinates into geodetic coordinates.

Updating of the current graph

The updating of the current graph is made after each approximation of the current RADAR image with a set of front contours expressed as vectors of coordinate pairs. We will further describe the algorithm for current graph updating with a new set of vectors considered as new measurements:

1. Let P_V be a point from the set of vectors. We search in the entire current graph for the closest node to our point, let it be P_G. If the distance between P_V and P_G is smaller than a certain limit, than the graph's node will be updated with the new measurement P_V. That is, the measurement's error covariance matrix will be computed with the equation 3.1, transformed in radians and than the Kalman gain matrix computed with the equation 3.2. The updating of the current position of the node from the current graph is given by:

$$\begin{pmatrix} Lat \\ Lon \end{pmatrix} = \begin{pmatrix} Lat \\ Lon \end{pmatrix} + K \cdot \left(\begin{pmatrix} MLat \\ MLon \end{pmatrix} - \begin{pmatrix} Lat \\ Lon \end{pmatrix} \right),$$

where MLat and MLon are the coordinates of P_V.
The updated error covariance is given by:

$$E = (I - K) \cdot E$$

If P_G if far from P_V then:

- search for the closest graph link and if the distance from P_V to the link is smaller than a certain limit, P_V is inserted between the link's end nodes. The new node will copy its Kalman filter characteristics from the neighbor node with the most updates;
- otherwise P_V becomes a new node into the current graph and its Kalman filter will be initialized as in paragraph 3.2.2;

2. Let P_V be the next point in the set of measurements (the set of approximated front contours). We firstly test the distance from the line between this and the previous P_V point and the nodes of the current graph[2]. If there is any close node, then it will be updated as we've seen in the previous step. The algorithm is then repeated from the step 1 with the current P_V point.

For a better understanding, figure 8 illustrates a small example

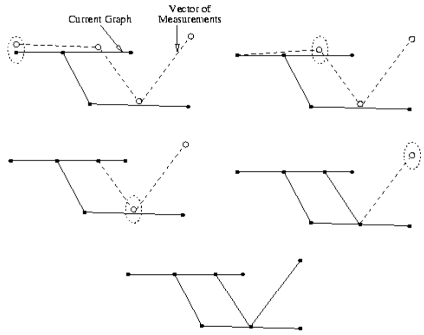

Fig. 8. Current graph updating

3.3. Final Graph Processing

After processing of a series of more consecutive RADAR images a nonoriented graph results which contains nodes and links that represents the navigation environment configuration. Before extracting the nodes with the smallest error covariance estimation matrix, we apply a last filtering procedure by joining the nodes that are closer than a certain limit. The position of the resulting nodes will be established by the number of updates of each initial node. For two nodes with coordinates (Lat_1, Lon_1) and (Lat_2, Lon_2) and n_1 and n_2 number of updates, the coordinates for the joining node will be approximated with:

$$Lat = Lat_1 + \frac{n_1}{n_1 + n_2} \cdot (Lat_2 - Lat_1),$$

$$Lon = Lon_1 + \frac{n_1}{n_1 + n_2} \cdot (Lon_2 - Lon_1)$$

The joining node will copy its Kalman filter from the node with the smallest norm in error covariance estimation matrix.

We finally obtain a graph from which we can now extract the nodes that represents the riverbanks contour with the highest probability. In order to do so, we use the Dijkstra algorithm for choosing the path between two nodes of the graph with the lower cost, where the cost function between two adjacent nodes v1 and v2 will be computed with:

$$g(v1, v2) = \frac{\tau(v2)}{|v1 - v2|},$$

where

- $\tau(v2)$ is the norm of the error covariance estimation matrix;
- $|v1-v2|$ is the distance between the two nodes, expressed in meters (Gern, 2000);

One finally obtains a set of coordinates and links between them that can easily be used in producing a simple chart that contains only the riverbanks.

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[2] Of course, only if the previous P_V point was not the last in a front contour.

Adding more information to the chart using other sources one can obtain a fully ECDIS compatible chart (Andrei, 2000). Figure 9 shows a result for a portion of the Danube River.

4. CONCLUSIONS AND FURTHER RESEARCH

The main purpose of this paper was to introduce an algorithm that can be used as a base for ECDIS chart production, known the fact that representing in such a chart (or any other type) the riverbanks contour is the activity that requires the most amount of work. The authors tested this algorithm using some records made on the Danube river and obtained along with promising results also new research directions. The main difficulty in using the algorithm is the tuning of its parameters, like limits for eliminating small RADAR objects, limits for distance between new measurements and the graph nodes, etc. It seems that the choices are greatly influenced by the configuration of the navigation environment.

Fig. 9. Adding information to complete the ECDIS chart

For example, when navigating between well defined riverbanks it is a good thing to eliminate the objects with areas bigger than 10 square meters (we obtained very good results eliminating objects smaller than 50 square meters). On the other hand, when the riverbanks are partially submerged, sometimes the small water waves cover some parts of the banks so the contours will appear truncated. In this case, eliminating big area objects will result in loss of useful information.

Environment configuration dependent is also the choice of the distance limit used in deciding if a point from a RADAR image is considered a new node in the graph or it updates an already existing one. If we choose this limit too small (in order to increase the accuracy of our algorithm) we may end up with a lot of points that represent the riverbank contour with the same probability, which makes it hard to choose between them. On the other hand, increasing this limit will result in obtaining fewer nodes with high probability of contour representation. This is an advantage only on straight parts of navigation channels, on the irregular channels the nodes will be badly placed.

But still, even with the drawbacks mentioned above the algorithm can and will be used in producing the electronic charts for the Romanian part of the Danube.

As further research we consider the possibility of recording the data provided by echo sounders which can be used along with the rest of information to build the navigation way's depth profile as well, another important feature of the electronic charts that require an important amount of human and material resources.

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