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Research Article

Determination of Black Sea Coastline Length with Oblique Stereographic Projection Using Affine Transformation

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Abstract

The Black Sea basin has rich oil and natural gas resources. As a result, determining the continental shelf in international relations and maritime law is a critical issue for countries with a shoreline on the Black Sea, which is a semi-enclosed sea. Global projections are generally used for the projection of satellites used to image the earth. The use of global projections causes increased deformation in applications in local areas. For this reason, the deformation of satellite images used as a base can be reduced by converting them to the appropriate projection. In this study, the coastline lengths of the countries neighboring the Black Sea were calculated by using remote sensing images and selecting the appropriate cartographic projection due to the aim of minimum map deformation. By using different numbers of control points to determine the six parameters of the 2D Affine transformation used for coordinate transformation, the change in the accuracy of the transformation depending on the number of control points was examined. The Black Sea coastline, which was digitized in the local coordinate system via the MODIS satellite image, was transformed into coordinates in the oblique stereographic projection system with 2D affine transformation. 11 test points were used in the affine transformation parameters calculated using different control points, and root mean square error (RMSE) of approximately 8.5 km on the X axis and approximately 9.5 km on the Y axis was achieved using 25 control points. As a result of the transformation, the coastline lengths of each country bordering the Black Sea were determined in oblique stereographic projection.

Keywords: Cartography, Map Projection, Affine Transformation, Satellite Image, Coastline

Introduction

The rocky area under the oceans and seas is also considered a part of the earth's crust. There are many different perspectives on the definition of the continental shelf. One of these is that the continental shelf is defined physically as the land's submerged border beneath the sea, with water depths ranging from 50 to 500 meters (130 to 200 meters on average) and increasing in dept (Gazioğlu et al., 2002; Yılmaz, 2009). In a global sense: “Coastal is not a boundary where continents cease; the continents continue to a certain point under the water (Erhan, 1977).

The Black Sea has strategic importance due to its geographical location. It is a semi-enclosed sea that serves as a security, energy, and transportation corridor between coastal countries. In addition, the existence of energy resources such as gas hydrates in the Black Sea attracts the attention of not only riparian countries but also other globally powerful countries. It is necessary to determine the continental shelf in the Black Sea, which is one of the seas with a coast in Türkiye. The countries that are parties to this determination are Türkiye, Bulgaria, Romania, Ukraine, Russia and Georgia.

Satellite images have their map projection for general purposes. There are few map projections that provide a true perspective (Alcaras et al., 2020). It may be necessary in cases such as redetermining the map projection, reducing deformation, or using data from different sources together. However, it is important to make an equitable distribution in sensitive tasks such as determining continental shelf areas. In such studies, where satellite images can be used as a base map, deformations can be reduced by converting the default map projection to the appropriate projection. There is a gap in the literature that needs to be developed in this sense. It is important what the problem is and which element of the map projection to be chosen is preserved and minimum deformation is aimed. In this study, since the MODIS satellite image has a sinusoidal projection, it was transformed into a new projection that will reduce the deformation. Therefore, neighboring coastal states for the determination of the coastline length in the Black Sea basin.

