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NGA STANDARDIZATION DOCUMENT

Map Projections for GEOINT Content, Products, and Applications
(2017-12-13)

Version 1.0

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NATIONAL CENTER FOR GEOSPATIAL INTELLIGENCE STANDARDS

Forward

This Standardization Implementation Guidance (SIG) document is approved for use by all Departments and Agencies of the Department of Defense.

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Change Log

Version	Approval Date	POC	Change Description
	2017-12-13		*Initial Release*

TBD/TBR Log

TBD/TBR	Paragraph	Description
Appendix A	All	*Analysis of additional map projections will be added in future versions of this document.*

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1 Scope

This Standardization Implementation Guidance (SIG) document describes the key properties, characteristics, and recommended uses for systems developers and analysts of the many map projections appropriate for GEOINT data. The goal of this document is to help form the framework of interoperability for military mapping and GEOINT analysis. Consistency, interoperability, and maintainability are desired across systems and services. This document will present evidence that the map projections best suited to these needs are the conformal map projections.

- Sections 4 through 11 present general descriptions and information on map projections and usages. These sections provide the foundation layer of common techniques, methods, and guides to algorithms ensuring that geospatial data can be clearly delivered, depicted, and evaluated for a desired purpose.
- Section 12 provides NGA's recommendations of map projections and usages. These recommendations are based upon NATO recommendations on map projections.
- Section 13 offers some user scenarios showing the implications of following or not following the recommendations in Section 12.
- Appendix A suggests a general method using UTM squares by which cartographers and analysts can ascertain how well chosen are their map projections for large scale work.

This document contains many references to other NGA documents and external public documents that provide more detailed information and algorithms on map projections. It is considered high-level in that it is not directed at specific systems. The DoD and IC members should review the recommendations in this document for new and life-cycle upgrades to systems, operational procedures, and content holdings.

2 References

The documents listed below are not necessarily all of the documents referenced herein, but are those needed to understand the information provided by this SIG document.

2.1 Government specifications, standards, and handbooks

- NGA.STND.0036_1.0.0_WGS84, Department of Defense World Geodetic System, 2014-07-08
- NGA.SIG.0012_2.0.0_UTMUPS, The Universal Grids and the Transverse Mercator and Polar Stereographic Map Projections, 2014-03-25
- NGA.SIG.0014_1.0_PROJRAS, Map Projections for Tiled Raster Graphics, 2015-04-24
- NGA.STND.0037_2.0.0_GRIDS, Universal Grids and Grid Reference Systems, 2014-02-28
- NGA.STND.0051_2.1_GEOPKG, National System for Geospatial-Intelligence (NSG) GeoPackage Encoding Standard 1.1 Interoperability Standard, 2017-08-10
- Mensuration Services Program (MSP), MSP Geographic Translator (GEOTRANS), National Geospatial-Intelligence Agency
- NATO Standard, AGeoP-21, Geodetic Datums, Projections, Grids and Grid References, Edition A Version 1, February 2016
- Snyder, John P. , *Map Projections — A Working Manual*, U.S. Geological Survey Professional Paper 1395, United States Government Printing Office, Washington, D.C., 1987

- Snyder, John P. and Voxland, Philip M., *An Album of Map Projections*, U.S. Geological Survey Professional Paper 1453, United States Government Printing Office, Washington, D.C. 1989

2.2 Non-government publications

- International Association of Oil and Gas Producers (IOGP), Publication 373-7-2 – Geomatics Guidance Note number 7, part 2 – September 2016
- International Association of Oil and Gas Producers (IOGP), Publication 373-23 – Web Mercator – September 2016
- International Standards Organization (ISO/IEC) 18026:2009I, Spatial Reference Model (SRM), Edition 2, 2009-07-15
- Kennedy, Melita, and Kopp, Steve, Understanding Map Projections, ESRI Press, 1994
- Iliffe, Jonathan and Lott, Roger, *Datums and Map Projections:* For Remote Sensing, GIS and Surveying, Whittles Publishing, distributed in North America by CRC Press, Taylor and Francis Group, Boca Raton FL 33487, 2008
- OGC 12-128r14 OGC® GeoPackage Encoding Standard version 1.2, 2017
- OGC 07-057r7 OpenGIS Web Map Tile Service Implementation Standard version 1.0 (6 April 2010)
- OGC Web Map Tile Service (WMTS) Simple Profile 13-082r2 version: 1.0 (19 Jan 2016)

3 Terms, Definitions and Acronyms

3.1 Terms and definitions

The terms and definitions used in this document are given in Table 1.

Table 1 – Terms applicable to this specification

Term	Definition
accuracy	The closeness of agreement between a test result or measurement result and the true value [ISO 6709:2008]
anti-meridian	Meridian at 180° difference in longitude (modulo 360°) from a given meridian
antipodal point	On a circle or sphere, the point diametrically opposite a given point
coordinate	One of a sequence of *n* numbers designating the position of a point in *n*-dimensional space [ISO 19111:2007] NOTE: In a coordinate reference system, the coordinate numbers are qualified by units.
coordinate reference system	A coordinate system that is related to a (physical) object by a datum. [ISO 19111:2007]
coordinate system	A set of mathematical rules for specifying how coordinates are to be assigned to points [ISO 19111:2007]

datum	A parameter or set of parameters that define the position of the origin, the scale, and the orientation of a coordinate system
easting	The distance in a coordinate system, eastwards (positive) or westwards (negative) from a North-South reference line [ISO 19111:2007] NOTE: In use, the first of two coordinates which comprise a Cartesian system for the plane of a map projection, typically increasing in an eastward-like direction.
ellipsoid	Surface of revolution that serves as a geometric model of the size and shape of the Earth and adopts (i) an ellipse as its profile curve, (ii) the radius of the Equator as its semi-major axis and (iii) a number close to 300 for its inverse flattening. For the WGS 84 ellipsoid, the inverse flattening is 298.257223563.
flattening	The ratio $(a - b)/a$ where a is the semi-major axis and b is the semi-minor axis of an ellipsoid model the Earth
geocentric coordinate system	An Earth-centered Cartesian 3D coordinate system where the Z-axis is aligned with the Earth's rotation axis, the X-axis lies within the equatorial plane and a plane containing the prime meridian, and the Y-axis is such that (X,Y,Z) forms a right-handed coordinate system
geodetic coordinate system	A coordinate system based on a reference ellipsoid as an approximation to the shape of the Earth. The position of a point relative to the ellipsoid is given by the triple, (λ, φ, *h*), where λ is the geodetic longitude, φ is the geodetic latitude, and *h* is the height of the point above the ellipsoid (taken perpendicularly to the ellipsoid).
geodetic datum	A datum describing the relationship of a two- or three-dimensional coordinate system to the Earth [ISO 19111:2007]
(geodetic) latitude	The angle from the equatorial plane to the perpendicular of the ellipsoid through a given point with northwards treated as positive [ISO 19111:2007] NOTE: Symbolized as φ (Greek letter 'phi').
(geodetic) longitude	The angle from the prime meridian plane to the meridian plane of a given point with eastwards treated as positive [ISO 19111:2007] NOTE: Symbolized as λ (Greek letter 'lambda').
graticule	Curves (possibly straight) on a map representing selected meridians and parallels, and usually chosen at intervals of the same number of degrees
grid	Two sets of parallel lines intersecting at right angles and forming squares [CJCSI 3900.01D] NOTE: A grid is superimposed on maps, charts and other similar representations of the Earth's surface in an accurate and consistent manner to permit identification of ground locations with respect to other locations and the computation of direction and distance to other points.

