Determining Areas from Maps

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ABSTRACT. Today, when most spatial data is in digital form, polygon areas can be determined from maps made in any map projection because the digital format allows projection distortions to be eliminated during measurement. When determining areas from Google Maps and Google Earth, distortion-free values are obtained. Some GIS software (e.g. QGIS, ArcGIS online, Global Mapper) give areas on the ellipsoid as a result of the measurement. In addition, QGIS enables area calculation in the map projection of the map without considering the projection distortion. CAD software (e.g. AutoCAD Map) and cartographic software (e.g. OCAD) as a result of the measurement give the area in the map projection without taking into account distortions caused by the projection. In each of the specified software, the area of Greenland is determined on a map downloaded from Open-StreetMap in the Web-Mercator projection. If the area is calculated in the map projection in which the map was made, even if it is an equivalent projection, the sides of the boundary polygon must be short enough so that the geodetic line can be considered as mapped as a straightline segment. In addition, projection distortions should also be considered.

Keywords: map, area determination, map projections, Google Maps, Google Earth, QGIS, ArcGIS online, Global Mapper, AutoCAD Map, OCAD.

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1. Introduction

In mathematics, area is one of the basic values that characterizes a geometric figure in a plane or on a surface. In the simplest cases, the area is expressed by the number of unit squares that cover the figure in the plane. Area measurement and calculation have long been one of the most important tasks of practical geometry or land surveying.

Determining areas in geodesy includes procedures for measuring and calculating areas based on the data obtained by measuring in the field or on a plan or map. The following methods are used in practical geodesy: numerical, graphical, mechanical and combined methods. In more recent times, areas are determined using appropriate software, so we are often not even aware of which mathematical method or formula is behind the result obtained (Lapaine 2015).

Is it more correct to say area computation, calculation, measurement, or determination in geodesy and cartography, or perhaps some other way (Lapaine 1994)?

The terminology related to the determination of area in geodesy and cartography is not unique in other languages as well (Fachwörterbuch 1971). Thus, in German, for instance, we have: Flächenberechnung, Flächenbestimmung, in English: area measurement, area determination, area measurement by calculation, area calculation. In this paper, we will use the term area determination. Namely, if nowadays we want to find out the area of a territory unit, we will need the coordinates of points distributed along the boundary of that territory, followed by mathematical processing, i.e. calculation. We will take the coordinates from the appropriate database, which is usually in the map layer showing the area of interest and use the appropriate formula for the calculation or leave it to the selected software.

In addition, it is significant that when we talk about determining areas in geodesy, we usually mean the use of cadastral plans. In so doing, we tend to forget that areas are also determined from maps and that it is extremely important to consider the distortions caused by map projection. Since all plans and maps are made in a map projection, it is necessary to take into account the mentioned distortions when measuring from them.

By territorial unit we mean the part of the land or sea delimited by a boundary line that is closed, i.e. that begins and ends at one and the same point. By definition, the area of a territorial unit is the area of its projection on the reference ellipsoid. The boundary of a territorial unit on the Earth's surface (e.g., state, county, municipality, island, or lake) is usually approximated by a polygon. The polygon on the map is obtained by mapping the polygon from an ellipsoid. The sides of polygons on an ellipsoid are geodetic lines; thus such polygons are called geodetic polygons (Sjöberg 2006). Geodetic lines are mapped into the plane of the map projection as curves. In order to be able to use the usual formulas in calculating the area in the plane, the sides of the polygon must be short enough so that the geodetic line can be considered mapped as a straight-line segment.

In cartometry, a special branch of cartography, a number of different methods have been developed to determine areas from maps. Maling (1989) mentions,

among others, area determination based on simple geometric figures, by comparison with standard figures, the square method, the method of counting the nodes of a square grid, the method of measuring by going around the edge of the territory (planimetrics), the weighing method.

The invention of the digitizer in the 1960s made it possible to digitize the boundaries of a polygon whose area was to be determined. It so doing, it is necessary to transform the coordinates from the local digitizer system using identical points, e.g. the intersection of meridian lines and parallels, into the map projection system in which the map was made. From the coordinates thus obtained in the projection, it is possible to calculate the area of the polygon on the ellipsoid, not only from the equivalent but also from other projections if the projection distortions are eliminated.

