Article

MAP PROJECTIONS FOR ELECTRONIC NAVIGATION AND OTHER MARINE GIS APPLICATIONS

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Abstract

The results of a research on the identification of suitable map projections for Electronic Chart Display and Information System (ECDIS) are presented. Eighteen map projections have been selected and evaluated according to criteria based on the calculation and analysis of distortion as well as on specific requirements for marine navigation. Six map projections are proposed for use in Electronic Navigation (e-Nav) systems together with specific selection rules based on the location and the extent of the area displayed on the screen. Additional map projections for potential use in other marine GIS applications are also identified and proposed.

Résumé

Les résultats d'une recherche sur l'identification de projections cartographiques adaptées au système de visualisation de cartes électroniques et d'information (ECDIS) sont présentés dans cet article. Dix-huit projections cartographiques ont été sélectionnées et évaluées selon des critères établis à partir de calculs et d'analyses de distorsion ainsi que des demandes spécifiques à la navigation maritime. Six projections cartographiques destinées à être utilisées dans le cadre de systèmes de navigation électronique (e-Nav) sont proposées en même temps que des règles de sélection spécifiques établies selon le lieu et l'étendue de la zone affichée à l'écran. Des projections cartographiques supplémentaires destinées à être éventuellement utilisées dans d'autres applications SIG maritimes sont également identifiées et proposées.

Resumen

Se presentan los resultados de una investigación sobre la identificación de proyecciones de mapas adecuadas para el Sistema de Información y Visualización de las Cartas Electrónicas (SIVCE). Se han seleccionado dieciocho proyecciones de mapas, que se han evaluado según los criterios basados en el cálculo y el análisis de distorsión, así como en los requisitos específicos para la navegación marina. Se proponen seis proyecciones de mapas, para su uso en los sistemas de Navegación Electrónica (e-Nav), junto con unas reglas de selección específicas basadas en la localización y en la extensión de la zona visualizada en pantalla. Se han identificado y propuesto también proyecciones de mapas adicionales para su uso potencial en otras aplicaciones del SIG marino.

1. Introduction.

This article presents the results of research on the feasibility of acquiring improved visual perception in ECDIS through the proper choice of map projections. Section 2 of the paper presents a brief overview on the status and the trends in the employment of map projections in marine Electronic Navigation (e-Nav). Section 3 presents the criteria and methodology used in the conducted study for the selection and evaluation of map projections. Section 4 presents the results of the selection and preliminary evalua-tion of an initial set of map projections for potential use in ECDIS and in other e-Nav applications. Eighteen map projections are initially selected and evaluated. As a result thirteen map projections are proposed for further analytical evaluation. Section 5 presents the results of the calculation and analysis of the distribution of distortion of the thirteen map projections selected in section 4. As a result nine map projections with reduced visual distortion over extended geographical areas are proposed for further evaluation. Section 6 presents the results of the final stage of evaluation of the nine map projections selected in the section 5 according to specific requirements and criteria for marine navigation. As a result six of the evaluated nine map projections are proposed for use in e-Nav systems (ECDIS and ECS). Section 7 presents consolidated rules for the choice of map projections for improved visual perception in e-Nav and other applications. Section 8 presents a brief overview of the results and proposals.

2. Trends in the use of map projections in marine navigation

2.1. Map projections in Traditional Navigation

In traditional marine navigation the employment of map projections is practically restricted to the "Mercator" and the "Gnomonic" projection. The Mercator projection depicts directions correctly, rhumblines (loxodromes) as straight lines and meridians and parallels as orthogonal straight lines. These properties have been exploited for the development of simple graphical solutions for the fundamental navigational problems, such as that of "Rhumbline Sailing" (Loxodromic Navigation) on the mercator chart. The Gnomonic projection depicts great circles (shortest navigational paths) as straight lines. This property is used in conjunction to the properties of the mercator projection in simple graphical solutions of "Great Circle Sailing' (orthodrome).

2.2. Map projections in Electronic Navigation

The official adoption of ECDIS for marine navigation in the mid 90s marked a revolutionary milestone in the evolution of marine Electronic Navigation (e-Nav) methods (IMO 1996). Despite the significant developments in many technical, operational and scientific aspects of ECDIS and Electronic Navigational Charts (ENCs) [IHO 2010], it is surprising that the international standards on ECDIS and on ENCs do not provide for specific requirements or recommendations on the employment of map projections. The lack of standardization on the use of map projections does not cause any real problem, since in ECDIS the solution of navigational problems and the measurements of distances and directions on the electronic chart can be conducted analytically on the surface of the reference ellipsoid without any graphical work on the nautical chart, as it is done in traditional navigation. Therefore, in electronic navigation the use of the mercator and the gnomonic projections is not indispensable and consequently it is possible to identify alternative map projections providing better visualization (Pallikaris and Tsoulos 2010).

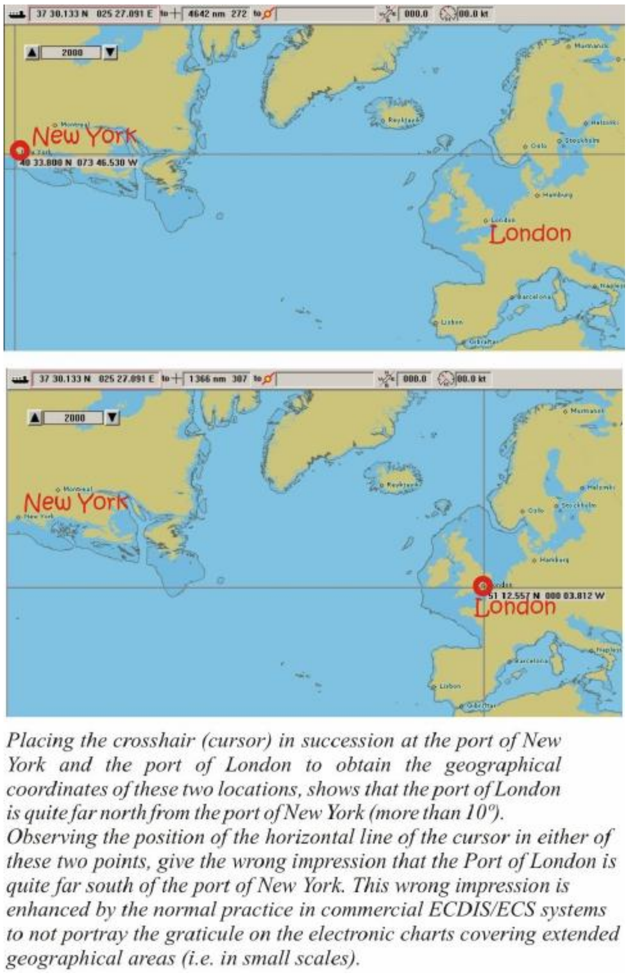


Figure 1. *Poor visual perception in Electronic Chart Display and Information System due to the automatic selection of map projections*

The possibility to adopt alternative map projections has been utilized from the evolution of the first commercial ECDIS systems in the 90's and is continuing up to nowadays. In the span of the seventeen years from the 1st edition of the IMO performance standards for ECDIS (IMO 1996) and despite the fact that these standards as well as the revised ones (IMO 2006) do not provide for specific requirements or recommendations on the use of map projections, many commercial ECDIS products have employed map projections, other than the mercator and gnomonic.