Different methods are applied in satellite-derived coastline mapping. In situ measurements are generally challenging to obtain. Other survey techniques, such remote sensing, are advised in this situation (Mallet, 2017). Toure et. al. (2019) presented a comprehensive review on shoreline detection using optical remote sensing and shared various examples of different region. Souto-Ceccon et al. (2023), produced the coastline with the profiles approach and k-means approach using PRISMA satellite images in 3 regions in the Mediterranean. Sánchez-García et al. (2020) present an automatic shoreline extraction system using L8 and S2 images using kernel size and polynomial degree algorithm. Specht et al. (2020) completed a study on the coastline changes between 2008-2018 using Landsat imagery on Google Earth Pro platform with vectorization process. Affine transformation is a type of transformation that is widely used in many fields such as cartography (Jenny and Hurni, 2011), photogrammetry (Wang et al., 2022, Ressl et al., 2012), surveying (Ansari et al., 2018) and navigation (Aguilar et al., 2017). Furthermore, some studies prefer an affine transformer for geometric correction and georeferencing of satellite images. Goksel et al. (2001) published on determining the coastline lengths of Türkiye and Greece in the Aegean Sea with different cartographic projections. Water areas were determined depending on the calculated coastline lengths. In another study (Alcaras et al., 2020), the application of coordinate transformation was examined by using data obtained from different sources within a coastal and marine information system. In the study, topographic maps and satellite images were used to extract the coasts of the Campania Region (Italy). Since these data have different datums and projections, coordinate transformation was applied between them. To examine the historical change of coastline in the same region (Giannini et al., 2011), coastline extraction was made from images obtained at different dates. Historical aerial images and more recent IKONOS satellite images were produced in different projections. For the projection transformation, a polynomial function was applied using different numbers of GCPs. There is a requirement in the literature regarding the extraction of the coastline from satellite images to detect the Black Sea continental shelf and the realization of projection transformation for spatial analysis. Coastline extraction is generally used for different purposes (change, detection, etc.). In this study, the purpose of determining the coastline is to provide a base map with minimum deformation to ensure a fair distribution of continental shelf between countries in Black Sea. For this reason, instead of directly extracting the coastline from the satellite image, conversion to the selected appropriate projection was performed.

As the base to be used in the application, up-to-date satellite images, which are the latest technology products that best express the region, were chosen. The fact that the study area is large enough and that the desired regions on the earth can be accessed with multi-band and different wavelengths due to satellite technology are also factors in this choice. On the satellite image, the coastal areas of the Black Sea Basin and the Sea of Azov, which is the inland sea in the northeast, were digitized on the digital platform and the coastal shape consisting of points with sufficient frequency on the coastline was obtained. The control points, which are selected among the points and whose geographical coordinates are also known, were directly converted to the coordinates in the selected new coordinate system. Then, two-dimensional affine transformation coefficients were determined with the help of selected control points. With these coefficients, firstly, the coordinates of the initially selected test points with known geographical coordinates in the new projection were calculated by direct transformation and affine transformation. The accuracy of this transformation made with the square mean error calculation has been tested. The obtained parameters of the 2D affine transformation were applied to all points forming the shore data. In computer-aided graphics programs, the digitized closed coastline of the satellite image and the closed coastlines obtained by combining the points formed as a result of the transformation in the selected new projection were compared. Depending on the new coastline drawn as a result of the transformed coordinates, the coastline lengths of each Black Sea's neighboring countries were determined.

Materials and Methods

Study Area

The Black Sea physiographically consists of four parts: continental shelf, continental slope, basin apron, and deep plains (Gedik et al., 1979). Longitudinal coastal type is seen along the coasts of our country due to the mountainous nature of the Black Sea coast of Türkiye and the fact that the mountains extend parallel to the coast. In addition, the continental shelf section is narrow due to the high cliff formation in Sinop Port.

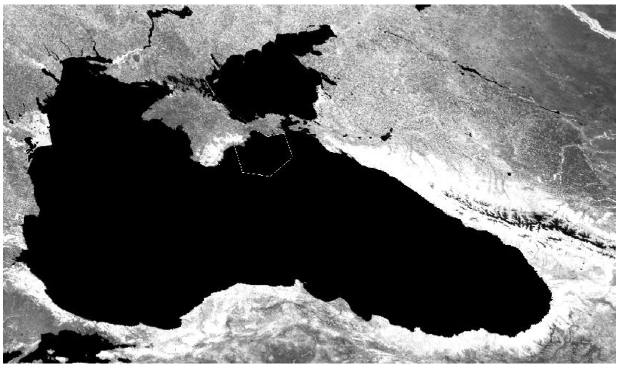

Fig. 1. Mosaic of MODIS satellite images of the Black Sea.