Yildirim and Kaya (2008) compared polygon areas in 14 different equivalent projections. All polygons with an area of 0.0001 km² to 10,000 km² were given by the geographical coordinates of four points which were then transformed into 14 different equivalent projections using ArcGIS 9.0. They then calculated the areas on the ellipsoid. "The most correct solution of area calculation for large regions is the one based on ellipsoidal geographic coordinates. However, there is no tool offered in all GIS software packages for area calculations based on these coordinates because of its difficulty." Today, in 2021, QGIS, ArcGIS online and Global Mapper, for instance, have the ability to calculate areas on an ellipsoid (see Section 5 of this paper). For the smallest polygons the areas are equal to the areas on the ellipsoid, or the differences are negligible. For the largest polygon, in which the sides of the polygon are about 100 km, the difference amounts to 91,907 m² in the Behrmann projection (authors wrongly called it conical instead of cylindrical) to 12,308,502 m² in the equivalent cylindrical projection. The authors do not state the causes of such large area distortions in equivalent projections. It is obvious that the areas of polygons with sides up to 100 km in length cannot be measured on maps in equivalent projections because these sides are not projections of geodetic lines.

Looking for the most favourable equivalent projection in ArcGIS 10.3 for measuring the area of large forest parcels in Turkey, Yildirim et al. (2020) write: "In spite of the fact that the area-preserving projections are based on the principle to preserve area information, area deformation is inevitable to some extent (Snyder 1987, Bugayevskiy and Snyder 1995)." In neither of these two books have we found confirmation of their claim. For 25 parcels with an area between 339 ha and 2857 ha, they calculated the areas on the ellipsoid and then in six equivalent projections. The maximum difference from the area on the ellipsoid in, for example, the Albers equivalent conical projection is 65 m² for a 1292 ha parcel, and 489.7 m² for a 2424 ha parcel in the equivalent cylindrical projection. Since there is no data in the article on the length of the polygon sides on the ellipsoid, it is difficult to explain this difference.

In the following sections of this paper, we will give an overview of the software that can be used to determine the area of a territorial unit shown on the map. In so doing, we will specifically explore the possibility of each individual software for determining the area of a territorial unit on an ellipsoid. Before that, in Sections 2 and 3, we will recall how to determine area from a map regardless of the software used.

2. Determining Area from Maps

Let the polygon in Fig. 1 be obtained by mapping from an ellipsoid to a map made in a map projection. The area of a polygon on an ellipsoid can be calculated using the formula (Štemberger 1992):

$$P_E = 0.5 \sum_{i=1}^{i=n} (y_{i+1} - y_i)(x_i + x_{i+1}) / p_i \tag{1}$$

where x_i, y_i are rectangular coordinates of the vertices of a closed polygon in the projection plane and p_i the correction factor of individual summands due to the projection distortion. The area of the polygon P_E is obtained by adding the areas of the trapezoid made up by each individual side (Fig. 1), where the projection distortion is calculated successively for each trapezoid. In so doing, we have two assumptions. First, that the sides of the polygon are "short enough" to be good approximations of the images of geodetic lines in the projection, and second, that the trapezoids are "small enough" to be able to apply to them the factors of local area distortions p_i. Thus, using formula (1) we obtain the approximate value of the area of the polygon on the ellipsoid. The accuracy of the area thus obtained will depend not only on the above mentioned, but also on the accuracy of the coordinates of the vertices of that polygon (Lapaine et al. 1994).
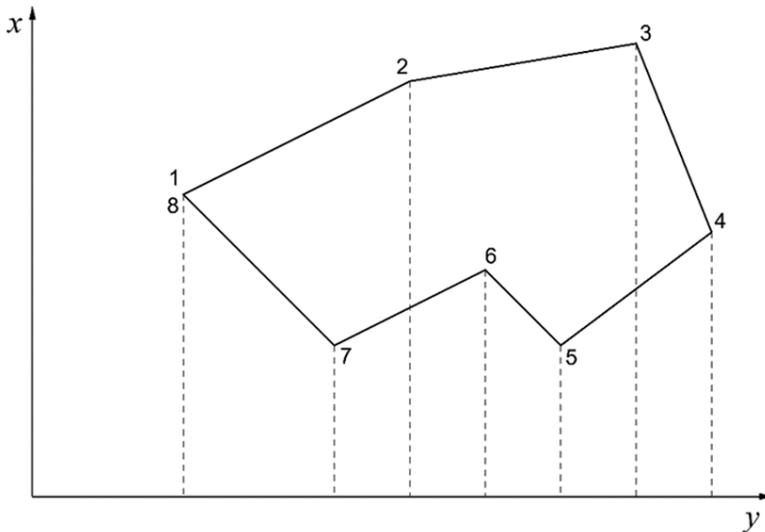