Most of the early ECDIS and ECS systems in the 90's used one map projection only "the plate carré". Subsequent systems (mainly in the period 2000 – 2005) provided the opportunity to manually select the desired projection between a limited number of cylindrical and azimuthal map projections such as: plate carré, mercator, gnomonic, orthographic, stereographic. In some new systems the selection of the proper projection is conducted automatically between only two map projections: the mercator and the azimuthal stereographic. Nevertheless the automatic selection of map projections in these systems may in some cases cause poor visual perception and misinterpretations, as those shown in figure 1.

Some ECDIS systems employ map projections that cannot depict polar areas. This deficiency can be overcome by the selection of a suitable map projection for very high latitudes (the Arctic).

3. Criteria and methodology for the selection of map projections in the conducted study

3.1. Generic criteria and methodology for the selection of map projections

In conventional cartography the selection of the proper map projection is accomplished according to various criteria that can be classified into the following three categories:

- Quantitative criteria for the assessment of the linear, angular and area distortions. These distortions can be initially evaluated through distortion ellipses and analyzed by the calculation of distortion and the plotting of relevant distortion isolines. Other specialized quantitative criteria and tools can be also used, such as: the Airy least square criterion and its variations and the Chebychev theorem and its variation (Bugayevskiy and Snyder 1995, Maling 1973, Snyder 1984) etc.

- Qualitative criteria such as perception of the shape of the earth, representation of the pole as a point or a line, shape of parallels and meridians, continuity, symmetry, eumormism [1], etc. (Bugayevskiy and Snyder 1995, Pearson 1990, Delmelle 2001).

- Combined quantitative and qualitative criteria.
  Quantitative criteria have been extensively used in conventional cartography for the minimazation and optimization of distortion to values that provide optimum results for cartometry (direct measurement of distances, angles and areas on the map or chart). Depending on the requirements of the application, the use of the proper quantitative criteria lead to the identification of existing map projections, or to the development of new map projections, with the desired characteristics such as "conformality", "equivalency", or "equidistance". Conformality is the property of map projections to depict directions correctly (projections with zero angle distortion). Equivalency is the property of map projections to depict areas correctly (projections with zero area distortion). Equidistance is the property of map projections to depict distances correctly (projections with zero linear distortion). "Conformality" and "Equivalency" are two essential but mutually inconsistent properties. There is no projection that is both conformal and equivalent. There is no real equidistant map projection preserving distances in all directions. Equidistance is possible only in certain directions, normally along the meridian(s) or parallel(s). A lot of quantitative criteria have been developed for the evaluation of conformality, equivalency and equidistance. Grafarend and Krumm (2006) present more than twenty such criteria.

In traditional cartography, qualitative criteria are mainly used for the selection of map projections for world maps and atlases in order to provide better representation of the reality, or in order to retain some special properties, such as: orthogonality of graticule lines, graticule equidistance, the manner of representing the poles (as points or as lines), the relative length of the equator, central meridian and poles (if the poles are represented as lines); visual perception of the projection in terms of how spherical it appears etc. (Bugayevskiy and Snyder 1995 p 235-237).

In GIS applications the selection of map projections has the advantage that there are not strict requirements for conformality, equivalency or equidistance, as in many applications of traditional cartography where the map or chart is used for direct measurements of angles, distances, or areas. In GIS applications these measurements can be conducted through direct access to and processing of the geospatial database of the system and not necessarily by graphical measurements on the map. It is therefore possible to select map projections in a more flexible way seeking best visualization results. Nevertheless, it appears that in GIS environments including ECDIS map projections are often used without rigorous selection criteria, and not as a result of relevant research for each application. (Pallikaris 2010, IHO/AHC 2011).

1 *The name eumorphism connotes approximate true shapes of continents (Delmelle 2001). Although it is possible to obtain true shapes at a local scale through conformal projections, it is impossible to obtain true shape representation of landmasses in world maps.*

The quantitative criteria of analytical cartography, depending on the requirements of a particular application, provide solutions for conformality, equivalency, or equidistance along a particular direction. The qualitative criteria provide best solutions for other desired properties such as the shape of orthodromes (Great Circles-GCs) and loxodromes (Rhumb lines RLs) on the projection.

The criteria used in the conducted research for the restriction of visual distortion to no noticeable limits over extended geographical and the fulfilement of other specific requirements for marine navigation are a combination of quantitative and qualitative criteria.

3.2. Basic principles for the selection of map projections in ECDIS and other e-Nav systems

In the conducted research the determination of specific selection criteria of map projections for e-Nav applications has been based on the following principles and requirements:

i. In ECDIS it is not imperative to use specific map projections for direct measurements of distances, directions and areas on the displayed chart or map.

ii. The set of map projections that will be finally proposed should not consist of a big number of map projections (less than 10) in order to avoid complicated and impractical selection/implementation rules.

iii. Due to the dynamic feature of e-Nav applications the employed map projections must have direct and inverse map transformation formulas allowing the convenient dynamic parameterization of the map projection.

iv. In ECDIS, map projections can be dynamically parameterized and calculated so that the central point or central line of the projection coincides or approximates the center of the area displayed on the screen in order to control the amount and the distribution of angular and area distortion to limits ensuring that no noticeable visual deformation is generated (§ 3.3.a).

v. The shape of Great Circles (GCs) and Rhumb Lines (RLs) should depict their basic true characteristics on the spherical/ ellipsoidal surface of the earth (§3.3.b).

vi. The shape and pattern of the meridians and parallels should facilitate the importance for marine navigation "visual perception of the relative geographical location between any two points" (§ 3.3.c).

The conducted study focused on small scale applications, corresponding to "display ranges" larger than 200 nm [2], which for a typical 21 inch ECDIS screen corresponds to natural scales smaller than 1:2.350.00. For medium and large scales, according to numerical tests and evaluations conducted by Pallikaris (2010), Pearson (1992) and Maling (1973), different map projections provide practically the same visual results on the screen.