grid north	The direction given by the positive *y*-axis, typically a small acute angle from true north, when grid coordinates (*x,y*) are defined for a portion of the Earth.
inverse flattening	Reciprocal of the flattening
magnetic north	The direction indicated by the north seeking pole of a freely suspended magnetic needle, influenced only by the Earth's magnetic field.
map projection	A set of mathematical algorithms and associated parameters that establish a systematic, one-to-one correspondence between points on the surface of an ellipsoid and points on a plane while controlling the resulting geometric distortions [CJCSI 3900.01D]
meridian	On the ellipsoid model of the Earth, a curve of constant longitude
north	See grid north, magnetic north, true north
northing	The distance in a coordinate system, northwards (positive) or southwards (negative) from an east-west reference line [ISO 19111:2007] NOTE: In use, the second of two coordinates which comprise a Cartesian system for the plane of a map projection, typically increasing in a northward-like direction.
parallel	See parallel circle
parallel circle	On the ellipsoid model of the Earth, a curve of constant latitude
precision	(i) A measure of the repeatability of a set of measurements [ISO 6709:2008] (ii) A quantization of the sensitivity of the device by which a measurement was made (iii) The number of digits carried through in a calculation or series of calculations
true north	The direction from an observer's position to the geographic North Pole. The north direction of any geographic meridian
World Geodetic System 1984	The Earth-centered, Earth-fixed, geodetic datum developed and maintained by NGA for the U.S. Department of Defense and its allies Note: Also called "WGS 84".

3.2 Acronyms

The acronyms that are used in this standard are given in Table 2.

Table 2 – Acronyms applicable to this document

AoI	Area of Interest
CORS	Continuously Operating Reference Station(s)
CRS	Coordinate Reference System

DoD	(U.S.) Department of Defense
EPSG	European Petroleum Survey Group
GEOINT	Geospatial Intelligence
GEOTRANS	MSP Geographic Translator
GIS	Geographic Information System
GPS	Global Positioning System
IC	Intelligence Community
IOGP	International Association of Oil and Gas Producers
ISO	International Standards Organization
MSP	Mensuration Services Program
NAD 83	North American Datum of 1983
NGA	National Geospatial-Intelligence Agency
SRM	Spatial Reference Model
UPS	Universal Polar Stereographic
UTM	Universal Transverse Mercator
WGS 84	World Geodetic System 1984

4 General Considerations

Specific map projections will be discussed, beginning in Section 5. To avoid repetition, and to define helpful categories, various common characteristics and various commonly adopted specifications of map projections are introduced in this section.

4.1 Datum

Throughout this document, it is assumed that the latitude and longitude used as input to the map projection is provided by the WGS 84 datum.

The latest realization of WGS 84 is WGS 84 (G1762). The “G” indicates that GPS measurements were used and the number following the “G” indicates the GPS week number in which the new realization was adopted by NGA for its GPS ephemeris production.

For many purposes, WGS 84 (G1762) is indistinguishable from its predecessors: WGS 84 (G1674), WGS 84 (G1150) and others. Additionally, for mapping and charting purposes at scales 1:25,000 and smaller, WGS 84 in any of its realizations is indistinguishable from North American Datum of 1983 (NAD 83) and its realizations – for example NAD 83 (CORS 96). Guidance about this topic is beyond the scope of this document.

4.2 Ellipsoid

Throughout this document, it is assumed that the map projection applies to the ellipsoid model of the Earth, in particular, the WGS 84 ellipsoid defined by semi-major axis $a = 6378137$ meters and the inverse flattening $f^{-1} = 298.257223563$.

Regardless of whether or not the **procedure** of the map-projection (set of formulas) is borrowed from theories about mapping a sphere to a plane, the **properties** of the map projection will refer to the WGS 84 ellipsoid. In other words, when asking whether the portrayals of distances, angles, and areas on the map are accurate, the comparisons will be made to the corresponding distances, angles and areas on the ellipsoid. With the advent of internet mapping and the web Mercator projection, there is a greater need to be clear about this. The procedure of web Mercator is borrowed from conformal math to go from the sphere to the plane, but the properties of web Mercator will refer to the ellipsoidal model of the earth.

4.3 Relationship of spherical models to datum and ellipsoid

This document assumes that every map projection is a map projection applicable to the WGS 84 ellipsoid. The concept of a map projection is very general and allows that formulas borrowed from other circumstances (*e.g.* spherical models of the earth) can form an unambiguous map projection of the earth (WGS 84 ellipsoid model of the earth). This can be done, but two implied questions have to be answered:

- What is the radius of the sphere to be used?
- Given that the latitude on the sphere is different from the latitude on the ellipsoid, is any conversion to be performed between the latitude on the ellipsoid (obtained from the WGS 84 datum) and latitude on the sphere? Fig. 1. Latitude on the sphere compared to latitude on the ellipsoidillustrates the latitude on the two surfaces. (The ellipsoid's flattening is greatly exaggerated).

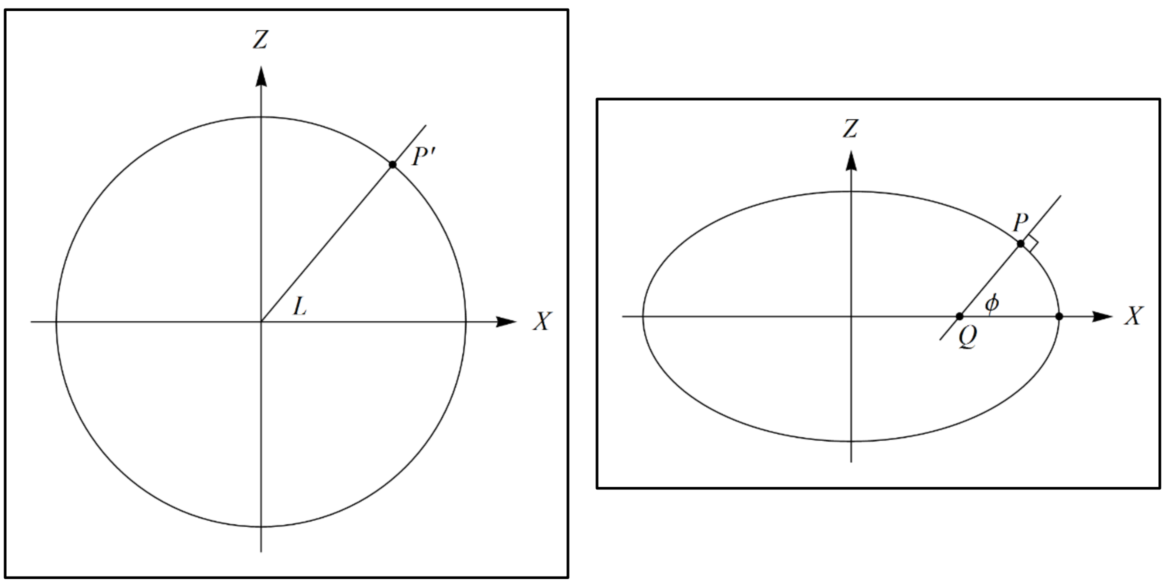

Fig. 1. Latitude on the sphere compared to latitude on the ellipsoid.

System developers and analysts should be aware that in many GIS components, the default conversion is to merely copy the WGS 84 latitude and use it as the latitude on the sphere, *i.e.* $L = \phi$. These two questions are pertinent to all instances for which system developers and analysts, desiring simplicity, adopt a spherical model of the Earth.

The application of a datum transformation is strictly to resolve the discrepancy between varying historical definitions of latitude and longitude on the ellipsoid. A datum transformation should not be used to adapt spherical formulas to a map projection of the ellipsoid. The adaption of spherical formulas should be considered part of the map projection logic and procedure rather than a datum transformation. Therefore, web Mercator and other map projections that have adapted formulas originally intended for the sphere are consistent with the WGS 84 datum, if the provenance of the latitude and longitude is the WGS 84 datum.