Fig. 1. *Polygon in a plane.*

In 1993, the Institute of Cartography of the Faculty of Geodesy, University of Zagreb, digitized the boundaries of Croatian municipalities from a 1:1,000,000 scale map made in the Gauß-Krüger i.e. conformal projection with the longitude of the central meridian $\lambda_0 = 16°30'$. The linear scale on the central meridian is $m_0 = 0.9997$. In total, about 19,000 points were digitized. The point file in the Gauß-Krüger projection was then obtained by using the Helmert transformation from a local digitizer system based on identical points (meridian and parallel intersections) (Frančula et al. 1993).

For the Gauß-Krüger projection with a linear scale on the central meridian 0.9997, the local linear scale m at an arbitrary point is equal to (Borčić 1976):

$$m = 0,9997 \left(1 + \frac{y^2}{2R^2} + \frac{y^4}{24R^4} \right),$$ (2)

where R is the mean radius of curvature of the ellipsoid at the observed point. Since y is always much smaller than R on the area of Croatia, R is taken to be a constant amount of 6,377,000 m. For conformal projections the local area scale is $p = m^2$, so

$$p = 0,9997^2 \left(1 + \frac{y^2}{R^2} + \frac{y^4}{3R^4} \right)$$ (3)

Given that the individual summand in formula (1) is the area of a very narrow trapezoid, it can be assumed in expression (1) that $p_i = p$, where p is determined by the expression (3), with $y = (y_{i+1} + y_i)/2$.

The area of the Republic of Croatia is determined as the sum of the areas of all municipalities, while the areas of individual municipalities were calculated using rectangular coordinates of points on their borders, taking into account the correction due to projection distortions. For the area of the mainland of Croatia, 56,488 km² were obtained, which differed by 50 km², or rather 0.1% from the then official data of 56,538 km². The area of the Croatian sea and the area of the 90 largest islands was also calculated (Frančula et al. 1993, Lapaine et al. 1993).

3. Determining Area from Maps in Equivalent Projections

Let the polygon in Fig. 1 be obtained by mapping from an ellipsoid to a map made in an equivalent map projection. The area of this polygon can be calculated using the formula (4):

$$P_E = 0.5 \sum_{i=1}^{i=n} (x_{i+1} - x_i)(y_i + y_{i+1}) \qquad (4)$$

This is formula (1) in which p_i =1 is set because it is not necessary to eliminate the projection distortions. It is necessary, however, as in non-equivalent projections, to consider the lengths of the sides of the polygon so that the sides in the projection can be considered as images of geodetic lines from an ellipsoid. The accuracy of the area thus obtained will also depend on the accuracy of the coordinates of the vertices of that polygon.

4. Determining Area using Google Maps and Google Earth

Google Maps and Google Earth have tools for measuring lengths and areas free from the effects of projection distortion. For example, to measure the area of Greenland on the world map in the Google Maps Web-Mercator projection, we right-click on the starting point and select *Measure Distance*. We roughly go around the coastline of Greenland and finish at the starting point. Then, the total length of the coastline of 8021 km and the area of 2,146,522 km² is written out in a special box. According to the Croatian Encyclopaedia (2021a), the area of Greenland is 2,166,086 km², so it is obvious that the area obtained is the approximate area of Greenland on the ellipsoid, thus an approximate distortion-free area. Let us mention that on the map in the Web-Mercator projection, the area of Greenland is approximately equal to the area of Africa, although it is about 14 times smaller. According to the Croatian Encyclopaedia (2021b), Africa has an area of 30,173,248 km².