3.3. Specific criteria and parameters for the selection and evaluation of map projections in ECDIS

The selection and evaluation of map projections for e-Nav systems (ECDIS, ECS) has been conducted in accordance to the criteria of Table 1.

a. Criteria for the control of angle distortion and area distortion within limits ensuring minimum visual distortion

In the conducted study the calculation and the analysis of angle distortion and area distortion aimed at the control of visual distortion to non noticeable limits over extended geographical regions. Visual distortion depends on area and angle distortion. The tolerances for not noticeable visual distortion depend on the experience and the visual ability of the user. Average values are listed in Table 2.

Table 1. *Basic criteria for the selection of map projections in ECDIS*

1. Criteria for the control of angle distortion and area distortion within limits ensuring that the overall visual distortion is minimum.
2. Criteria and parameters for the assessment of the shape of Great Circles (GCs) and Rhumb Lines (RLs)
3. Criteria for the desired shape and pattern of the graticule lines (meridians and parallels).

Table 2. *Distortion values for reduced visual deformation [Bugayevskiy and Snyder 1995, Pallikaris 2010]*

kind of distortion	no visual distortion is noted	some visual distortion may be noted	some visual distortion is noted
Area Distortion	up to ±(6-8)%	between ±(8 -10)%	between ±(10-12)%
Angle Distortion	up to 6º-8º	between 8º-10º	between 10º -12º

For the restriction of visual distortion over extended geographic areas, the tolerances of angle and area distortion have been initially set to 8° for angle distortion and 12% for area distortion. These tolerances have been intentionally set stricter for angle distortion than those for area distortion, since for marine navigation it is reasonable that conformality takes precedence over equivalency.

[2] *According to the IHO standardization (IHO 2006) the scale of an electronic chart can be described by "natural scale" given as a ratio (e.g. 1:100,000) like in traditional paper charts, or by "display range" given in nautical miles like in radar (e.g. 3, 6, 12 or 24 nm). The display range (e.g. 6 nm) corresponds to the distance from the centre of the chart to the top and bottom edge of the screen.*

b. The criteria of the shape of Great Circles (GCs) and Rhumb Lines (RLs)

For better portrayal of the reality in e-Nav systems the lines showing Orthodromes (Great Circles - GCs) have to be shorter than corresponding Loxodromes (Rhumb Lines - RLs). In addition GCs should preferably bend towards the equator and RLs towards the poles, as on the surface of the spherical or ellipsoidal earth.

In the conducted study the assessment of the proper shape of Orthodromes (GCs) and Loxodromes (RLs) has been based primarily on the calculation of the loxodromicity factor ξ_L and the orthodromicity factor ξ_O (Fig.2), given by [1] and [2] (§ 6).

$$\xi_L = \left|\frac{h_\lambda}{L}\right| \qquad [1]$$

$$\xi_O = \left|\frac{h_o}{L}\right| \qquad [2]$$

Where:

- L is the length of the straight line segment connecting the points of departure and destination on the projection.
- h_O and h_L are the maximum distances of the GC or the RL from the straight line segment connecting the points of departure and destination on the projection.

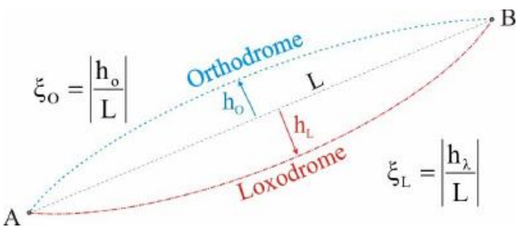


***Figure 2.** Loxodromicity and Orthodromicity factors*

c. The criterion of the shape and pattern of meridians and parallels

In e-Nav systems it is very useful to portray meridians and parallels as straight lines, intersected orthogonally.

This property offers direct perception of the relative geographic location of any points appearing in the electronic chart.

Direct perception of the relative geographic location of any points is the ability to conclude for any point appearing on the screen if this point is located "to the north or to the south", and "to the east or to the west" of any other point on the screen. These conclusions should not depend on the portrayal of the parallels and meridians, since this portrayal is not always available in ECDIS. The implementation of map projections that do not satisfy the requirement for the shape and pattern of the meridians and parallels contains the risk of creating false impressions, as those in figure 1.

4. Determination of the initial set of map projections for potential use in e-nav applications.

According to the criteria and methodology outlined in Section 3 and the results of the comparative study of the basic characteristics of all kinds of map projections, as they are presented in the relevant bibliography [Snyder and Voxland 1989], [Delmelle 2001], [Capek 2001], [Pearson 1990], the eighteen map projections listed in Table 3 have been selected for further evaluation.

The initial assessment of the map projections of Table 3 has been based on the construction of special maps for each projection showing distortion ellipses, orthodromes (Great Circles - GCs) and Loxodromes (Rhumb Lines - RLs), such as those shown in figure 3. The eighteen map projections of Table 3 have been also evaluated against the simplicity of map projection equations in order to provide convenience in the incorporation into any GIS application. As a result of this initial assessment the thirteen map projections of Table 4 have been selected for further analytical evaluation.

***Table 3.** Map projections selected for initial evaluation*

Cylindric	Conical	Azimuthal	Pseudocylindric
Mercator	Conformal	Gnomonic Orthographic	Robinson
Plate Carré	Equidistant	Conformal	Loximuthal
Cylindric equidistant	Equivalent (equal area)	Equidistant	
Miller		Equivalent (equal area)	
Miller modified			
Cylindric Stereographic/Braun			
Cylindric Sterographic/ Gall			
Cylindric Sterographic /BASM*			

** BASM: Bol'soy Sovetskiy Atlas Mira cylindric projection (Cylindric stereographic at 30°)*

Cylindric	Conical	Azimuthal	Pseudocylindric
Mercator, Plate Carre, Equidistant, Miller, Miller modified, Cylindric Sterographic/ Gall, Cylindric Sterographic /BASM	Conformal Equidistant Equivalent	Conformal Equidistant	Loximuthal

***Table 4.** Map projections selected for further analytical evaluation*

5. Distortion analysis.

The distortion analysis of the map projections of Table 4 has been conducted by:

- The calculation of "angle distortions" and "area distortions" for each projection and the construction of relevant plots, such as those shown in figure 4.
- The construction of special maps showing isolines of area and angular distortions for each projection, such as those shown in figures 5 and 6.