Among the images of MODIS satellite with spatial resolution varying between 250-1000 m, data with 250 m resolution was selected to be used in this study. The entire working area was obtained with a total of two images with an image size of 4800 x 4800. MODIS (Moderate Resolution Imaging Spectroradiometer) The Land Processes Distributed Active Archive Center (LP DAAC) MODIS Water Mask MOD44W (250 m spatial resolution) is used as the reference data for the Black sea. (http://earthexplorer.usgs.gov\). The two-pair images were mosaiced to complete the whole Black Sea boundary (Fig. 1). Considering the total coastline of the Black Sea (7990 km) in the study, processing at a pixel resolution of 250 meters provides a geometrically sufficient basis. Generally, high spatial resolution satellite images are preferred for shoreline extraction in short and small areas (Souto-Ceccon et al., 2023; Specht et al., 2020; Sánchez-García et al., 2020). In this study, the MODIS satellite was selected to provide sufficient detail for a large sea with a coastline of 7990 km. The location of the coastline can be determined precisely with the MODIS satellite image.

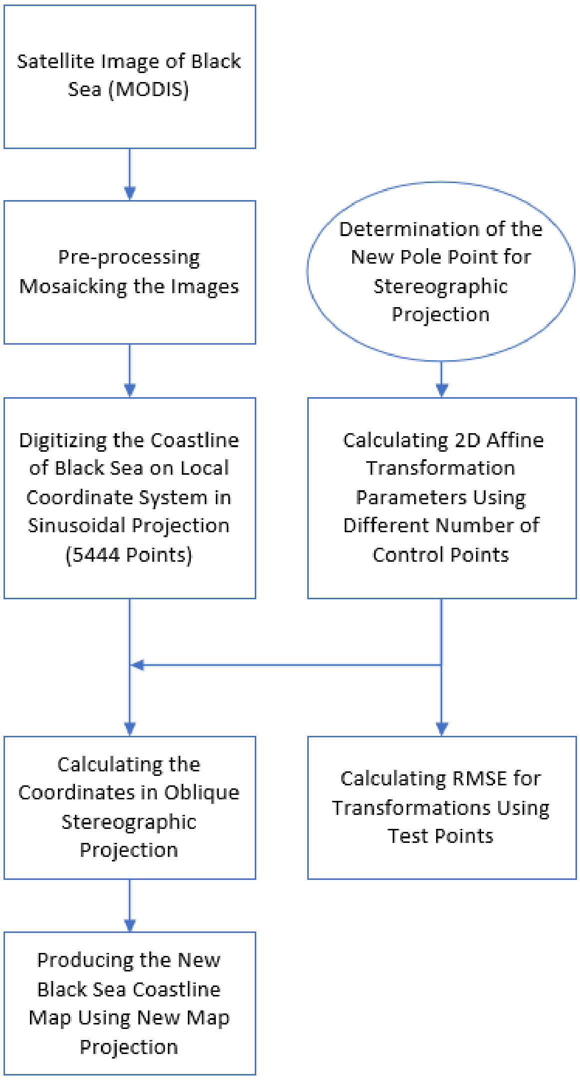

Fig. 2. General flowchart of the study.

The final image of the base image was brought to tif format and made workable in computer-aided graphic design programs. Digitization was performed over the coastline on the image covering the work area on the AutoCAD program. As a result of the digitization, with the help of points in the 5444 arbitrary local system, a closed shape forming the coast of the Black Sea was obtained. The general flowchart is shown in Fig.2

2D Affine Coordinate Transformation

Due to the oblique stereographic coordinates found, it is aimed to find the oblique stereographic coordinates of each point cluster representing the coastline. For this purpose, "Two-Dimensional Affine Transformation" was chosen as the method to be applied (Equation 1, 2). 2D Affine transformation has six unknowns (Equation 3,4). To determine these unknowns (a, b, c, d, e, f) at least 3 points should be used. Varying numbers of control points were selected for parameter calculation (Laganà et al., 2004).

$$X = (S_x \cos\theta)x - (S_y \sin\theta)y + T_x \qquad \text{(Eq.1)}$$

$$Y = (S_x \sin\theta)x + (S_y \cos\theta)y + T_y \qquad \text{(Eq.2)}$$

$$a = S_x \cos\theta, \quad b = -S_y \sin\theta, \quad c = T_x \qquad \text{(Eq.3)}$$

$$d = S_x \sin\theta \quad e = S_y \cos\theta \quad f = T_y \qquad \text{(Eq.4)}$$

Then, equations 5 and 6 are obtained for the 2D affine transformation. In the equations, T is translation.