To measure lengths and areas using Google Earth, select *Show ruler* on the toolbar. To measure the area, we choose *Polygon*, for the *Perimeter* (circumference) unit we choose kilometres, and for *Area*, square kilometres. We get 13 938 km for the length of the Australian coastline, and 7,599,812 km² for the area. According to the Croatian Encyclopaedia (2021c), the area of Australia is 7,623,623 km². Given that we measured on a small-scale map and only approximately went around the Australian coastline and that the measured area differs from the exact one by only 0.3%, we can conclude that the described measurement gave an approximate area of Australia on an ellipsoid (Frančula 2020).

5. Determining Area in GIS Software

5.1. Determining Area using QGIS

QGIS is free and open source GIS software licensed under the General Public License (GNL). It is the official project of the Open Source Geospatial Foundation (OSGeo). It operates on Linux, Unix, Mac OSX, Windows and Android. It supports many vector and raster formats and many database formats, and it contains many features and add-ons. It enables data visualization, editing and analysis and the creation of maps (QGIS 2021). The QGIS Desktop version 3.16.5 was used in this paper.

To determine the area of Greenland using QGIS, the OpenStreetMap layer was loaded, located between the layers in *XYZ Tiles*. Like Google Maps, Open-StreetMap is in the Web-Mercator projection (in QGIS it is defined as the Pseudo-Mercator projection).

Using QGIS it is possible to determine distances and areas that are free from the influence of projection distortions. When calculating the area of Greenland in the Web-Mercator projection, in the *Project Properties – General* dialogue box, the ellipsoid WGS 84 was selected in the *Measurements* section. In the same box, units of measure for calculating distances and areas (kilometres and square kilometres) are selected.

The *Attributes Toolbar* contains tools for measuring lengths, areas, and angles. Selecting the *Measure Area* tool opens the *Measure* box, in which you can select the measurement of areas in the projection plane or on the ellipsoid. The same box contains information about the selected ellipsoid and in which units the areas will be measured. To measure the area of Greenland we left-click the starting point and approximately follow the coastline of Greenland, finishing the measurement at the starting point by right-clicking. The frame shows an area of 2,169,398 km^2 (Fig. 2), which means that the approximate area of Greenland on the ellipsoid is obtained and that this area is free from the influence of projection distortions.
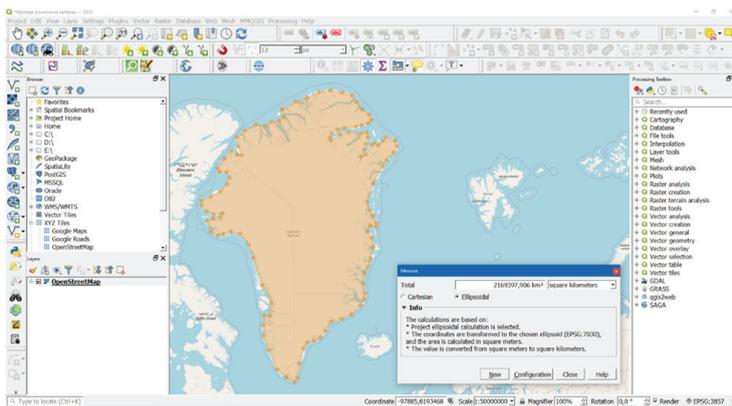