4.4 Conformal projections

A map projection is conformal if it has at least one of the following properties (each property implies the other two):

- Small areas are preserved in shape
- Angles of intersection are preserved between linear features, such as roads, political boundaries, ground tracks of airplanes, meridians, and parallels
- The local scale function is independent of direction. For example, on a large-scale city map, (city block map), the scale bar for North-South is the same as the scale bar for East-West.

A map projection is non-conformal if it has none of the above properties. No map projection can be both conformal and equal area (Snyder p.4).

4.5 Equal area projections

A map projection is equal area ("authalic") if the area of any shape has the same number of square kilometers (km^2) on the (conceptual) map as it does on the ellipsoid.

If the areal scale is not 1:1, such as paper maps to be printed, then "equal area" means this: any two regions that have the same area (km^2) on the ellipsoid also have the same area (cm^2) on the map.

No map projection can be both equal area and conformal (Snyder p.4).

4.6 "Equidistant" projections

Unlike "conformal" and "equal area", the adjective "equidistant" by itself is ambiguous. For the cylindrical, polar azimuthal, and conic families of projections, there are two common interpretations of "equidistant" and they need to be defined separately – "equidistant-by-latitude" and "equidistant-by-arclength". See Fig. 2. What they have in common is that each determines the spacing of the parallels for these families of projections. Here are the definitions:

- <u>Equidistant-by-latitude:</u> A map projection within the cylindrical, polar azimuthal, or conic families of projections is equidistant-by-latitude if the parallel circles are equally spaced on the map for equal intervals of latitude.

- <u>Equidistant-by-arclength:</u> A map projection within the cylindrical, polar azimuthal, or conic families of projections is equidistant-by-arclength if it preserves arclength along a meridian (any meridian). In consequence, the parallel circles are equally spaced on the map for equal lengths of intercepted arcs of a meridian.

For small-scale mapping, these concepts are equivalent in practice, but large-scale mapping will show the difference. The difference should be understood this way: On the ellipsoid, because of its flattening, a selection of parallel circles chosen at equal intervals of latitude are spaced wider apart near the Poles (as measured in meters along a meridian) than near the Equator. Therefore, on an equidistant-by-arclength projection, they will be wider apart near the Poles than near the Equator. By contrast, the same selection of parallel circles are spaced equally apart on the equidistant-by-latitude projection.

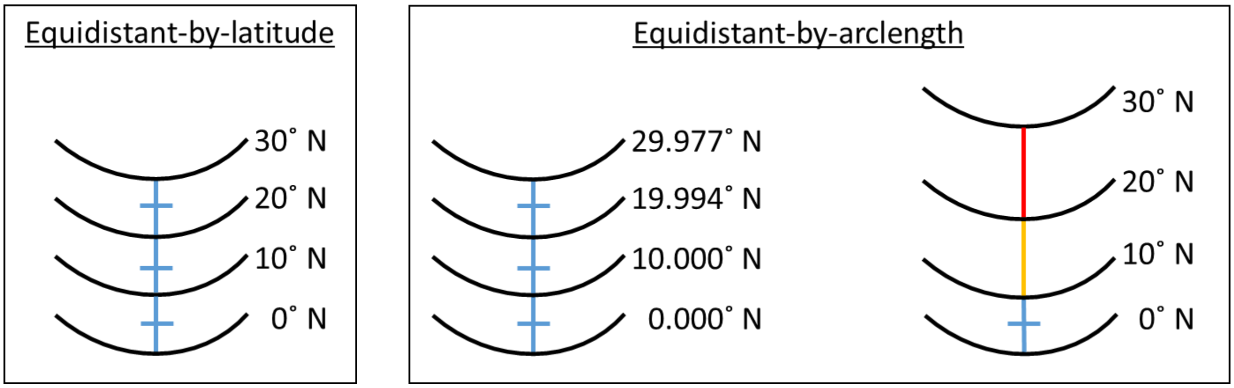

Fig. 2. Equidistant projections.

The differences between the two interpretations of equidistant. Both are valid, but the choice needs to be specified. The blue segments represent equal distances on the map. The yellow and red segments are exaggerated, but show the increasing lengths of central meridian segments.

4.7 Cylindrical projections

Map projections in this class have these properties:

- The meridians are represented as vertical straight lines
- The meridians are spaced equally for equal intervals of longitude
- The parallels are horizontal straight lines
- The spacing of the parallels depends on the particular projection. The specification to be conformal determines this spacing. Likewise the specification to be equidistant (either definition, see above) determines this spacing. Area-preservation ("equal area") is a looser requirement that does not, by itself, determine this spacing.

4.8 Polar azimuthal projections

Map projections in this class have these properties:

- One pole is represented as a single point on the map. If the other Pole is represented, it will be a circle.
- The meridians are represented as straight lines emanating from the portrayed Pole like the spokes of a wheel. One of them, the "central meridian", is vertical on the map.
- The angle on the map between two meridians equals their difference in longitudes
- On the map, the parallels are (complete) circles whose center is the Pole
- The spacing of the parallels – which radius to use to draw the parallels – depends on the particular projection. The specification to be conformal determines this spacing. Likewise the specification to be equidistant (either definition, see above) determines this spacing. Area-preservation ("equal area") is a looser requirement that does not, by itself, determine this spacing.

4.9 Conical projections

Map projections in this class have these properties:

- One pole is represented on the map as either a single point, or a circular arc
- The meridians are represented as straight lines emanating from the portrayed Pole. One of them, the "central meridian", is vertical on the map.
- The angle on the map between two meridians equals their difference in longitudes times a constant factor called the cone constant

- On the map, the parallels are circular arcs whose center is the Pole or the Pole's circular arc's center. Their angular extents are 360° times the cone constant.
- The spacing of the parallels – which radius to use to draw the parallels – depends on the particular projection. The specification to be conformal determines this spacing. Likewise the specification to be equidistant (either definition, see above) determines this spacing. Area-preservation ("equal area") is a looser requirement, and does not, by itself determine this spacing.
- The arcsine of the cone constant is called the latitude corresponding to the cone constant

4.10 System Engineering

In many systems, the map projection is a component of the end-to-end process, for which much system engineering is required. A map projection that is not well chosen for the intended purpose can be surrounded by other processes that fix its defects. A map projection that is well chosen does not need to be surrounded by these ameliorative processes and some unnecessary development efforts can be avoided. This document provides recommendations to software developers to avoid the unnecessary engineering.

5 Map Projections Used in NGA Standard Products

5.1 NGA standard products

NGA produces many standard products. Most of these products have a map projection specified within the product's standard or guidelines. Many systems are built to accept these products seamlessly and training doctrine allows the warfighter to employ these products.

5.2 Mercator

References for its procedure:

- GEOTRANS software
- Snyder, pp. 44-45
- EPSG coordinate operation methods 9804, 9805, and 1044
- ISO/IEC 18026:2009I ("Spatial Reference Model") Section 5.9.12, "Mercator CS specification"

Properties

- Conformal
- Cylindrical type (see above)
- North is upwards on the map
- Neither Pole occurs on the map
- Distortion of size increases going poleward, and is severe near the Poles
- The track of an airplane or ship that has a constant course, *i.e.* intersects every meridian at the same angle, is a straight line on the map
- See Fig. 3 for general appearance

The Mercator projection is the only map projection in the family of cylindrical projections that is conformal.