$$X = ax' + by' + c \qquad \text{(Eq.5)}$$

$$Y = dx' + ey' + f \qquad \text{(Eq.6)}$$

Determining Cartographic Projection for Transformation and Calculating Polar Coordinates

The appropriate projection type is determined to be used within the scope of the project is oblique stereographic projection. In oblique stereographic projection, the deformation ellipse turns into a circle, and the projections of all circles on the sphere are also circles. In this projection, which accepts the polar point as the center, as the origin; the center that will be determined in the waters on which we will work has been selected. In this type of projection, deformation will increase as you move away from the pole point chosen as the center. However, the size of the area to be worked on in the project is sufficient to keep deformation to a minimum. At the same time, since it is conformal, the deformations are equal in the directions from the center to the coastlines. For example, from the place considered the midpoint of the Black Sea Basin; The deformation towards the Sochi region in the north-west direction will be equal to the deformation towards the Romanian coast in the west. For these reasons, the projection to be used in the study was chosen as an inclined angle-preserving (conform) azimuthal projection, also known as an oblique stereographic projection. Equations related to map projection are shown in Equations 7 – 12 (Uçar et al., 2004; Reerink et al., 2010).

$$\cos \delta_P = \sin \varphi_H \sin \varphi_P + \cos \varphi_H \cos \varphi_P \cos \Delta\lambda \quad \text{(Eq.7)}$$

$$\Delta\lambda = (\lambda_P - \lambda_H) \quad \text{(Eq.8)}$$

$$\tan \alpha_P = \frac{\sin \Delta\lambda}{\cos \varphi_H \tan \varphi_P - \sin \varphi_H \cos \Delta\lambda} \quad \text{(Eq.9)}$$

$$m_P = 2 \tan \frac{\delta_P}{2} \quad \text{(Eq.10)}$$

$$y_P = R m_P \sin \alpha_P \quad \text{(Eq.11)}$$

$$x_P = R m_P \cos \alpha_P \ * \quad \text{(Eq.12)}$$

x_P and y_P are cartesian coordinates of P in oblique stereographic projection. m_P is azimuthal polar coordinate. φ_P and λ_P are polar coordinates of the points. δ is the function of distance from the pole point (δ = 90° - φ) and α is azimuth. R is radius of the Earth and taken as 6 370 km.

Determination of the New Pole Point in Map Projection

After determining the map projection to be used in the project as an oblique stereographic projection, in order to make coordinate transformations; The approximate middle point of the working area should be selected, which will be considered as the new pole point of the projection. For this, previously selected control and test points were used. The average of these points, whose geographical coordinates are also known, was taken. In addition to this approach, other approaches can also be applied to determine the midpoint. However, in the selection of control and test points; since care was taken to ensure that the points were as homogeneous as possible, it was decided to use them.

$$\varphi_H = \frac{\sum_{i=1}^{n} \varphi_P}{n} \quad \text{(Eq.13)}$$

$$\lambda_H = \frac{\sum_{i=1}^{n} \lambda_P}{n} \quad \text{(Eq.14)}$$

φ refers latitude, λ refers to longitude of H (new pole point) and n refers to number of points. α_P refers to azimuth.

Experimental Results

The aim is the decrease the deformation of the area in terms of area. Black sea has the distance from equator and the north pole that is almost same. So, area deformation is increasing. For eliminating this, the polar point can be chosen as the middle point of the Black Sea The reason for determining new middle point for the projection is the more distance is from polar, the more deformation will be occurred).

By transferring the MODIS satellite image from raster format to vector format, a total of homogeneous distributed 36 points with known geographical coordinates were selected with the help of a map covering the entire study area on a closed shape formed by certain points with coordinates in a arbitrary local system. Control and test points were determined homogeneously distributed over the study area (Fig. 3). Firstly, the polar geographical coordinates of the control and test points with known geographical coordinates, 36 in total, were calculated. Then, stereographic coordinates were found with the help of polar geographical coordinates. Equations related to map projection were used for these calculations. Then, as a result of the calculations, oblique stereographic coordinates were obtained for these points.

