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Using GIS to Obtain Celestial Fix under the Framework of an ECDIS System

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ABSTRACT: This study proposes a simple method for obtaining a celestial fix, developed within a Geographic Information System (GIS) under the framework of an ECDIS system. The underlying principle is dependent on the most fundamental theory in celestial navigation; the circle of position (COP) of the celestial bodies is plotted to find the fix. Through the spatial data processing, analysis, and visualization capabilities available in GIS, a celestial fix may be obtained directly from plotting. This eliminates the limitations associated with finding the fix manually using a paper map, but also avoids the cumbersome work and inaccuracy of the traditional Intercept Method (IM) or the complicated, and often obscured, computation involved in numerical methods. The proposed method is simple and accurate, and it applies to problems involving two or more celestial bodies and high-altitude observations. It provides a reference for the development of a celestial positioning module in an ECDIS system, and could also be integrated into an educational program on electronic celestial navigation.

1 INTRODUCTION

ECDIS systems can integrate various types of navigation information and display them on an System Electronic Navigation Chart (SENC), providing a platform for real-time navigational decisions. In MSC Resolution 232(82), an amendment regarding ECDIS performance standards released in 2006, it is emphasized that an ECDIS system must provide an automatic Dead Reckoning (DR)/Estimated Position (EP) facility for DR navigation in the event of GPS failure, and to crosscheck received positions by other means, such as visual bearings (Radar, Line of Position [LOP], celestial fix). Thus, celestial positioning has already been listed as one of the assisted-positioning options [1]. Generally, however, only positioning by plotting LOP using the traditional Intercept Method (IM) is provided while celestial positioning methods are not yet implemented. GIS is an important base module for visual display and processing of navigational information in an ECDIS system, and eliminates some of the restraints in previous positioning techniques conducted on paper maps. Therefore, the positioning approach proposed in this study was developed using the ECDIS framework. The method was implemented within a GIS module, and relies on fundamental theories of celestial navigation (obtaining a fix by plotting celestial circle of position - COP). Electronic chart work is performed using the spatial data processing and analysis capabilities found in GIS, achieving outcomes that would be impossible with paper chart work. The proposed method is simple, fast, and accurate, and can avoid the cumbersome work and inaccuracy of the traditional Intercept Method (IM) or the complicated, and often obscured, computation involved in numerical methods [2, 3, 4, 5, 6, 7]. The method can also provide a reference for the development of next-generation electronic celestial navigation modules that improve the visual-fixing functions in ECDIS systems.

2 POSITIONING BY PLOTTING COP

The principle of the COP fix is quite simple, and can be carried out provided one can plot the COP directly onto a paper chart. According to the relationship between celestial and Earth coordinates, in which they are each other's projections, an observer's COP is the projection of the circle of zenith distance onto the surface of the Earth. The center of the COP is the Geographic Position (GP) of the celestial body. The point of intersection closest to the estimated vessel position is the observed vessel position (Figure 1).

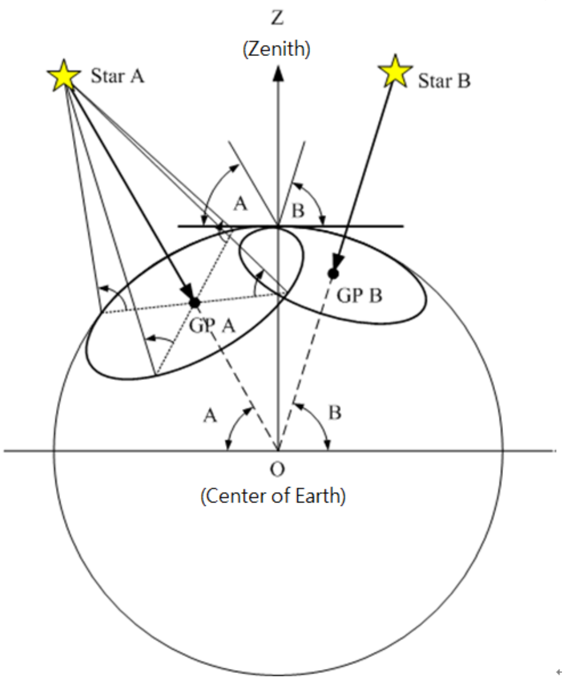

Figure 1. The principle of COP positioning[4]