The analysis of distortion distribution according to the tolerances of 8° for angle distortion and 12% for area distortion that have been set in section 3 (§ 3.3.a), showed that:

- For the restriction of visual distortion over extended geographical regions, the evaluated map projections have different visual distortion characteristics in the geographic areas of the latitude zones of Table 5 instead of the areas of low, medium and high latitudes [($\varphi \leq 30°$), ($30° < \varphi \leq 60°$), ($60° \leq \varphi \leq 90°$)] that are normally suggested for the initial evaluation of map projections in the standard bibliography (Iliffe 2000, Pearson 1990, Snyder 1987, Maling 1973).
- Nine of the thirteen projections of Table 4 have values of angular and area distortion within the accepted levels over extended geographical areas. These nine map projections are listed in Table 6.
- The determination of the geographic areas over which the map projections of Table 6 have distortion values within the accepted tolerances, depends on the location of the central line, or the central point of each projection.

The basic features of the distortion distribution of the nine map projections of Table 6 are presented below.

The Mercator modified projection at latitude 15° has zero angle distortions and retains area distortions within limits ensuring reduced visual distortion over extended geographic areas of latitudes on the zone [-24° 24°].

The Miller cylindrical modified projection at latitude 30° restricts considerably the great area distortions of the Mercator projection and concurrently retains the angle distortions to less than 8° in order to avoid visually detectable angular distortions over extended geographic coverage of latitudes on the zone [-59° 59°]. The Miller cylindrical projection is normally used in the equatorial form. Nevertheless for the requirements of the conducted research, some modified versions of this projection have been also evaluated. These modified versions of the Miller cylindrical projection have been derived according to the methodology for the derivation of formulas of projections on the ellipsoid suggested by Snyder (1978).

The Cylindrical Stereographic projection with standard parallels at 30° (BASM[3] projection), retains reduced visual distortion over geographical areas of latitudes on the zone [24° 37°].

The Cylindrical Stereographic projection with standard parallels at 45° (Gall cylindrical projection) retains reduced visual distortion over geographical areas of latitudes on the zone [37° 49°].

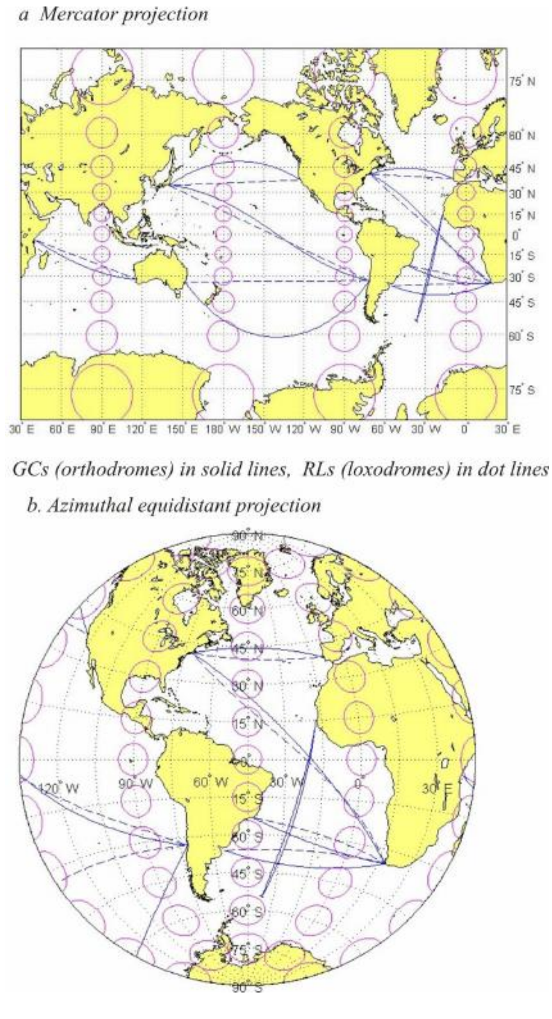


Figure 3. *Distortion ellipses and navigational paths (GCs and RLs) on different map projections*

The Conical Equivalent with standard parallels at φ_1=40° and φ_2=80° has zero area distortions and retains angle distortions within no visually detectable values (≤8°) over extended geographic areas of latitudes on the zone [25° 82°].

The Conical Equidistant with standard parallels at φ_1=40° and φ_2=80° retains area distortions within no visually detectable values (≤8%) over extended geographic areas of latitudes on the zone [28° and 83°]. In addition this projection retains angle distortions within no visually detectable values (≤8°) over extended geographic areas of latitudes on the zone [18° 85°].

[3] *BASM: Bol'soy Sovetskiy Atlas Mira cylindric projection*

The Conical conformal with standard parallels at φ_1=40° and φ_2=80° has zero angle distortions and retains area distortions within no visually detectable values (≤8%) over extended geographic areas of latitudes on the zone [28° 83°].

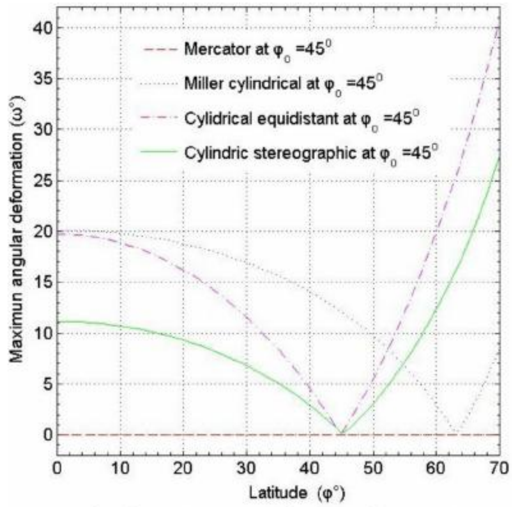
The azimuthal equidistant projection provides the best results in terms of the control of the distribution of distortion to no visually detectable values, over extended ocean regions. This projection retains area distortions within no visually detectable values (≤8%) over extended geographic areas of angular distances of 36° from the central point. Angle distortions are retained within no visually detectable values (≤8°) over extended geographic areas of angular distances of 52° from the central point.

The loximuthal projection, compared to other pseudo-cylindrical projections, provides the best compromise between restriction of visual distortion, desired shape and pattern of graticule lines, and simple map projection equations providing convenience in the incorporation into any GIS application.

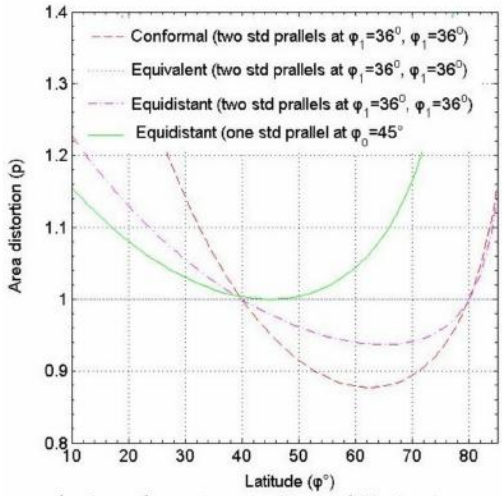
The nine map projections of Table 6 that have been selected as the result of the conducted distortion analysis, have been further evaluated for potential use in e-Nav systems against the specific requirements for marine navigation as they are set in section 3 (§3.3.b, § 3.3.c). The results of this evaluation are presented in the following section 6.