Parameters (options)

"Mercator" is a three-parameter family of planar coordinate systems. There is flexibility about scale (one-parameter) and flexibility about the origin of its (x, y) coordinates (two more parameters). There is no flexibility about the shape of any geographic feature. Greenland is the same "wrong" **shape** on every Mercator map, compared to a globe. (It is also the wrong **size** compared to South America, if both appear on the map). Also, there is no flexibility about the orientation of any feature. At every point, the direction, North, is always vertical on the map.

Indications for use

- The area of interest is equatorial or mid-latitude. The projection is not appropriate north of the Arctic Circle or south of the Antarctic Circle.
- Navigation procedures where a track (intended or actual) that has a constant course (heading) should be a straight line
- Large-scale topographic mapping near the Equator. For example, there is less scale distortion for the Indonesian Archipelago using Mercator than using transverse Mercator (the typical projection for topographic maps), if the entire archipelago is to be placed on a single map or grid system.
- Design of grid systems near the Equator (*e.g.* Indonesia)
- When true north must be vertical and conformality is required

Appropriate Applications (from Table 5 of Section 12)

- Navigation
- Relative Positioning
- Mission Planning
- Visualization
- Usable Scale: All
- Tiled Raster Graphics

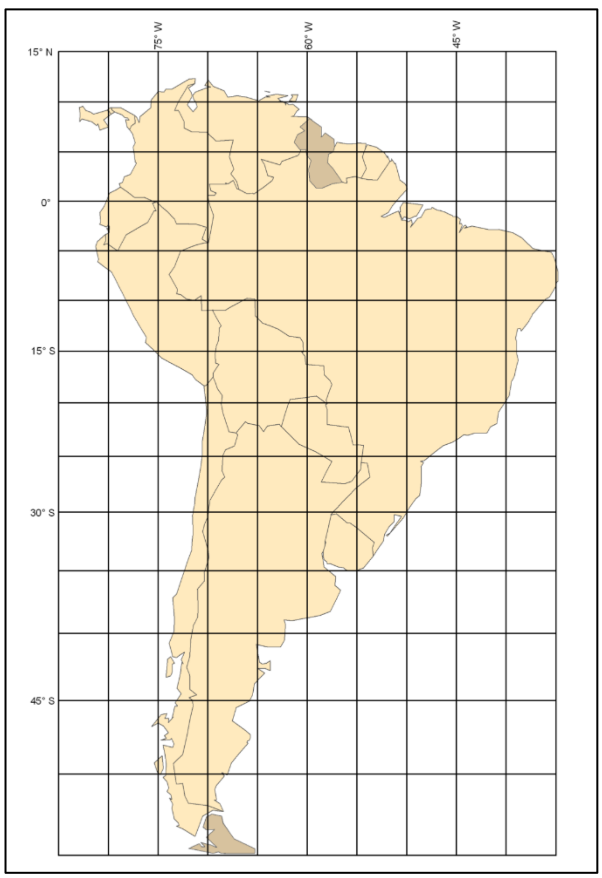

Fig. 3. South America as portrayed on the Mercator projection.
To show the particular effects of this projection, South America is used as an example. See Section 5.2 for where this projection is recommended.

Use in NGA standard products

- Nautical charts at many scales between latitudes 70°S and 70°N
- World map at scale 1:22,000,000 at the Equator for wall displays

5.3 Polar stereographic

References for its procedure

- NGA document, NGA_SIG_0012_2.0.0_UTMUPS
- GEOTRANS software
- Snyder, pp. 160-163
- EPSG coordinate operations methods 9810, 9829, 9830
- ISO/IEC 18026:2009I ("Spatial Reference Model") Section 5.9.16, "Polar stereographic CS specification"

Properties

- Conformal
- Polar azimuthal
- A selected meridian is vertical on the map
- One of the Poles but not the other occurs on the map
- Distortion of size increases going away from the Pole that is shown, and is severe in the opposite hemisphere near the opposite Pole
- See Fig. 4 for general appearance

The Polar Stereographic projection is the only map projection in the family of polar azimuthal projections that is conformal.

Parameters (options)

"Polar Stereographic" is a four-parameter family of planar coordinate systems. There is flexibility about scale (one-parameter), flexibility about the orientation of the map (one-parameter), and flexibility about the origin of its (x, y) coordinates (two parameters). There is no flexibility about shape. Greenland is the same more-or-less correct shape on every North polar stereographic map or chart.

Indications for use

- Polar areas
- Large-scale topographic mapping in the Polar areas
- Design of the Universal Polar Stereographic (UPS) grid system, part of MGRS. UPS is an instance of the polar stereographic projection, with a particular specification of the four parameters.

Appropriate applications

- Navigation
- Relative Positioning
- Mission Planning
- Visualization
- Usable Scale: All
- Tiled Raster Graphics

Use in NGA standard products

- Nautical charts and aeronautical charts in the Polar areas
- Submarine navigation in the Arctic Ocean

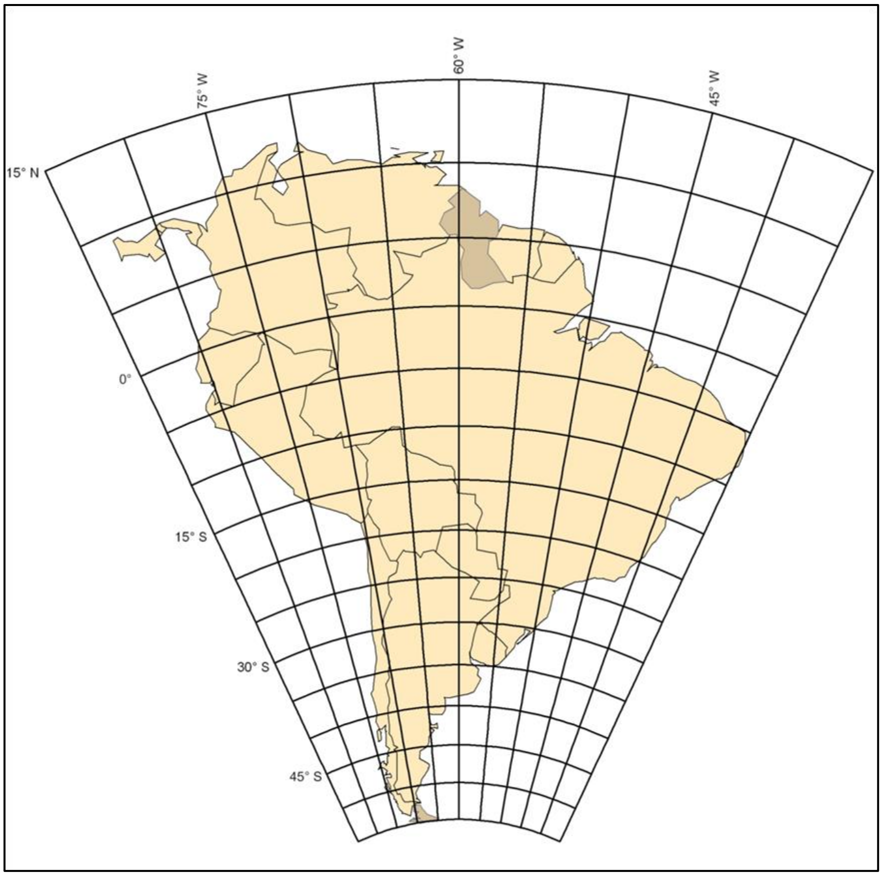

Fig. 4. South America as portrayed on the south polar stereographic projection.
To show the particular effects of this projection, South America is used as an example. See Section 5.3 for where this projection is recommended.