3 LIMITATIONS OF TRADITIONAL COP POSITIONING

Although the principle of obtaining the position fix by plotting COP is simple, it is difficult to use in practice due to the following reasons:

1 The radius of COP is too large when plotted on a typical paper chart.
2 As the measured latitude becomes further from the equator, there is more distortion of the circle at higher latitudes (Figure 2).
3 If a globe were used for direct positioning, the diameter of the globe would need to be very large to achieve the required accuracy. This is clearly impractical.

In view of these limitations, the graphical positioning method using COP can only be applied to high-altitude observations for celestial bodies with an altitude greater than 87°. However, such cases are rare in practice, and therefore this case has very limited value.

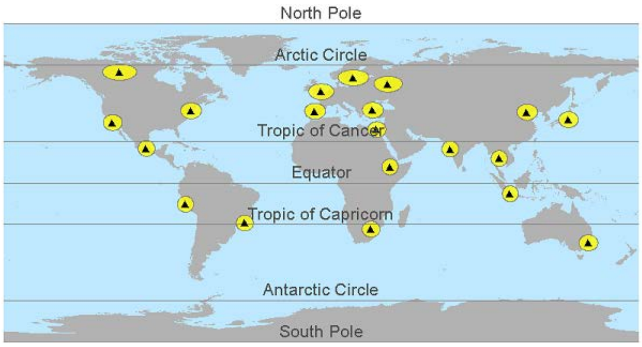

Figure 2. The projected curve of a COP, with the same diameter, at various latitudes

4 REVISITING GRAPHICAL POSITIONING USING COP

Digital storage and processing in ECDIS systems has removed some limitations associated with paper charts. When displaying vector data, for example, the entire world or any part thereof may be displayed at any scale provided adequate computer memory is available. Maps covering different regions match perfectly at the boundaries, and may therefore be viewed as a single contiguous map with no limit on map size. Moreover, on an ECDIS system, within which GIS plays a key role, geodetic datum, and projection can be changed to plot projected curve of COP easily. For COP positioning, a general chart with a small scale or an electronic plotting sheet covering the whole world is enough. Upon completion, the results can be overlaid on a chart with a larger scale for display without compromising the accuracy.

5 CELESTIAL NAVIGATION FIX BASED ON GIS.

GIS has been widely applied in a variety of fields. For example, Traffic Geographic Information Systems (GIS-T) are an extension of GIS technology into the realm of transportation, integrating GIS with various kinds of traffic information analysis and processing techniques. Marine Geographic Information Systems (MGIS) are an important application of GIS in the management of the marine environment and ocean resource data. Both systems have their own areas of expertise and technologies. Provided it can be integrated into Marine Traffic GIS (MTGIS), the new system can be applied in marine traffic and ocean surveying. ECDIS can be viewed as such an example.

6 THE INTEGRATION OF GIS WITH THE NAVIGATION INFORMATION SYSTEM

Figure 3 demonstrates the framework of a Navigation Information System (NIS). The ECDIS system, as the core of the NIS, manages spatial data (GIS) and attribute data (Management Information System – MIS), and provides a platform for integration of navigation data and decision-making. Most common features, such as navigation route planning (e.g., checking safety contours and critical area) and position monitoring (e.g., XTE alerts, waypoint alerts, and anchor watch) are derived from the geo-processing capabilities in MTGIS. It is also shown in Figure 4 that only a very small portion of GIS functionality is used in ECDIS at present. To develop more intelligent NIS in the future, the capabilities of MTGIS must be expanded.