Fig. 2. *Determination of the area of Greenland using QGIS.*

If in the *Project Properties – General* dialogue box, in the *Measurements* section we select *None / Planimetric*, and area measurement on the ellipsoid remains selected in the *Measure* box, then the box says that no ellipsoid is selected and that the area calculation will be performed in the project reference coordinate system. Based on the above settings, the area of Greenland is 35,922,290 km² (Fig. 3), from which it can be concluded that the distortions of the Web-Mercator projection were not taken into account when measuring the area. The same value for the area of Greenland is also obtained by selecting the *Cartesian* option.
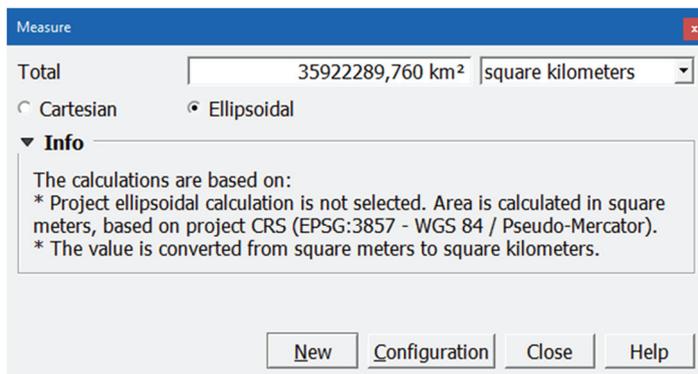

Fig. 3. *The print-out of the area of Greenland in the Web-Mercator projection, obtained using QGIS.*

5.2. Determining Area using Online ArcGIS

ArcGIS Online is geospatial cloud-based software that enables the use, creation and sharing of maps, scenes or applications. It can be used standalone or extended with other ArcGIS products such as ArcGIS Desktop, ArcGIS Server, ArcGIS Web API, ArcGIS SDK and others. Unlimited use of any product from the ArcGIS software is possible during the free trial period, but a license (ArcGIS Online 2021a) is required for permanent use. For use in teaching and research projects, students and teachers of the Faculty of Geodesy, University of Zagreb, have at their disposal 100 licenses donated by the company GDi Zagreb.

Map Viewer is used for data visualisation, and the uploaded data is displayed in the Web-Mercator projection (the ESRI documentation states "Web Mercator Auxiliary Sphere").

It is possible to determine the linear distance, area and circumference from a map using a measuring tool (ArcGIS Online 2021b). The Map Viewer calculates the shortest ellipsoidal distance. The default units of measurement can be changed during the measurement.

To determine the area of Greenland using Online ArcGIS, the map must be loaded in the Web-Mercator projection into Map Viewer. Launching the *Mea-*

sure command on the tool bar opens a window that offers the option to specify linear distances, areas, and circumferences.

You start the procedure by left-clicking on the starting point, drawing the line in an arbitrary path. Left-clicking the mouse adds connection points, while measurement is ended by a quick double-click. The results are displayed at the bottom of the measurement window.

For the area of Greenland (Fig. 4) a value of 2,195,320 km^2 was obtained, which is the approximate value of the area of this island.
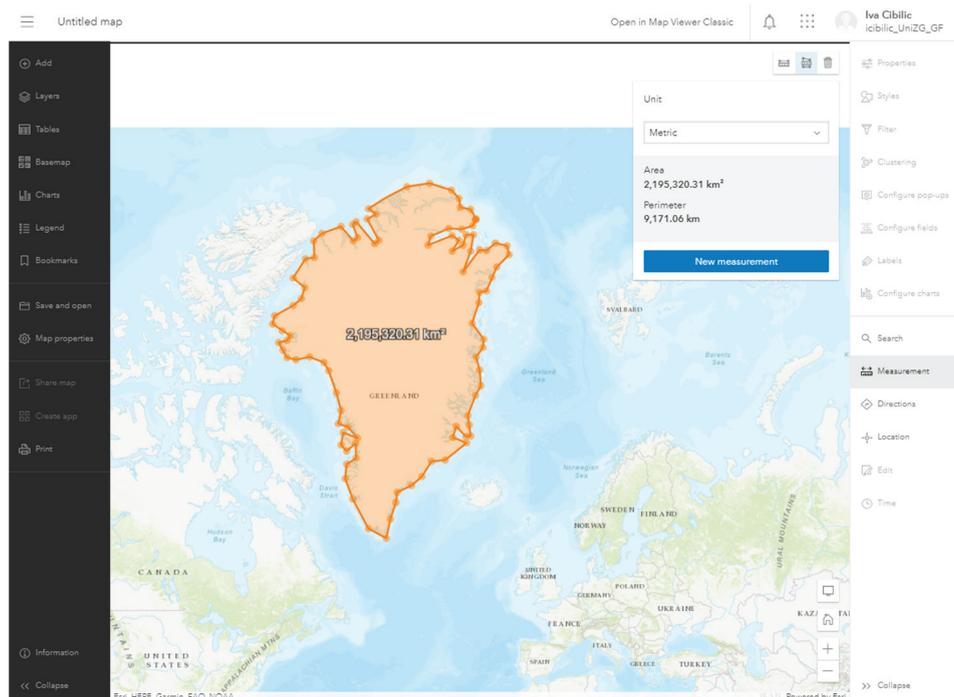