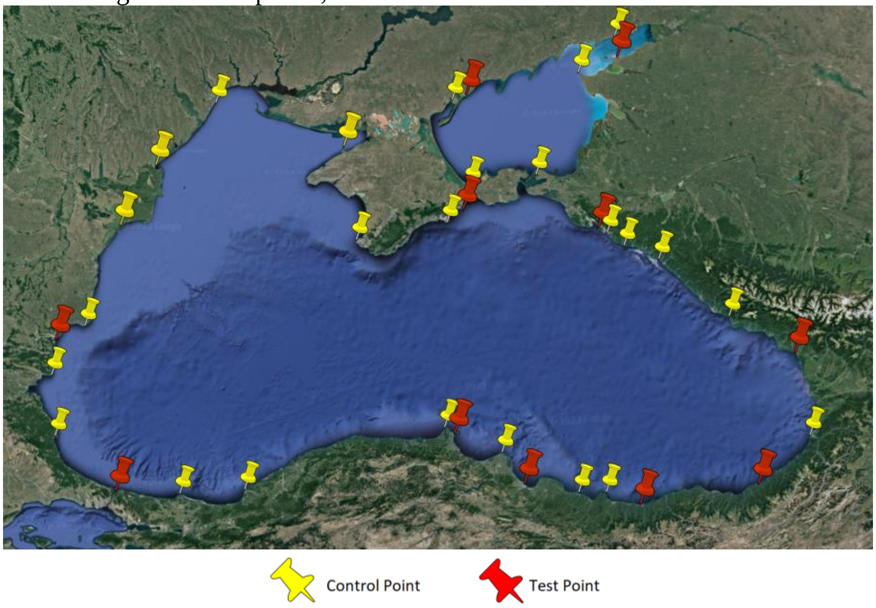

Fig. 3. Control and test points distribution for the 2D affine transformation.

To calculate the unknowns of the 2D affine transformation, 5, 10, 15, 20, and 25 points of the 36 points were used, respectively. 11 points were determined as test points for error calculation (Table 1). As the number of control points changed, new affine transformation parameters were calculated. Then, errors were calculated by transforming 11 test points. For error calculation, root mean square error (RMSE) was calculated separately between the point coordinates in the X direction and Y direction. RMSE is around 8.5 km in the X direction while around 9.5 km in the Y direction and approximately 13 km RMSE was obtained by using 25 control points. Following this determination, oblique stereographic coordinates were obtained for 5444 points with the help of 2D Affine transformation parameters (Fig. 4-8).

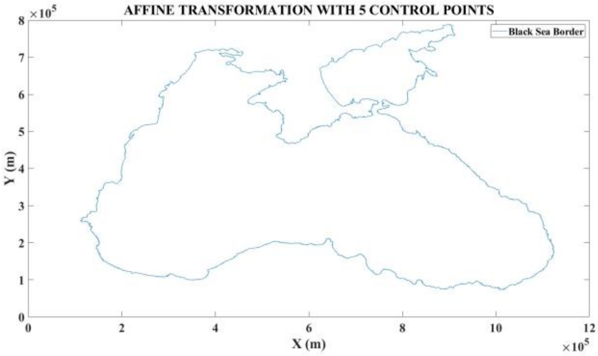

Fig. 4. Black Sea coastline resulting from the transformation of 5444 points with parameters calculated with 5 control points.

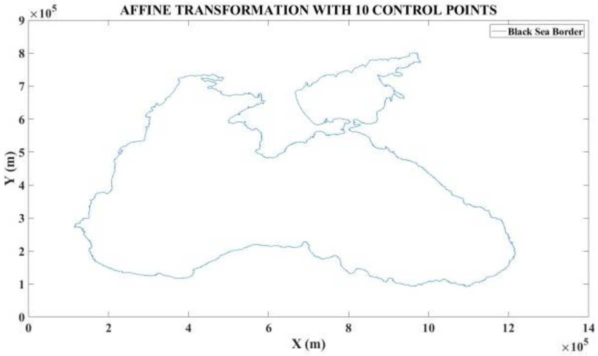

Fig. 5. Black Sea coastline resulting from the transformation of 5444 points with parameters calculated with 10 control points.