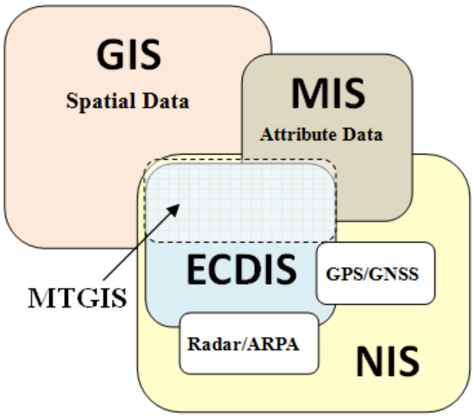

Figure 3. The relationship between GIS and ECDIS in the NIS framework [9]

7 IMPLEMENTATION OF GIS IN CELESTIAL POSITIONING

GIS software ArcGIS 10.5 released by ESRI is employed in this study; this software package includes complete GIS functionality and has been widely applied in geographical information related research. There is no extra data required other than the general astronomical observation data. The GIS functions used are also basic functions that may be found in any normal GIS software package.

7.1 *Input Data*

To plot COP of a celestial body in the ECDIS system, the required input data are a map, the Greenwich Hour Angle (GHA) and Declination (Dec), and the observed altitude (Ho) of the body. A general chart with a small scale or an electronic plotting sheet covering the whole world may be used. The results may subsequently be overlaid onto any electronic navigation chart. Dec corresponds to the latitude of the GP of the celestial body. GHA must be converted to represent the longitude of GP. Ho is used to calculate the radius of COP with the unit of nautical miles. DR position is used to determine the vessel position.

7.2 *Main Functions in GIS and Operating Procedure*

To make the execution automatic, the ModelBuilder module in ArcGIS was used. The procedure is shown in Figure 4. The main GIS functions involved in the process are:

1. Defining the Geodetic Datum: The default geodetic datum in ECDIS is WGS84, which assumes that the earth is an ellipsoid with a semi-major axis of 6378137 meters and semi-minor axis of 6356752.3 meters. Both the celestial sphere and the Earth are considered as perfect spheres in celestial navigation. The coordinates between the two are each other's projections. In astronomical positioning, COP plotted with respect to the geodetic datum (WGS84) in an ECDIS system is slightly different to the COP plotted by assuming the earth as a perfect sphere. Therefore, the former datum cannot be directly applied in celestial positioning. To adjust the geodetic datum, the average radius of earth (6371000 meters) is taken as the geodetic datum of Earth as a perfect sphere. All subsequent distance calculation is based on this datum.
2. Buffer: In this study, it is proposed that the buffer function may be used to construct the COP of the celestial body. The circle is centered at its GP, and radius is the co-altitude (90°–Ho). In the GIS environment, different distance units can be used as radius of the buffer ring, and previously arduous tasks (such as plotting COP on Mercator paper chart in high latitude regions or for large areas) may be easily achieved. In the construction of COP, radius of the buffer ring must be set as the co-altitude in nautical miles.
3. Intersections: Locate the intersection of spatial entities; the intersections of the resultant COPs are the possible vessel positions.
4. Spatial Query: As there may be more than one point of intersection between COP, DR position is needed for further determination. In this study, the spatial query function is used to search for the point of intersection near the DR position and to determine vessel position. The query operator is set to 'within a distance'. The radius for the search is user-defined; however, 60 NM is generally sufficient. In a two-body fix, a single point is obtained from this operation, and this point is the celestial fix of the vessel; in case of a multi-body fix, a further processing step is required .
5. Mean Center: In a multi-body fix, a group of intersection points in the proximity of the DR vessel position is obtained via a spatial query from multiple COP intersections. The mean center function calculates the center of this group; this is the most probable position (refer to Figure 5). This operation is equivalent to finding vessel position from the cocked hat region between the points of intersection.