Fig. 4. *Determination of the area of Greenland using Online ArcGIS.*

ArcGIS Online does not have the ability to determine the area in the projection plane. This feature is only available in desktop products, ArcGIS Map (ArcMap 2020) and ArcGIS Pro (ArcGIS Pro 2021).

5.3. Determining Area using Global Mapper (trial version)

Global Mapper® is Blue Marble Geographics GIS software that includes a number of spatial data processing tools with access to a wide variety of data formats (Global Mapper 2021).

As in the previous measurement of the area of Greenland using QGIS, a WMS layer was added, i.e. an OpenStreetMap in the Pseudo-Mercator projection (EPSG: 3857). After that, the Greenland coastline was approximately vectorized on a computer screen.

Now with the simple *Feature information* (Alt + P) command and by selecting Greenland you can read all the information about that object, including its area. In this case, an area of 2,091,080 km^2 was determined (Fig. 5). Thus, the approximate area of Greenland on the ellipsoid was obtained.
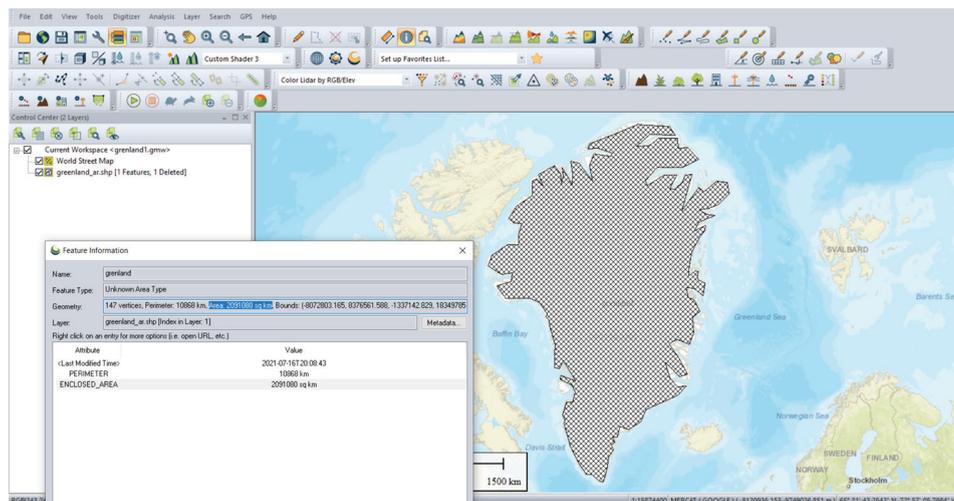

Fig. 5. *Determination of the area of Greenland using Global Mapper.*

6. Determining Area using Cartographic Software

6.1. Determining Area using OCAD

OCAD is a commercial software from Switzerland that serves primarily for creating maps; it supports a number of vector and raster formats and many database formats, and it contains many features and add-ons. It enables data visualization, editing and analysis and map creation, although it is not primarily a GIS or analytical tool. Version 12 was used.