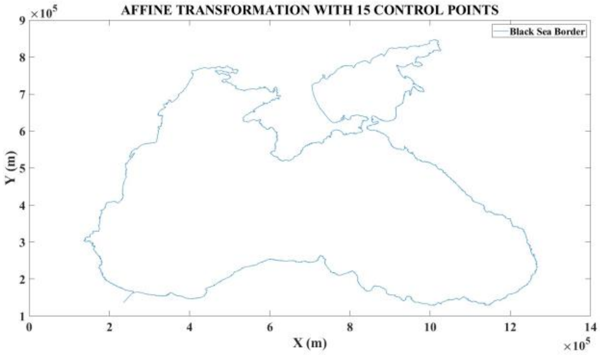

Fig. 6. Black Sea coastline resulting from the transformation of 5444 points with parameters calculated with 15 control points.

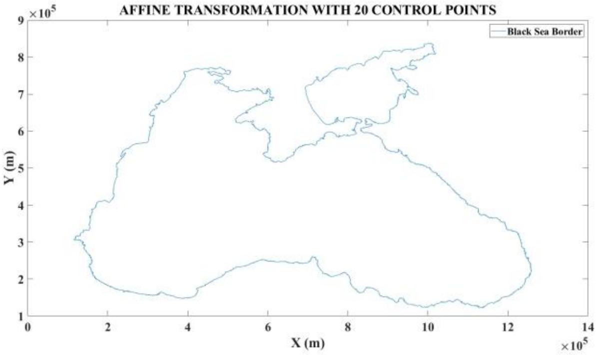

Fig. 7. Black Sea coastline resulting from the transformation of 5444 points with parameters calculated with 20 control points.

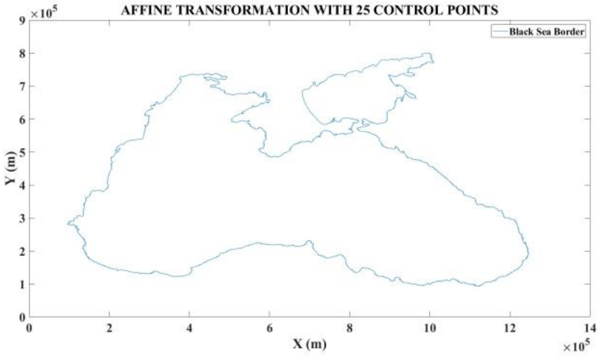

Fig. 8. Black Sea coastline resulting from the transformation of 5444 points with parameters calculated with 25 control points.

Table 1. RMSE based on the number control points that are used in 2D affine transformation.

Control Points	X (m)	Y (m)	Total (m)
5	8925.32	48625.28	49437.63
10	8211.40	24417.27	25761.02
15	10153.97	16524.72	19395.09
20	9016.11	12509.33	15419.91
25	8416.84	9696.58	**12840.05**

Table 2. Coastline lengths computed for the countries neighboring the Black Sea in stereographic projection.

Country	Coastal length (km)	Coastal length ratio
Türkiye	2068.42	0.26
Bulgaria	461.16	0.06
Romania	334.63	0.04
Ukraine	2870.14	0.36
Russia	1714.69	0.21
Georgia	541.52	0.07
Total	7990.58	