Table 5*: Geographical areas for the evaluation of Map projections*

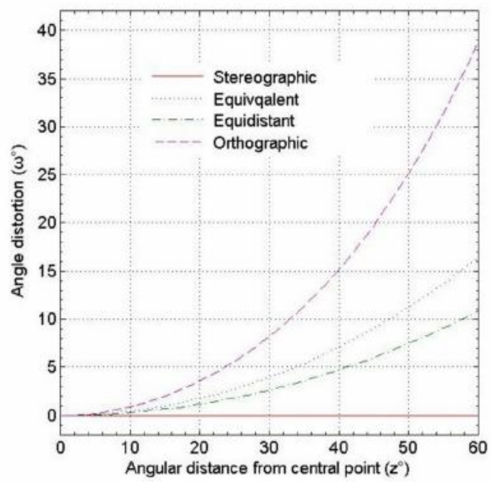
1	Geographical areas of latitude on the zone [-24°, 24°]
2	Geographical areas of latitude on the zone (24°, 37°] north or south
3	Geographical areas of latitude on the zone (37°, 49°] north or south
4	Geographical areas of latitude other than above and coverage less than a hemishere
5	Hemishere coverage
6	Worldwide coverage



a. Angle distortions in Cylindrical Projections

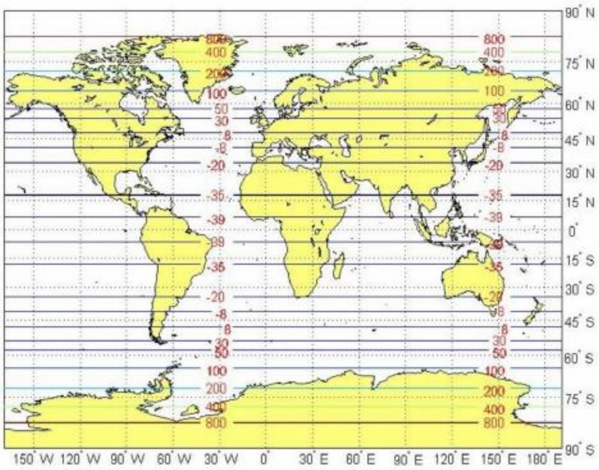


b. Area distortions in Conical Projections

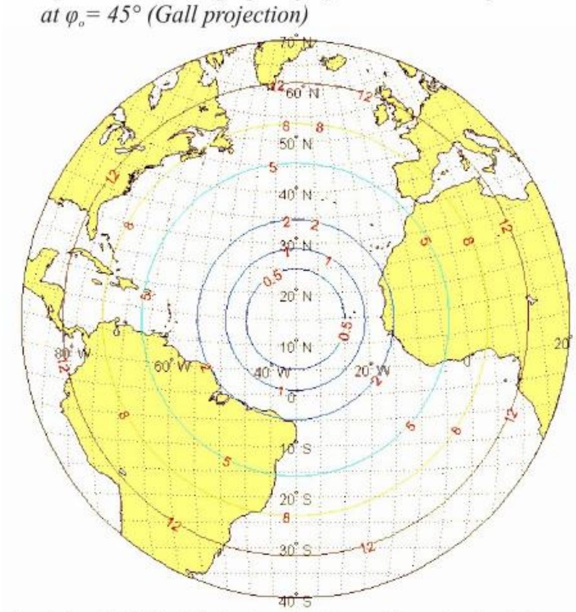


c. Angle distortions in Azimuthal Projections

Figure 4. *Angle and area distortions in different map projections*



a. Cylindrical Stereographic projection with std. parallel at φ_o= 45° (Gall projection)



b. Azimuthal Equidistant projection with central point at 15° N, 35° W

Figure 5. *Area distortion isolines in selected map projections*

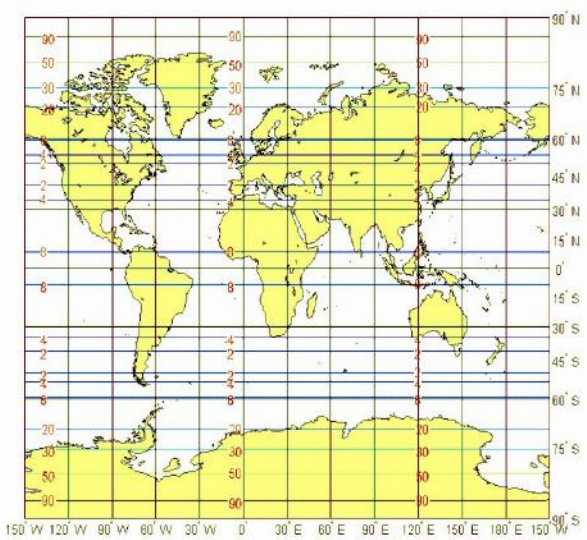
6. Map projections proposed for use in e-nav and other applications.

The evaluation of the nine map projections of Table 6 for potential use in e-Nav systems (ECDIS, ECS) has been conducted by:

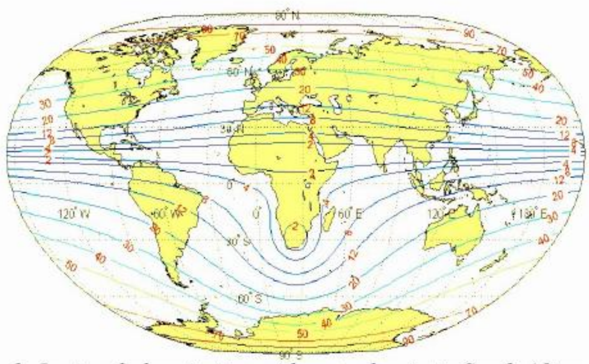
- The assessment of the shape of Great Circles (GCs) and Rhumb Lines (RLs) by the calculation of the orthodromicity and loxodromicity factors for selected long navigational paths. The criterion was that preferred projections are those in which the ortho-dromicity factor is greater than the loxodromicity factor (§ 3.3.b).
- The final assessment of the criteria of Table 1 as a whole set, taking into consideration that some of the criteria cannot be met simultaneously, as in the case of the desired shape of "meridians and parallels" and the shape of "Great Circles (GCs) and Rhumb Lines (RLs)".