As with previous Greenland area determinations, a layer was added from OpenStreetMap in the Pseudo-Mercator projection.
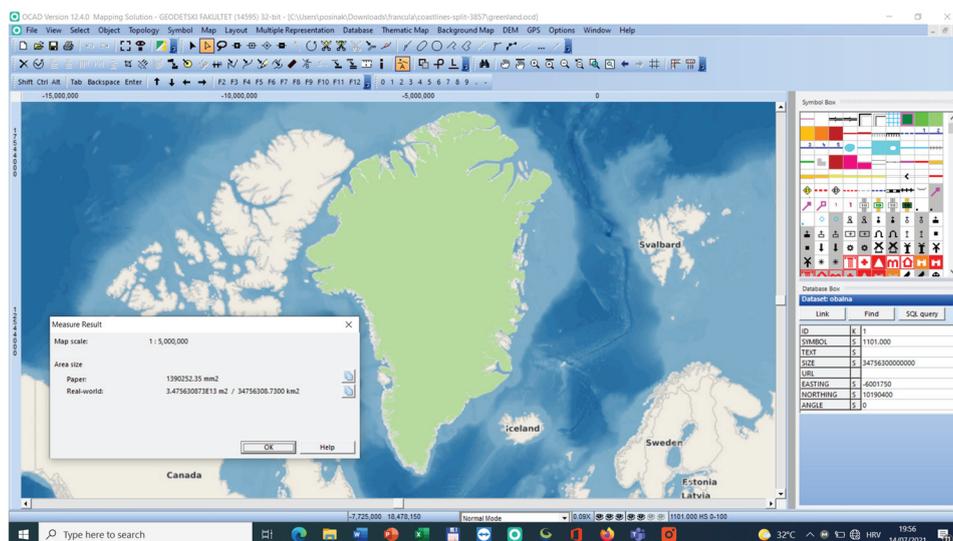
Fig. 6. *Determining the area using OCAD.*

OCAD enables reading the length and area using the *Measure* command. As can be seen in Fig. 6, an area of 34,756,309 km² was read, so that in measuring the area, the Web-Mercator distortions were not considered. Unfortunately, the mentioned software has no possibility of determining areas which would give the area on an ellipsoid.

7. Determining Area in CAD Software

7.1. Determining Area using AutoCAD Map 3D

AutoCAD Map 3D is a commercial CAD (Computer-Aided Design) software from the Autodesk corporation. AutoCAD is the best known and most widely used software in the field of computer-aided technical drawing. AutoCAD Map 3D is an upgrade of AutoCAD because it contains tools for working with spatial data; it supports all major raster and vector formats and enables GIS analysis and mapping (Autodesk 2021). The current version of AutoCAD Map 3D is included in AutoCAD 2022 and AutoCAD Civil 3D 2022, while it could be downloaded as a separate program in the previous versions of AutoCAD Map 3D. The AutoCAD Civil 3D 2022 version was used in this paper.

In order to measure the area of Greenland using AutoCAD Map 3D, we loaded OpenStreetMap as a layer, i.e. we added a WMS layer to the workspace. By doing this, we changed the initially offered EPSG:4326 (WGS84) to EPSG:3857,

i.e. to the Pseudo-Mercator projection. After loading the base layer, we drew the coastline of Greenland with 250 breaking points. Using the *Area* command, the area was measured within the enclosed polyline, amounting to 35,489,308 km^2 (Fig. 7). This means that the total area was obtained in the plane of the Web-Mercator projection without taking distortions into account. In addition, we searched relevant available information on the Internet to determine whether there is a possibility of measurement that gives the area on the ellipsoid, but to our knowledge this possibility is not supported.
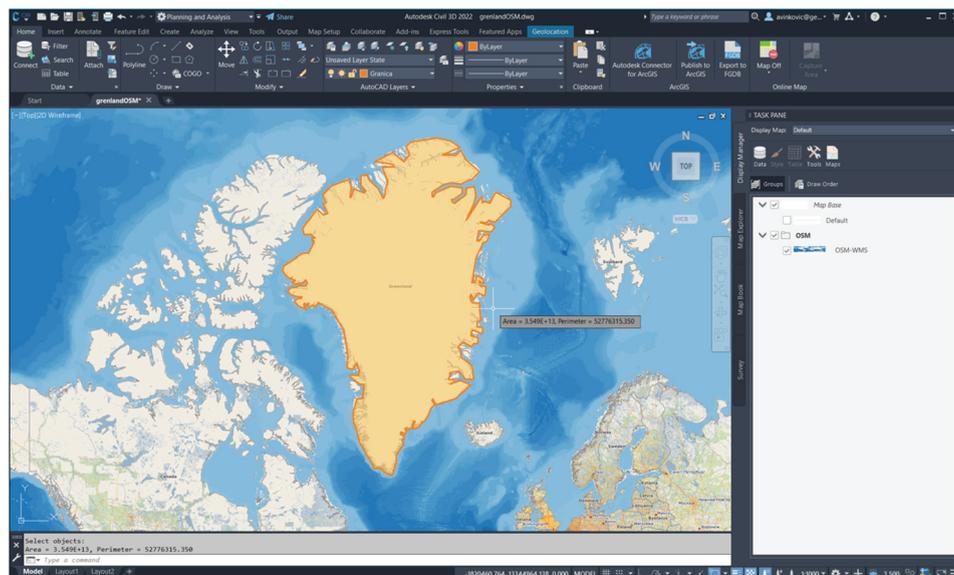