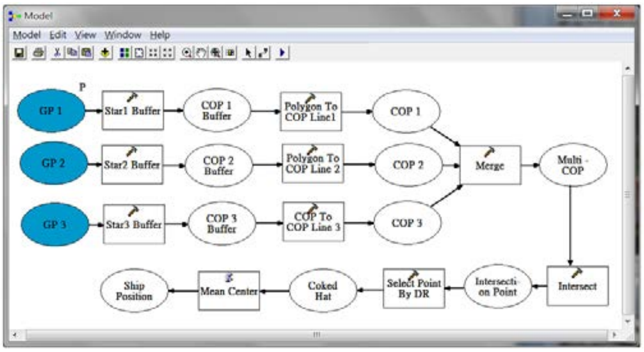

Figure 4. The procedure used to obtain a multi-body celestial fix in GIS

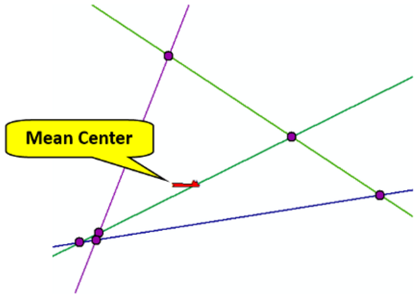

Figure 5. Determination of the Mean Centre.

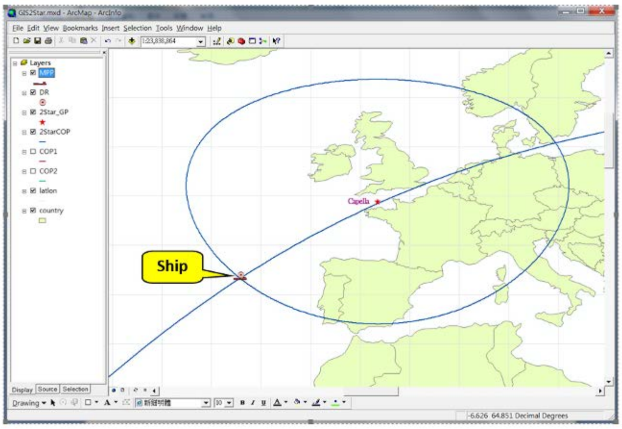

Figure 6. Results of the two-body fix

8 RESULT VALIDATION.

Two-body fix, multi-body fix, and high-altitude observation data was used to validate the proposed graphical approach using COP in GIS, by comparing results with those from three previously published methods for obtaining a celestial navigation fix. The three methods used for comparison are traditional IM, programed IM by Dewit [8], and the computational method proposed by Metcalf and Metcalf [10].

8.1 *TWO-BODY FIX*

The data in this case study is taken from Hsu et al. (2005). It can be seen from Table 1 that the observed altitude of Alkaid is as high as 77°34.9′, which exceeds the upper limit of 70° in the intercept method. Hsu et al. (2005) found that at high altitude, LOP drawn using the intercept method shifted due to curvature error, resulting in an inaccurate estimate of vessel position. Comparison in Table 2 indicates that GIS COP is not affected by the altitude or latitude of observation, and the obtained results are the same as those from other computational methods except for tradition IM.

Table 1. Extract of relevant information from Hsu et al. (2005) for two-body

Body	Capella	Alkaid
ZT	20-03-58	20-02-56
Ho	15° 19.3'	77° 34.9'
GHA	131° 24.8'	003° 14.2'
Dec	45° 58.4' N	49° 25.7' N

Table 2. Two-body fix position

DR : L = 41° N, λ = 017° W

Method	L	λ
IM	41° 38.6' N	017° 08.1' W
Dewit	41° 39.1' N	017° 07.3' W
Metcalf	41° 39.1' N	017° 07.3' W
GIS COP	41° 39.1' N	017° 07.3' W

8.2 *MULTI-BODY FIX*

There are four celestial bodies used for calculation in this case study. In addition to the increased number of celestial bodies, correction on the running fix is also applied. Except for IM, where graphical errors may have resulted in some discrepancies, the vessel position estimate from the proposed method is close to the estimate obtained using computational methods.