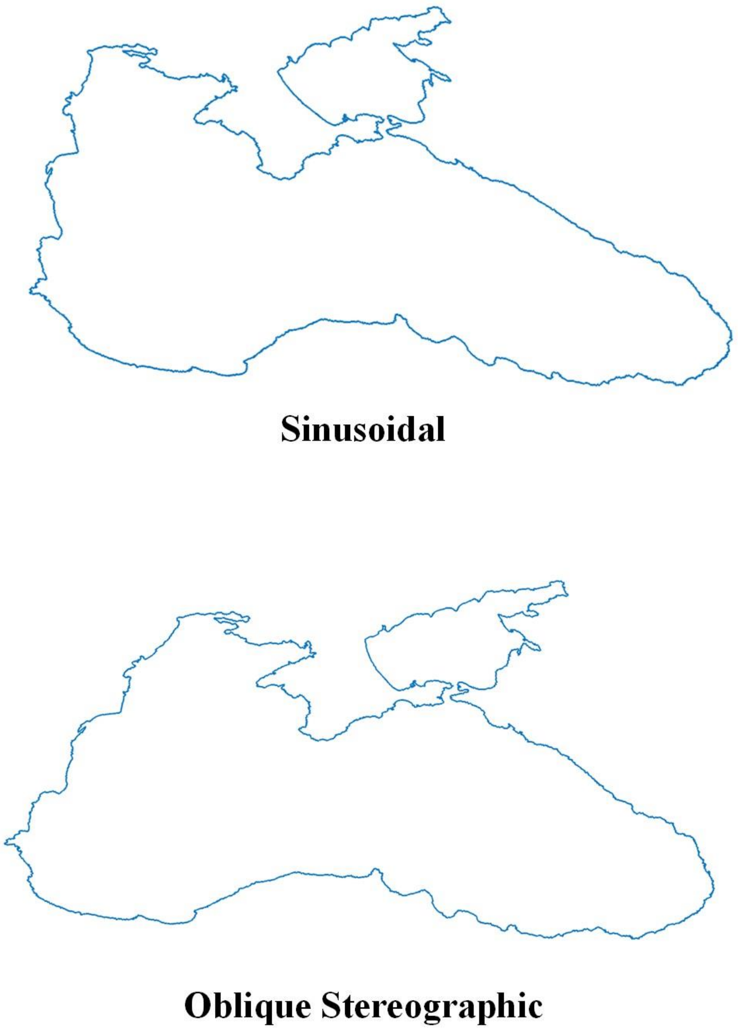

Fig. 9. Comparison of the coastline created by converting the coordinates in the sinusoidal projection into oblique stereographic projection with 25 control points.

Determination of Coastline Lengths

Coastal lengths for six countries bordering the Black Sea Basin or the Inner Sea of Azov were calculated with the help of the coordinates in the new projection. Accordingly, the coast lengths (S) of the countries are computed and are shown in the relevant column in Table 2. In addition, the coast lengths of the countries are proportional to the total coast length.

Discussion and Conclusion

In this study, 2D affine transformation was applied to transform the local coordinates determined from the satellite image into the system created by angle-preserving oblique stereographic projection to determine the coastline of the countries bordering the Black Sea that are Türkiye, Bulgaria, Romania, Ukraine, Russia, and Georgia. In order to make the coastline calculation correctly, the appropriate projection type was selected and the transformation was applied. An experiment was carried out to select the appropriate number of control points to determine the 6 parameters of the 2D affine transformation. The transformation of 5444 points used to digitize the coastline was carried out with the parameters calculated using 25 control points. According to the results, as the number of control points increases, total error of the transformation decreases drastically. Although the amount of error decreases as the number of control points increases, when 25 points are used, a sufficiently homogeneous distribution is achieved over the area and the amount of error converges. When 20 to 25 control points are distributed homogeneously, the change in the amount of error in the test points decreases with the affine transformation parameters obtained. More precise parameter calculations can be performed with more points. Since the dimensional change of the Black Sea along the Y axis is less, the amount of error in the Y axis increases when a small number of control points are used. As the number of points increases, the extension on the Y axis can be obtained more accurately. When the figures are examined, this inference can be noticed in the change of the Black Sea coastline (Fig. 9).

Determining the coastline with correct projection has the potential to provide a basis for a more reasonable solution, especially for determining the continental shelf. In determining the continental shelf; The proposal for possible sharing in varying geographies and in seas with different undersea natural resources can be prepared by the relevant countries and submitted to the International Court of Justice. For this reason, in this study, as an alternative to the general guidelines applied in other seas, due to the resources (hydrate gases, oil, etc.) that promise economic value in the future, a sea such as the Black Sea, which is coastal to more than two coastal states, is determined by the equitable distribution among six coastal states. It is aimed to determine the coastline lengths appropriately so that they are proportional to the coast lengths.

According to maritime law conventions, there are some procedures applied for equitable continental shelf distribution. However, in addition to all these, the geometric accuracy of the base maps on which the distribution will be made is as important as the distribution to be made. Because, as it is known, the deformations of the maps and their protected elements (angle, length and area) can be determined to a large extent with the effect of the map projection used. With the help of these calculations, it is very important to choose the appropriate map projection for the problem.

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