Table 6*: Map projections providing reduced visual distortion over extended geographical areas*

Cylindric	Conical	Azimuthal	Pseudocylin-dric
Mercator modified Miller modified Cylindric Stero-graphic/ Gall Cylindric Stero-graphic / BASM	Confor-mal Equivalent Equidis-tant	Equidis-tant	Loximuthal



a. Miller Cylindrical Modified projection at latitude 30°



b. Loximuthal projection with central point in South Africa

Figure 6. *Angle distortion isolines in selected map projections*

The calculations of the loxodromicity and orthodromicity factors have been conducted on the eight standard routes (baselines) that have been repeatedly used for the comparison of calculations of shortest navigational paths in various studies, as they are summarized by Pallikaris and Latsas (2009). The initial and final points of these eight baselines lie on the successive parallels 10°, 20°, 80° and all of them have the same difference of longitude equal to 100°. For better visual perception, these eight routes have been mapped over the geographical area of the Pacific Ocean (Fig. 7). The results of the calculations of the loxodromicity and orthodromicity factors of these trial routes are shown in figure 7.

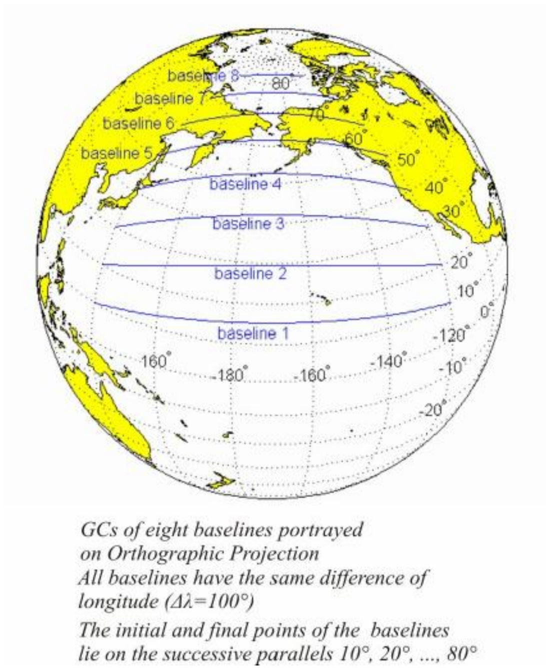


Figure 7. *Baselines for the assessment of the shape of GCs and RLs*

The results of the final evaluation of the nine map projections of Table 6 for potential use in e-Nav systems has been conduced in accordance to the criteria of Table 3 and showed that:

- The map projections that satisfy the whole set of the selection criteria of section 3 in the best possible degree and consequently can be used in ECDIS and in other e-Nav systems are listed in Table 7.
- The map projections that satisfy the requirements for reduced visual distortion over extended geographical areas and consequently are proposed for other GIS applications are those listed in Table 7.
- The proper choice between the map projections of Table 7 must be done according to specific selection rules based on the location and the extend of the area portrayed on the screen. These rules are presented in section 7

Table 7. *Map projections proposed for use in e-Nav and other GIS applications*

[The selection of the proper projection depends on the location and the extend of the area portrayed on the screen]

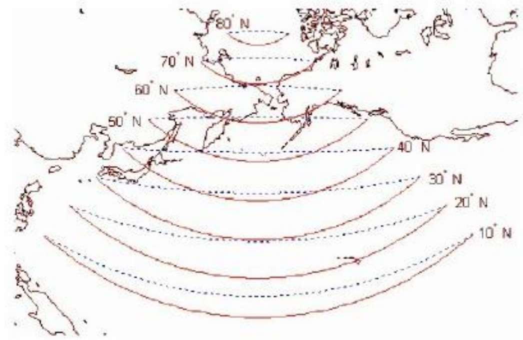
Map projections	Proposed for	
	E-Nav	other GIS applications
Mercator modified at latitude 15°	√	√
Miller modified cylindrical at latitude 30°	√	√
Cylindrical Stereographic with standard parallels at 30° (BASM projection)	√	√
Cylindrical Stereographic with standard parallels at 45° Gall projection)	√	√
Conical Conformal with standard parallels at φ_1=36° and φ_2=54°		√
Conical Equivalent with standard parallels at φ_1=40° and φ_2=80°		√
Conical Equidistant with standard parallels at φ_1=40° and φ_2=80°		√
Azimuthal Equidistant	√	√
Loximuthal	√	√

7. Rules for the selection of map projections in ECDIS and other GIS applications

The analysis of the results of the evaluation of the nine map projections of Table 7 showed that the choice of map projections in ECDIS and other MGIS applications over extended geographical areas, according to the tolerances for reduced visual distortion set in §3.3.a (8° for angle and 12% for area distortion) must be done according to the following rules.

7.1. Map projections for Regional/Oceanic Coverage

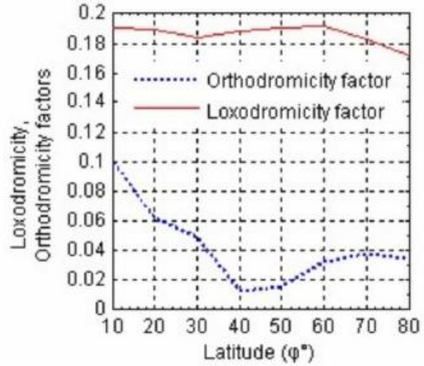
i. When the location of the depicted on the screen geographic area corresponds to geographic areas of lati-tudes on the zone [-24° 24°], then the Mercator modified projection with standard parallel at φ_o=15° should be used.
ii. When the location of the geographic area depicted on the screen corresponds to geographic areas of latitudes on the zone [24° 37°], in north or south hemisphere, then the Cylindrical Stereographic projection with standard parallel at φ_o=30° (BASM projection) should be used.
iii. When the location of the geographic area depicted on the screen corresponds to geographic areas of latitudes on the zone [37° 49°], in north or south hemisphere, then the Cylindrical Stereographic projection with standard parallel at φ_o=45° (Gall cylindrical projection) should be used.



i. GCs (dotted lines) and RLs (solid lines)