5.4 Lambert conformal conic

References for its procedure

- Snyder, pp. 160-163
- GEOTRANS software
- EPSG coordinate operation methods 9801, 9802
- ISO/IEC 18026:2009I (“Spatial Reference Model”), Section 5.9.15, “Lambert conformal conic CS specification”

Properties

- Conformal
- Conical projection
- A selected meridian is vertical on the map
- One of the Poles but not the other occurs on the map
- There is a single latitude at which the local scale function is minimum, namely the latitude corresponding to the cone constant. (See under “Conical projections” in Section 4.9.) The local scale increases northward and southward from there.
- See Fig. 5 for general appearance

The Lambert Conformal Conic (LCC) is the only map projection in the family of conical projections that is conformal.

Parameters (options)

LCC is a five–parameter family of planar coordinate systems. There is flexibility about shape (one parameter, the cone-constant or its equivalent). There is flexibility about scale (one-parameter), flexibility about the orientation of the map (one-parameter – which meridian will be portrayed as a vertical line), and flexibility about the origin of its (x, y) coordinates (two more parameters). Greenland's shape varies dramatically depending on the cone-constant (or its equivalent). If the cone-constant is near zero, Greenland on an LCC looks like Greenland on a Mercator projection, but if the cone-constant is near one, then it looks like Greenland on a Polar Stereographic projection.

The above organization of the five parameters, with their separate effects on the shape, size, orientation and position of everything (*e.g.* Greenland) is designated LCC-1. There is also another organization of parameters, designated LCC-2, in which two latitudes are specified in place of the separate shape and size parameters of LCC-1. Together they determine both the shape and size of everything, but neither separately determines either shape or size. LCC-2's parameters for orientation and position are the same as in LCC-1.

LCC-1 and LCC-2 are the same map-projection merely differing in the procedure regarding which constants are defined, and which constants are computed. Any map constructed according to LCC-1 can be constructed according to LCC-2, and *vice versa*.

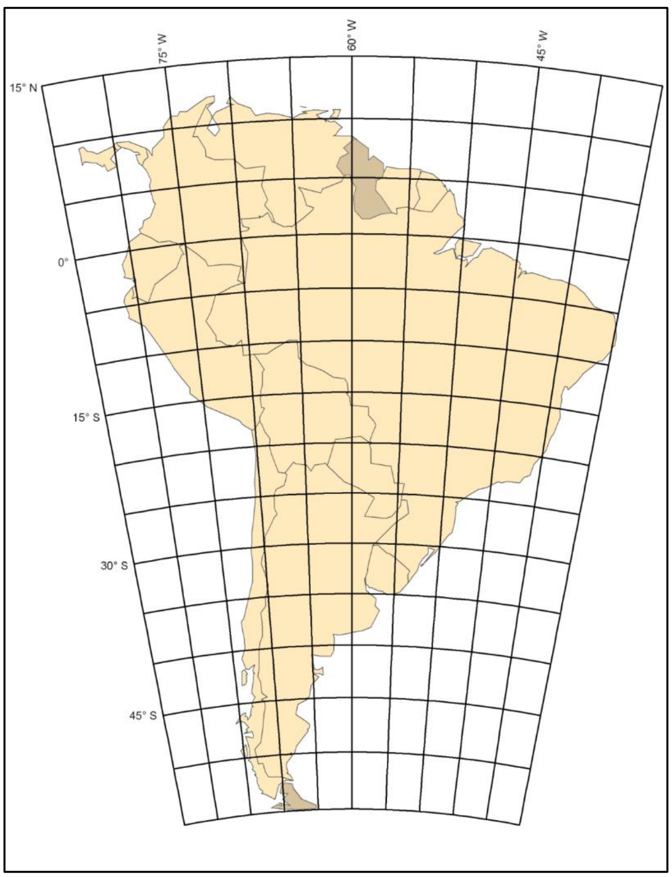

Fig. 5. South America as portrayed on the Lambert conformal conic projection.
To show the particular effects of this projection, South America is used as an example. See Section 5.4 for where this projection is recommended.

Indications for use

- Mid-latitudes
- When the area of interest is greater in E-W extent than in N-S extent

- When the intersection of linear features (roads, political boundaries, airplane ground tracks, etc.) need to be portrayed at correct angles

Appropriate applications

- Navigation
- Relative Positioning
- Mission Planning
- Visualization
- Usable Scale: All

Use in NGA standard products

- Aeronautical charts such as the GNC and JNC series

5.5 Transverse Mercator

References for its procedure

- NGA document, NGA_SIG_0012_2.0.0_UTMUPS (recommended)
- Snyder, pp. 60-64
- GEOTRANS software
- EPSG coordinate operation method 9807
- ISO/IEC 18026:2009I ("Spatial Reference Model"), Section 5.9.14 Transverse Mercator CS specification

Properties

- Conformal
- Both Poles are showing, assuming the algorithms in NGA_SIG_0012_2.0.0_UTMUPS are implemented. Some versions of transverse Mercator, based on DMA TM 8358.2 or on Snyder are limited in latitude range (typically 80°S to 84°N) and will not show the Poles.
- A particular meridian ("central meridian") is portrayed on the map as a vertical line segment. Its anti-meridian is portrayed as the continuation of this line beyond each Pole.
- The central meridian and its anti-meridian are portrayed at a constant scale
- See Fig. 6 for general appearance

Transverse Mercator is the only map-projection with the above properties.

- The meridians at longitudes ±90° from the central meridian are portrayed as horizontal straight lines. The central meridian and its anti-meridian are portrayed as one continuous vertical line. All other meridians are complex curves. Likewise, the parallels are complex curves.
- The meridians intersect the Equator at right angles.
- The meridians intersect each other at the Poles at angles equal to their longitude differences
- The local scale function has its minimum along the central meridian. Scale increases with increasing distance from the central meridian.
- The name "transverse Mercator" implies a connection with the Mercator projection. This is partly true, as follows:
    - For the sphere, a transverse graticule is the set of great circles ("transverse meridians") meeting at two specified antipodal points on the Equator ("transverse Poles") together with the small circles ("transverse parallels") that meet them at right angles. In other words, the transverse graticule is a rotation of the graticule by 90°.
    - This analogy is valid for the spherical case of this projection: transverse Mercator is to the transverse graticule as Mercator is to the graticule.
    - The ellipsoid model of the Earth does not have a transverse graticule obtained as a rotation of the graticule. The above remarks apply only to the sphere.

Parameters (options)

"Transverse Mercator" is a four-parameter family of planar coordinate systems. There is flexibility about shape (one-parameter – the central meridian), flexibility about size (one parameter) and flexibility about the origin of its (x, y) coordinates (two more parameters). The orientation of everything is fixed by the choice of central meridian.

Fig. 6. South America as portrayed on the transverse Mercator projection.
To show the particular effects of this projection, South America is used as an example. See Section 5.5 for where this projection is recommended.

Indications for use

- When the area of interest is greater in N-S extent than in E-W extent
- Large-scale mapping (*e.g.* 1:500,000)
- Flight plans from anywhere to the North or South Pole
- Design of the Universal Transverse Mercator (UTM) grid system, part of MGRS. Each UTM zone is an instance of the transverse Mercator projection, with a particular specification of the four parameters

Appropriate applications

- Navigation
- Relative Positioning
- Mission Planning
- Visualization
- Usable Scale: All

Note: For tiled raster graphics, the world could be covered in 4, 5, or 6 seamless transverse Mercator panels, but this proposal is not active at this time, and therefore not recommended here. Separate tiling for each of the 60 UTM zones is not what is usually intended under “tiled raster graphics”.