Fig. 7. *Determining the area using AutoCAD Map.*

8. Conclusion

Today, when most spatial data is in digital form, areas of territorial units can be determined from maps in any map projection because the digital form theoretically allows projection distortions to be eliminated during measurement. Google Maps, Google Earth, and GIS software give areas on the ellipsoid (Table 1). We cannot conclude with certainty whether calculation on the ellipsoid was applied, e.g. according to Sjöberg's formulas (2006), or whether the calculation was performed in the projection plane considering the projection distortions.

Table 1. *Analysed software and their possibilities for area determination.*

Software	Determination of the area considering projection distortion	Determination of the area without considering projection distortion
Google Maps	yes	no
Google Earth	yes	no
QGIS	yes	yes
ArcGIS Online	yes	no
Global Mapper	yes	no
OCAD	no	yes
AutoCAD Map 3D	no	yes

The area of a territorial unit is the area of its projection on the reference ellipsoid. The boundary of a territorial unit on the Earth's surface is usually approximated by a geodetic polygon, and the polygon on the map is obtained by mapping that polygon from an ellipsoid into a plane.

Therefore, determining the area of a territorial unit is not an easy task. If we solve this task using software, we need to know the answers to the following questions:

- Will the result be an area on the ellipsoid or in the projection plane without considering projection distortions?
- How does the software realize the sides of the polygon: as straightline segments or as geodetic lines?
- How does the length of the polygon sides affect the area value?
- What is the accuracy of the obtained area?
- How does the accuracy of polygon vertices affect area accuracy?

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Određivanje površina s karata

SAŽETAK. Danas, kada je većina prostornih podataka u digitalnom obliku, površine poligona moguće je određivati s karata izrađenima u bilo kojoj kartografskoj projekciji jer digitalni oblik omogućuje da se pri mjerenju eliminiraju deformacije projekcije. Pri određivanju površina s karata Google Mapsa i Google Eartha dobivaju se vrijednosti oslobođene deformacija zbog kartografske projekcije. I neki GIS softveri (npr. QGIS, ArcGIS online, Global Mapper) kao rezultat mjerenja daju površine na elipsoidu. Uz to QGIS omogućuje i računanje površine u kartografskoj projekciji karte bez uzimanja u obzir deformacije zbog projekcije. CAD softveri (npr. AutoCAD Map) i kartografski softveri (npr. OCAD) kao rezultat mjerenja daju površinu u kartografskoj projekciji karte bez uzimanja u obzir deformacije nastale zbog projekcije. U svakom od navedenih softvera određena je površina Grenlanda na karti preuzetoj s OpenStreetMapa u web-Mercatorovoj projekciji. Ako se površina računa u kartografskoj projekciji u kojoj je izrađena karta, pa bila to i ekvivalentna projekcija, stranice graničnog poligona moraju biti dovoljno kratke da se može smatrati da se geodetska linija preslikala kao dužina i uz to treba uzeti u obzir deformacije zbog projekcije.

Ključne riječi: karta, određivanje površina, kartografske projekcije, Google Maps, Google Earth, QGIS, ArcGIS online, Global Mapper, AutoCAD Map, OCAD.