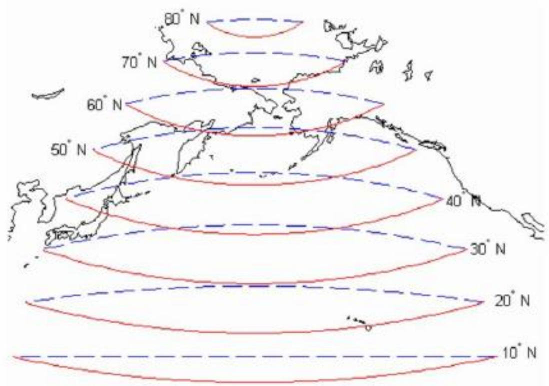
φ	Loxodromicity and Orthodromicity factors	
	ξo	ξλ
10°	-0,099	0,191
20°	-0,062	0,189
30°	-0,048	0,184
40°	-0,012	0,188
50°	0,015	0,190
60°	0,032	0,192
70°	0,037	0,183
80°	0,034	0,172

ii. Values of Loxodromicity and Orthodromicity factors



iii. Plots of Loxodromicity and Orthodromicity factors

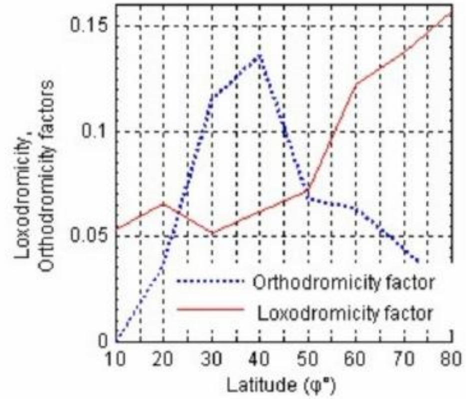
a. Conical Equidistant Projection with standard parallels at $\varphi_1=40°$ and $\varphi_2=80°$



i. GCs (dotted lines) and RLs (solid lines)

φ	Loxodromicity and Orthodromicity factors	
	ξo	ξλ
10°	0,000	0,053
20°	0,036	0,066
30°	0,115	0,052
40°	0,136	0,062
50°	0,068	0,072
60°	0,063	0,122
70°	0,044	0,138
80°	0,024	0,157

ii. Values of Loxodromicity and Orthodromicity factors



iii Plots of Loxodromicity and Orthodromicity factors

b. Azimuthal equidistant projection with central point latitude 15°

Figure 8. *Assessment of the shape of GCs (Orthodromes) and RLs (Loxodromes)*

iv. For coverage less than a hemisphere and for geographical areas within latitude limits other than those mentioned in the above cases i, ii and iii, the azimuthal equidistant projection with central point selected on the basis of the limits (outline) of the area should be used. Nevertheless in most cases, zero or little visual distortion over extended geographical areas can be achieved if the central point of the azimuthal equidistant projection is selected as follows:
   - For the depiction of geographical areas with approximately the same extend of latitude in either hemisphere the azimuthal equidistant equatorial (central point at 0°) can be used.
   - For the depiction of large ocean areas exceeding the parallel of 45°, the selection of the central point at latitude 15° provides very satisfactory results, as in the example of figure 5b for the depiction of the area of the North Atlantic Ocean.

7.2. Map projections for Coverage approximating a hemi-sphere

For e-Nav systems and coverage approximating a hemi-sphere, normally it is not possible to fulfil concurrently the requirements for the shape of GCs and RLs and the requirements for the desired shape and pattern of the graticule lines. If priority is given to the shape and pattern of the graticule, then the Miller Cylindrical modified projection at latitude 30° can be used. Otherwise if priority is given to the shape of Orhodromes (CLs) and Loxodromes (RLs), the azimuthal equidistant projection can be used.

7.3. Map projections for the Arctic

The expectation of increasing shipping in the Arctic in both easterly and westerly directions evolved the require-ment for the identification of suitable map projections for navigation with ECDIS[4] in very high latitudes [ARHC 2011]. Navigation with ECDIS in the Arctic needs some special consideration due to the following reasons.

- For some projections it is impossible to depict Polar Regions. Consequently some ECDIS systems that employ these projections cannot depict ENCs for the Arctic. This inefficiency has nothing to do with the structure and content of the ENCs, but is due only on the map projections employed by ECDIS.
- In the Arctic there is a very significant difference between Great Circle and Rhumb line sailing even for small sailing distances.
- In the Arctic the dynamic parameterization of map projection employed in many ECDIS systems and the subsequent orientation of the ENC may cause incon-venient changes in the geographical directional perspective (Fig 9).

Taking into consideration the abovementioned special conditions, the results of the conducted analysis showed that for navigation with ECDIS in the Arctic the projections that provide minimal visual distortion are the azimuthal equidistant and the azimuthal stereographic projections. The polar azimuthal equidistant projection provides zero or little visual distortion for areas extending from the pole down to the 75° parallel. The polar azi-muthal stereographic projection provides zero or little visual distortion for areas extending from the pole down to the 82° parallel.

In order to avoid incon-venient changes of the directional perspective of the ENC, the central meridian of the polar azimuthal projection should be preferably set at longitu-des 000° or 180° only [Fig 9a and 9c] instead of the longi-tude of the vessel's current position, as in the normal prac-tice for oceanic ship routing used in most ECDIS systems.

7.4. Map projections for Worldwide Coverage

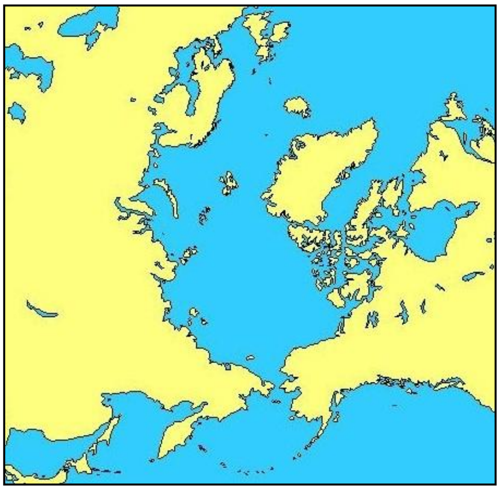
For worldwide coverage and concurrent restriction of distortion in an extended geographical area the loximuthal projection should be used. The proper selection of the central point, as in the case of figure 6B for the restric-tion of angle distortion in the coasts of Africa, is vital.

7.5. Map projections for other than e-Nav applications

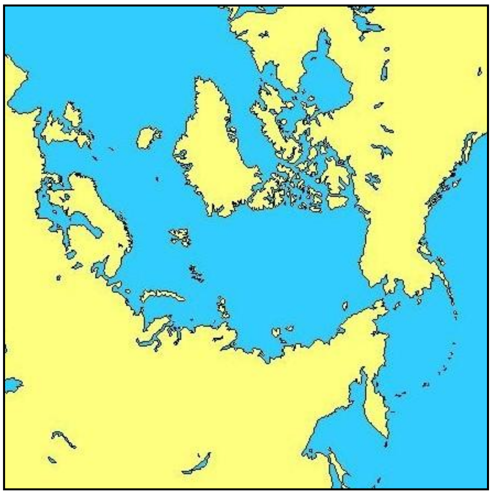
For other than Electronic navigation GIS applications, where only criteria for reduced visual distortion are applied, conical projections can be also used. In these cases depending on the requirements of each application (e.g. percentage of equivalency over conformality) the tolerances for reduced visual distortion set in §3.3.a may be modified accordingly. For the tolerances set in section 3 (8° for angle and 12% for area distortion), best results, in terms of the extent of the geographic region with reduced visual distortion, can be obtained in the following three cases.