Table 3. Multi-body fix

Course: 220° Speed: 18 kts

Body	ZT (1993/9/13)	Ho	GHA	Dec
Altair	18-00-00	37° 53.0'	325° 06.6'	08° 51.4' N
Fomalhaut	18-04-00	27° 54.0'	279° 24.2'	29° 39.1' S
Achernar	18-08-00	17° 46.5'	240° 21.7'	57° 15.8' S
Rasalhague	18-12-00	41° 35.5'	002° 04.8'	12° 34.1' N

Table 4. Milti-body fix position

DR : L =35° S, λ = 005° E

Method	L	λ
IM	35° 19.0' S	005° 26.5' E
Dewit	35° 18.6' S	005° 27.0' E
Metcalf	35° 18.6' S	005° 27.0' E
GIS COP	35° 18.5' S	005° 27.1' E

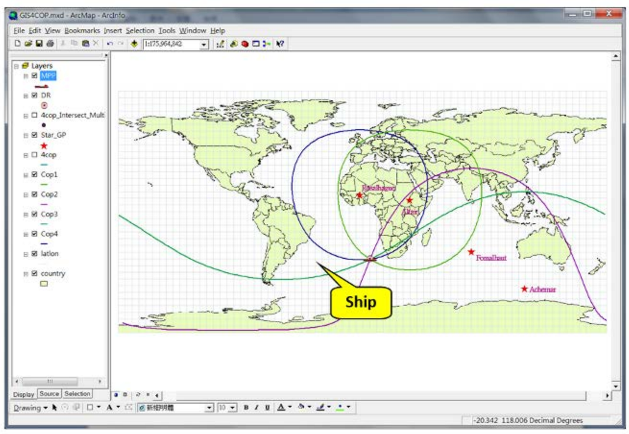

Figure 7. Results of the multi-body celestial fix

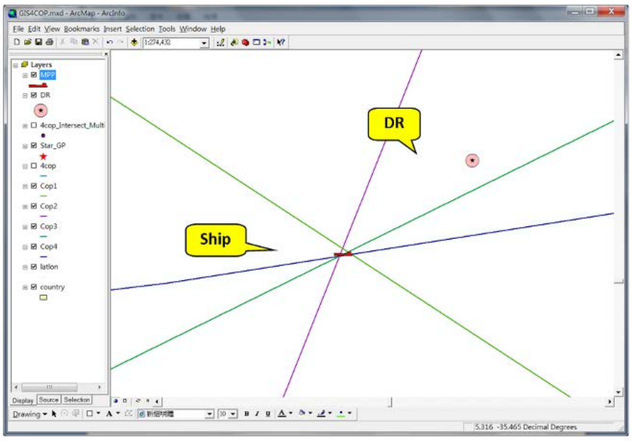

Figure 8. Cocked hat region in a multi-body fix

8.3 *HIGH ALTITUDE OBSERVATION FIX*

In this case, three high-altitude observations were conducted before and after the sun transit time. Due to curvature of the line of position, IM is no longer applicable, and it would be necessary to resort to graphical methods for high altitude or computational methods to find the vessel position. Results from the current study resemble those obtained by computational methods, and are evidently superior to those obtained from the graphical method using COP.

Table 5. High altitude observation

Course: 290° Speed: 15 kts				
Body	ZT (1996/9/8)	Ho	GHA	Dec
Sun	11-56-13	89° 19.4'	269° 38.9'	05° 34.6' N
Sun	11-58-19	89° 36.2'	270° 10.5'	05° 34.5' N
Sun	12-00-41	89° 19.2'	270° 46.0'	05° 34.5' N

Table 6. High altitude fix position

DR : L = 06° N, λ = 090° E		
Method	L	λ
COP Plot	05° 59.0' N	089° 47.8' E
Dewit	05° 58.1' N	089° 47.6' W
Metcalf	05° 58.1' N	089° 47.6' W
GIS COP	05° 58.0' N	089° 47.6' W