Use in NGA standard products

- Most large-scale topographic products including:
  - Image City Graphics
  - Topographic Maps, 1:50,000
  - Topographic Maps, 1:100,000
  - Joint Operations Graphics
- Some large-scale nautical charts above latitude 70°N or below latitude 70°S

6 Map Projections for Small-Scale Briefing Graphics and Small-Scale Thematic Maps

6.1 Introduction

This section discusses small-scale briefing graphics and small-scale thematic maps. These are maps and graphics which show a large part of the world without the means or intention to make accurate measurements of distances, angles or areas. There is a need for these projections, but their limited uses should be understood. The scale-bar typically shown on large-scale topographic maps is not appropriate for these. The following are some of the map-projections that are appropriate for these maps and graphics.

6.2 Miller

References for its procedure

- Snyder, pp. 86-89

Properties

- Cylindrical projection
- Neither conformal, nor equal-area, nor equidistant by either definition given in Section 4.5
- Innovative spacing of the parallels designed to partially retain Mercator’s familiar shapes of land masses, yet partially reduce Mercator’s size distortions near the Poles
- Each Pole is represented by a horizontal straight line
- Close in appearance to the Mercator projection near the Equator
- See Fig. 7 for general appearance

Parameters (options)

- None given that would be described as map-projection parameters. The formulas are offered in spherical form only. Therefore a radius for a spherical Earth must be chosen.

Indications for use

- When the need is to depict the whole world on a cylindrical projection
- When preservation of geometric properties (shape, area, distance) is not a requirement
- When detail maps (insets), on the same projection, are not needed

Appropriate applications

- Mission Planning
- Visualization
- Usable Scale: Global

Use in NGA standard products

- The World with Commanders Area of Responsibility, Series 1107, Edition 8, NGA

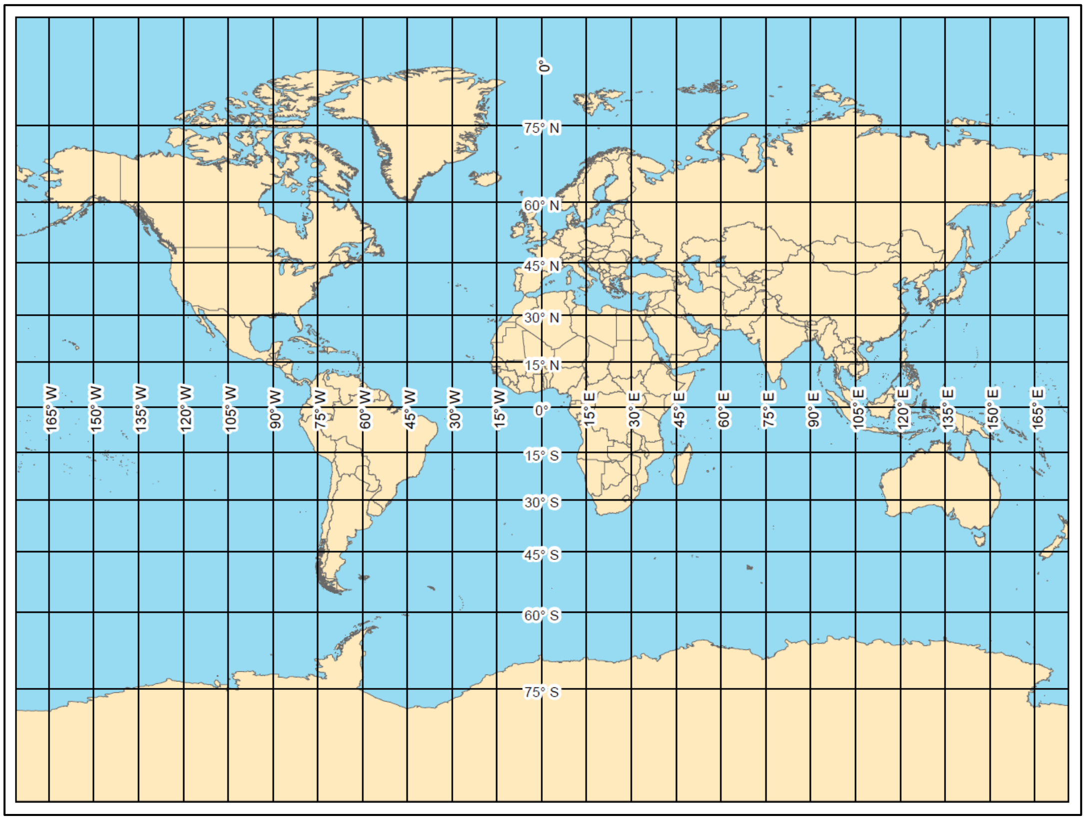

Fig. 7. The World as portrayed on the Miller projection.
See Section 6.2 for where this projection is recommended.

6.3 Robinson

References for its procedure

- Robinson, Arthur, H., “A new map projection: Its development and characteristics”, 1974. International Yearbook of Cartography 14:145-55.
- ESRI code 43030

Properties

- Pseudo-cylindrical projection
- Parallels are horizontal straight lines
- The central meridian is a vertical straight line and the other meridians are curves concave toward the central meridian and cutting the parallels in equal segments for equal-intervals of longitude
- The Poles are horizontal straight lines
- Neither conformal nor area-preserving
- See (Canters, Frank, *Small-Scale Map Projection Design*, Taylor & Francis, New York, 2002) for a discussion of the properties chosen for its design
- See Fig. 8 for general appearance

Parameters (ESRI version):

- Central meridian, which determines the shape of everything
- Two parameters to move the origin

Indications for Use:

Invented by Arthur H. Robinson in 1963 at the request of Rand McNally Co., it is suitable for general-purpose world maps. It was later adopted by the National Geographic Society for use in its atlas.

Appropriate applications

- Mission Planning
- Visualization
- Usable Scale: Global

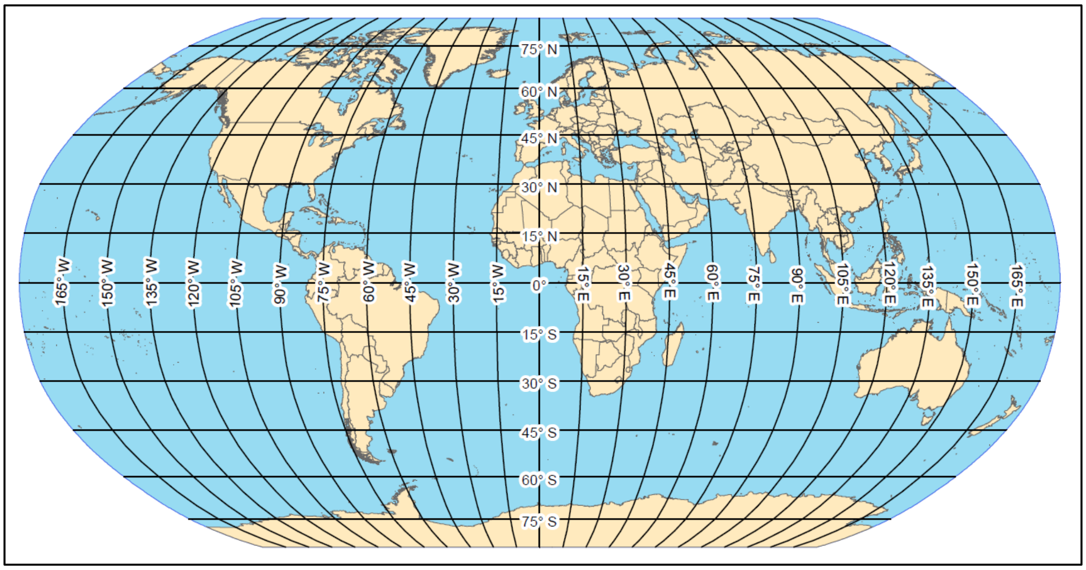

Fig. 8. The World as portrayed on the Robinson projection.
See Section 6.3 for where this projection is recommended.