- Conical Conformal with standard parallels at φ_1=36° and φ_2=54°. This projection provides zero or mini-mum visual distortion between latitudes of 18° and 66°.
- Conical Equivalent with standard parallels at φ_1=40° and φ_2=80°. This projection provides zero or mini-mum visual distortion between latitudes of 25° and 82°.
- Conical Equidistant with standard parallels at φ_1=40° and φ_2=80°. This projection provides zero or mini-mum visual distortion between latitudes of 28° and 83°.

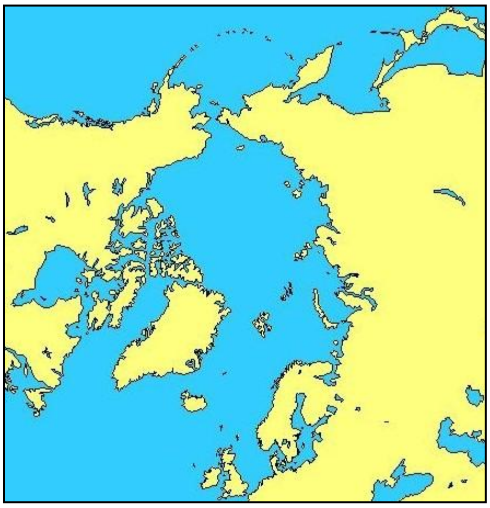
[4] *Report of the 2nd meeting of the Arctic Regional Hydrographic Commission (ARHC). September 28-29 2011. Copenhagen, Denmark*



a. Azimuthal equidistant with central meridian at 000°



b. Azimuthal equidistant with central meridian at 120°



c. Azimuthal equidistant with central meridian at 180°

Electronic Chart depicted on the ECDIS screen with different choices of the central meridian

Figure 9. *The visual effect of the choice of central meridian in polar projections*

8. Conclusions overview

Eighteen map projections have been initially selected for evaluation in order to identify those that provide reduced visual distortion for potential use in Electronic Navigation systems (ECDIS, ECS). The comparative study of the features and the calculation and analysis of the magnitude and the distribution of angle and area distortions of these projections showed that in e-Nav systems, as well as in other GIS applications, the use of map projections other than those commonly used can provide better visualization results. In addition the employment of proper map projections can overcome the inadequacy of some ECDIS systems to depict ENCs in very high latitudes.

The study focused on small scale applications (≤1:2.350.00). Map projections for medium and large scale applications are not proposed, since at these scales different map projections practically provide the same visual results.

Six map projections are proposed for optimum distribution of angle and area distortion ensuring reduced visual distortion in the ECDIS screen: Mercator modified at latitude 15°, Miller cylindrical modified at latitude 30°, Cylindrical Stereographic with standard parallels at latitude 30° (BASM projection), Cylindrical Stereographic with standard parallels at latitude 45° (Gall projection), Azimuthal Equidistant and the Loximuthal pseudo-cylindric projection.

If it is desirable to restrict the number of map projections that are used in ECDIS, only two projections can be used: i) The Miller cylindrical modified at latitude 30° and ii) The Azimuthal equidistant. These two projections provide better visualization results than the Mercator and the Azimuthal Stereographic that are used in many commercial systems.

In any case the choice of the proper map projection must be done according to specific selection rules based on the location and the extent of the area depicted on the screen.

For "hemisphere depiction" the **azimuthal equidistant projection** provides the best results in terms of the control of the distribution of angle distortion and area distortion to limits ensuring reduced visual distortion over extended ocean regions.

For "worldwide depiction" the **loximuthal projection**, compared to other pseudocylindrical projections, provides the best compromise between restriction of visual distortion, desired shape and pattern of graticule lines, and simple map projection equations providing conven-ience in the incorporation into any GIS application.

For navigation with ECDIS in the Arctic, the **azimuthal equidistant projection** and the **azimuthal stereographic projection** provide the best results for reduced visual distortion.

The proposed six map projections for use in ECDIS and e-Nav systems have been determined not only for the satisfaction of the requirement for the control of angle distortion and area distortion to values ensuring reduced visual distortion over extended geographical areas but also for the satisfaction of additional requirements for the shape and the pattern of the graticule lines, and the shape of othodromes (CLs) and loxodromes (RLs).

Conical map projections have not been proposed because for small scale applica-tions they do not fulfill satisfactory the requirements for the shape of GCs and RLs .

Despite the fact that the scope of the conducted study was the identification of suitable map projection for ECDIS, the basic results can be also applied to other than e-Nav GIS applications. Thus the following nine map projections can be used in other than marine navigation small scale GIS applications (≤1: 1:2.350.00): Mercator modified at latitude 15°, Miller cylindrical modified at latitude 30°, Cylindrical Stereographic with standard parallel at 30° (BASM projection), Cylindrical Stereographic with standard parallels at 45° (Gall projection), Azimuthal Equidistant, Conical Conformal with standard parallels at φ_1=36° and φ_2=54°, Conical Equivalent with standard parallels at φ_1=40° and φ_2=80°, Conical Equidistant with standard parallels at φ_1=40° and φ_2=80° and the Loximuthal pseudocylindric projection.
The selection of suitable map projections for marine GIS applications is not usually unique. Normally more than one map projections fulfill the requirements for a particular application. Depending on the main scope of the application, different or additional requirements may be determined which in turn result to more specialized selection rules, so that the set of the proposed map projections can be further reduced. In any case the choice of map projections for a particular application must be based not only on criteria for the restriction of visual distortion, but also on additional criteria based on the requirements for the particular application, as it has been done in the conducted research for the case of e-Nav systems (ECDIS, ECS).

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Biography of the author

Athanasios Pallikaris is associate professor at the Hellenic Naval Academy [HNA]. He holds a Phd from the National Technical University of Athens, a M.Sc. in Oceanography (Hydrography) from the Naval Postgraduate School/USA and a B.Sc. in Nautical Science from HNA. From 1979 to 2002, as an officer of the Hellenic Navy, he served in various posts of the Hellenic Navy Hydrographic Service, including those of the Head of the Department of Cartography, Head of the Department of Hydrographic Surveys and Head of the Department of Digital Cartography. In 2002 he retired as Commodore and in 2003 has been elected member of the faculty of the HNA. He has served on a number of national and international committees and working groups on Hydrography, Cartography and Navigation. He is the author/co-author of a number of books and articles in Navigation and Hydrography. [e-mail: palikari@snd.edu.gr].

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