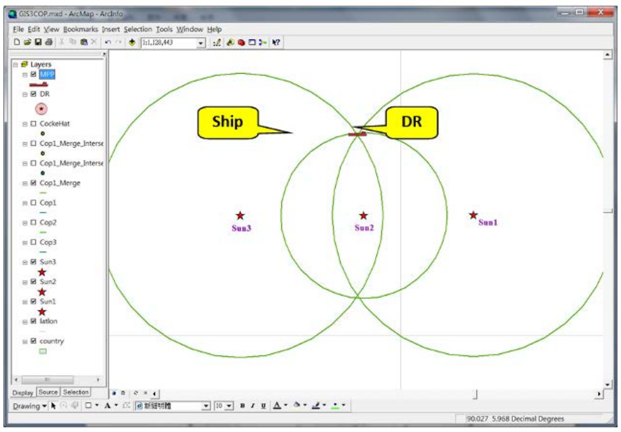

Figure 9. Results of a high-altitude observation fix

9 RESULT DISCUSSION

While the results of this study are slightly different from those of the other computational methods described, they are evidently more accurate than those obtained using the graphical method. The main reason for the difference lies in the mean-center function used in multi-body fix procedure, and the resolution of the COP constructed using the buffer function (refer to Figure 10). However, the resolution of the COP produced in the buffer function is sufficient for normal navigation purposes. Moreover, the macro functions in the GIS software can link related functions and make the process more automatic. The execution time of the whole positioning process is very short, satisfying the requirement for real-time positioning.

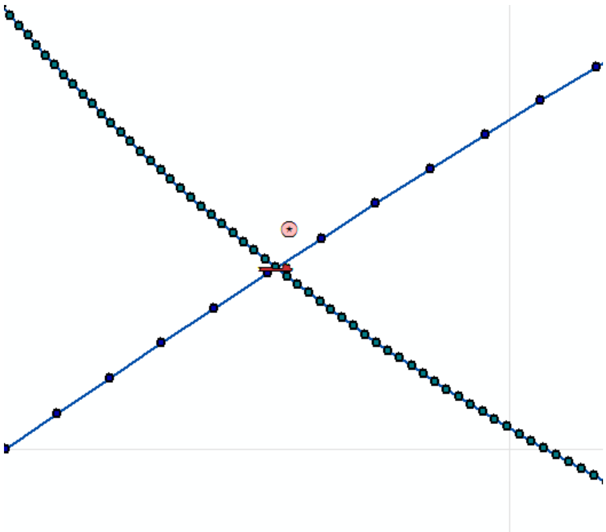

Figure 10. Different vertex resolution at the intersection of two COPs

10 CONCLUSIONS

Considering the applications of GIS in marine traffic, current ECDIS only uses a small portion of GIS capabilities. To give ECDIS more capability to support decision-making during navigation, and hence enhance navigational safety, the functionality of GIS in ECDIS needs to be expanded. In this work, a direct celestial fix technique using the COP fix principle within a GIS system is proposed. The method applies to two-body fix, multi-body fix, and high-altitude observation problems; it is simple compared to other numerical analysis methods, and avoids the cumbersome calculation and plotting that is required in more manual methods. Experience with the system demonstrates that the complicated and cumbersome calculation and plotting of traditional methods are avoided, and the proposed method is easier to perform than other numerical methods. Through complete integration with an ECDIS system, positioning results can be presented visually, facilitating the promotion and application of celestial navigation. Currently, ECDIS lacks comprehensive support for celestial fix procedures, and new functions in this area need to be implemented to offer alternatives to the existing assisted-positioning system in ECDIS so that GPS position can be crosschecked during ocean voyages. The proposed framework provides a reference for future development of celestial positioning modules in an ECDIS system. The graphical positioning procedures are simple, fast to perform, produce accurate results and are also suitable for use in modern celestial navigation education.

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