6.4 Web Mercator

"Web Mercator" is a name often used for this projection. The authority below, Geomatics Guidance Note 7, refers to it as "Popular Visualization Pseudo-Mercator".

References for its procedure

- Geomatics Guidance Note Number 7, Part 2, "Coordinate Conversions and Transformations including Formulas", Revised – June 2013, International Association of Oil & Gas Producers, pages 40-42
- EPSG operation method code 1024
- The formulas (EPSG::1024) are a modification of the Mercator formulas in Section 5.2 in this way: To get from longitude and latitude to *x* and *y*, the eccentricity of the ellipsoid is set to zero. This is the procedure even when, as is typical, the provenance of the longitude and latitude is the WGS 84 datum, in which the Earth is modeled as an ellipsoid with eccentricity.
- EPSG projected CRS code 3857 is the combined specification:
  - The operation method code is 1024
  - The provenance of the longitude and latitude is the WGS 84 datum
  - These map projection parameters are set:
    - The Equator is represented at unity scale
    - The origin of map projection coordinates, *i.e.* the point where $(x, y) = (0,0)$, is the intersection of the Equator with the Prime Meridian (Greenwich Meridian)
- ESRI map projection code 43104 ("Mercator Auxiliary Sphere") with Type 0 for the Auxiliary Sphere Type

Properties

- Cylindrical projection
- The same as Mercator in general appearance
- Non-conformal by a small amount that depends on latitude. The factor by which the North-South scale is greater than the East-West scale is greatest at the Equator, where it is 1.007.
- See Fig. 9 for general appearance

Parameters (options)

Web Mercator has the same parameters as Mercator, and the parameters have the same effects on the sizes and shapes of everything such as the examples of Greenland and South America. At every point, the direction North is vertical on the map.

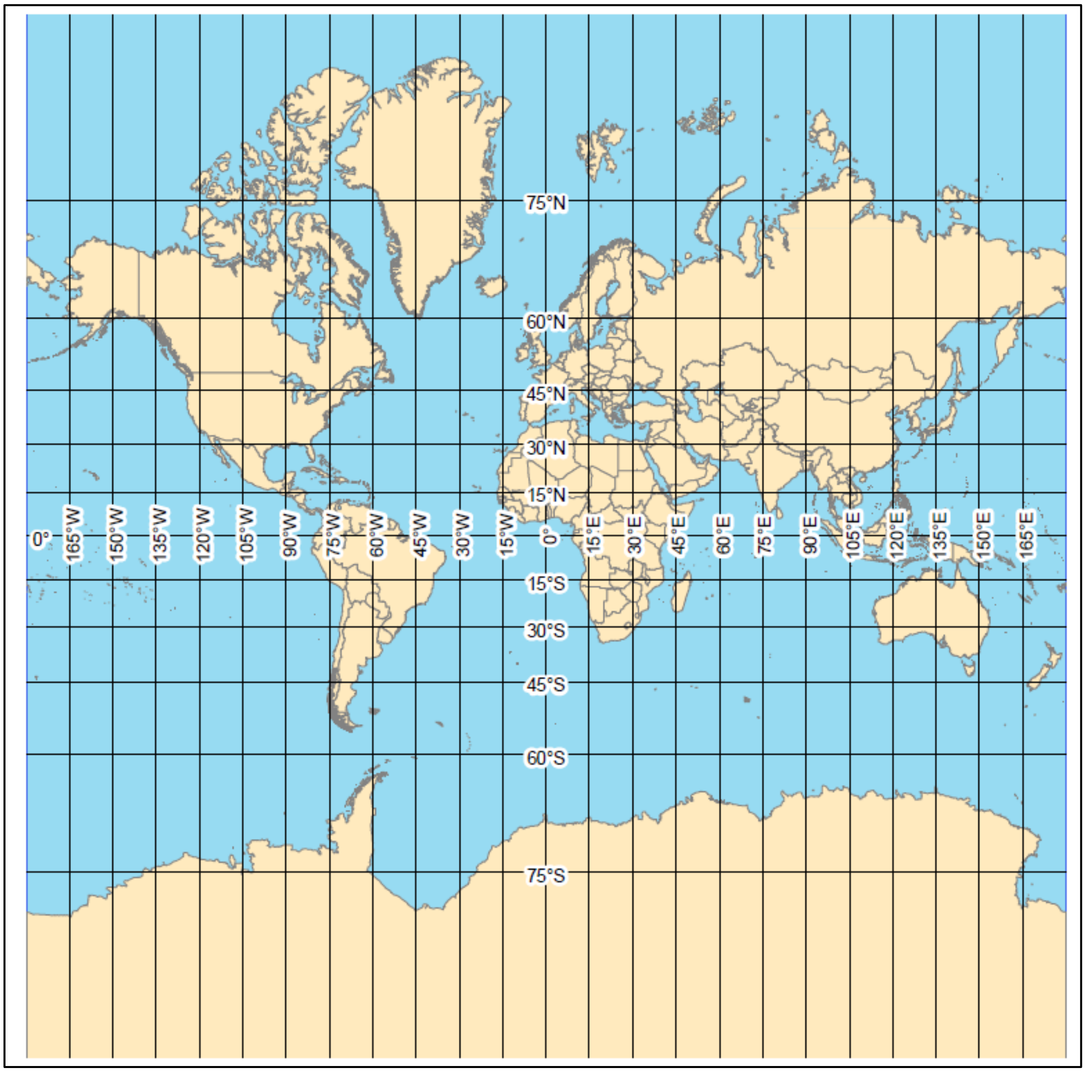

Fig. 9. The World as portrayed on the web Mercator projection
See Section 6.4 for where this projection is recommended.

Indications for use

- When the area of interest is equatorial or mid-latitude. The projection is not appropriate north of the Arctic Circle or south of the Antarctic Circle.
- Small-scale briefing graphics and small-scale thematic maps

Appropriate applications

- Mission Planning
- Visualization
- Usable Scale: All

Note: For a discussion of web-Mercator in connection with tiled raster graphics, see Section 9.4.

6.5 Plate Carrée

Plate Carrée (French for "flat squares") is a map projection identical in appearance to the map obtained by plotting $x =$ degrees of longitude and $y =$ degrees of latitude. The difference is merely a matter of units. If, instead of marking the *x*-axis, *i.e.* the Equator, in degrees of longitude, it is marked in meters (kilometers), and if the same conversion factor (degrees to meters) is applied to the *y*-axis, Plate Carrée is obtained. If x and y remain as decimal degrees and are not converted to meters, the map obtained has code EPSG::4326. Neither Plate Carrée nor EPSG::4326 ("geographics") should be called "The WGS 84 Projection." "WGS 84" is an ellipsoid and a datum, but not a map projection.

References for its procedure

- Snyder, pp. 90-91, where it is also called Simple Cylindrical
- Equidistant-by-latitude cylindrical projection together with the specification that the Equator be represented at unity scale
- ESRI map projection code 43001
- EPSG operation method code 1029 ("Equidistant cylindrical (spherical)") with the Equator selected as the standard parallel
- EPSG operation method code 9825 ("pseudo-Plate Carrée") followed by the degree-to-meter conversion specified above

Properties

- Cylindrical projection
- All cells of size 1° of longitude by 1° of latitude are squares. Likewise all cells 1′ by 1′, or 1″ by 1″, etc
- The parallels are spaced equidistantly by latitude but not equidistantly by length of intercepted meridional arc
- Non-conformal. Severely non-conformal at high latitudes.
- See Fig. 10 for general appearance

Parameters (options)

None, in practice. If it is desired to move the origin of the (x, y) coordinates, the equidistant-by-latitude cylindrical projection should be used instead.

Indications for use

- When the whole world needs to be portrayed
- When severe shape distortion in the polar areas is acceptable
- When the theme of the map is longitude-and-latitude or items that directly depend on or illustrate longitude-and-latitude. Plate Carrée should be used to explain graticule-based reference systems, such as the Global Area Reference System (GARS) or the World Geographic Reference System. (These are defined in NGA.STND.0037_2.0.0_GRIDS).

Appropriate applications

- Mission Planning
- Visualization
- Usable Scale: Global

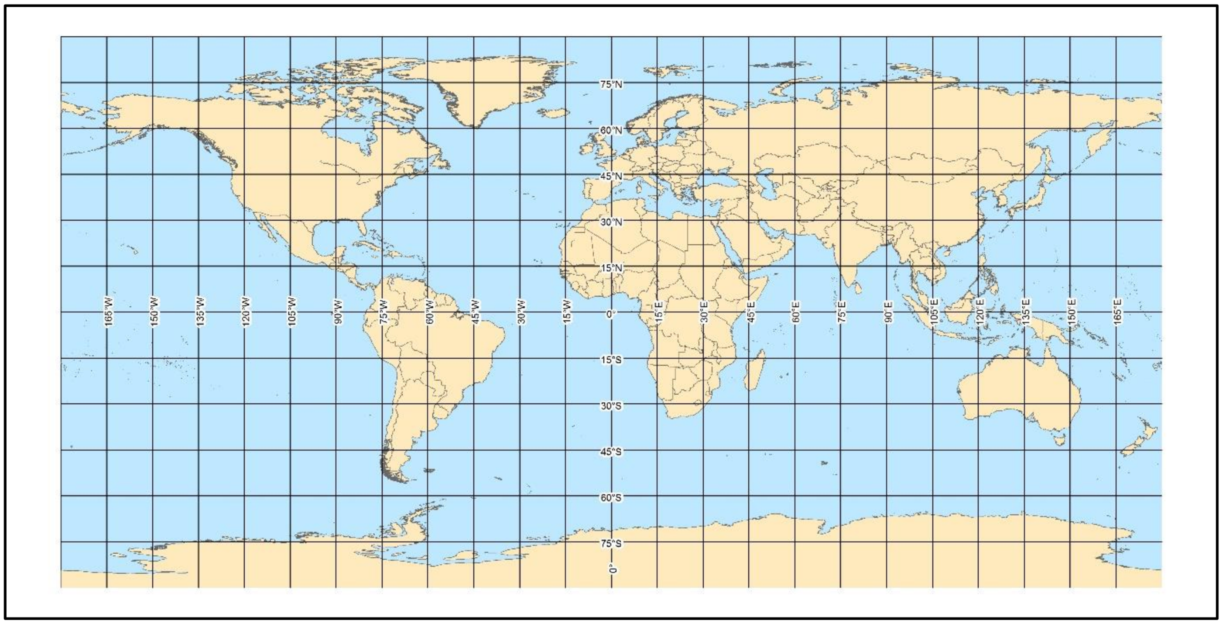

Fig. 10. The World as portrayed on the Plate Carrée projection
See Section 6.5 for where this projection is recommended.

6.6 Other map-projections for small-scale graphics

Other map projections suitable for small-scale briefing graphics or small-scale thematic maps are:

- Cylindrical equidistant projection (spherical), (EPSG::1029), *i.e.* equidistant-by-latitude, and called by another authority, equidistant cylindrical (ESRI::43002)
- Cylindrical equal area projection (ESRI::43034). The choice of the standard parallel will greatly influence where the shapes of countries, islands, other features etc. are relatively undistorted.
- Pseudo-cylindrical equal area projections. There are several, such as Sinusoidal, Eckert IV & VI, and Molleweide. See the literature, such as Snyder and Voxland.
- Albers equal area conic (ESRI::43007). See the literature, such as Snyder.
- Polar azimuthal equidistant (spherical), *i.e.* equidistant-by-latitude, Snyder, pp. 191-202, especially, page 195 concerning the polar aspect of the azimuthal equidistant projection for the spherical case. See also ESRI::43132 (“Azimuthal_Equidistant_Auxiliary_Sphere”) with Type 0 for the Auxiliary Sphere Type.
- Orthographic projection (Snyder, pp. 145-153) and other perspective projections (Snyder, pp. 169-181). These projections are customary and well-suited to showing the Earth from space. Instead of “flattening the Earth”, the usual conception of a map projection’s purpose, these projections show the Earth’s curvature prominently. In textbooks and other media, they are used to show the Earth as the entire round planet it is, viewed from space.

7 Map Projections for Large-Scale Products

Large-scale topographic mapping generally uses a conformal projection. This is the recommendation here. Examples of such are Mercator, Polar Stereographic, Lambert Conformal Conic, and transverse Mercator.

A conformal map projection guarantees three things. (i) Small areas are preserved in shape. For example, Central Park in Manhattan is the same (correct) shape on all the above projections. (ii) Angles-of-intersection between linear features are preserved. For example, the ground track of an airplane meets a political boundary at the same angles on the map as it does on the Earth. And, (iii), the local scale function is independent of direction. In particular, for large-scale mapping of a small area, the North-South scale will be the same as the East-West scale and a single scale bar on the map will suffice.

If the map projection for a small portion of the Earth is conformal, the formulas of plane geometry are applicable for the relationships between distances, angles, and areas. A non-conformal projection does not adhere to the formulas of plane geometry, in general. Therefore, traditional guidance about map projections has recommended conformal projections with suitably chosen parameters for large-scale topographic mapping. Further guidance has been to (i) use Mercator for areas near the Equator or in situations where geographic North must be vertical everywhere on the map; (ii) use polar stereographic for the Polar regions and (iii) use Lambert Conformal Conic (LCC) or transverse Mercator for the mid-Latitudes. Use LCC if the area of interest (AoI) is greater in E-W extent than in N-S extent; use transverse Mercator if the AoI is greater in N-S extent than in E-W extent. For special circumstances, other conformal projections are used. For example, the State Plane Coordinates for the panhandle of Alaska uses oblique Mercator.

Fig. 11 and Fig. 12 show Central Park in Manhattan, NY. Because the AoI is small, all conformal projections are alike in their accurate depiction of the AoI. Plate Carrée (Fig. 12) is not conformal and distorts the AoI.

As stated above, if the map projection for a small portion of the Earth is conformal, the formulas of plane geometry are applicable for the relationships between distances, angles, and areas. A non-conformal projection does not have this property, unless its linear approximation agrees with that of a conformal projection, in which case this property is retained only in the small area of agreement. The AoI must be within this area of agreement for the non-conformal projection to be successful.

An exception to the above guidance (use only a conformal projection) is granted if the non-conformal projection agrees with a conformal projection over the AoI to the desired accuracy. Therefore, if the AoI is sufficiently small, and the map projection parameters are chosen with relevance to the AoI, some substitutions can be made. Here are some examples. The equidistant-by-arclength cylindrical projection can substitute for Mercator, the equidistant-by-arclength conic can substitute for LCC, and the equidistant-by-arclength polar azimuthal can substitute for polar stereographic. But these substitutions work for the immediate AoI only. The latitude-of-unity-scale for these projections should bisect the AoI (roughly). This requires a different choice of latitude-of-unity-scale for each AoI, and the resulting patchwork for several AoIs, even if they abut, would have discontinuities.

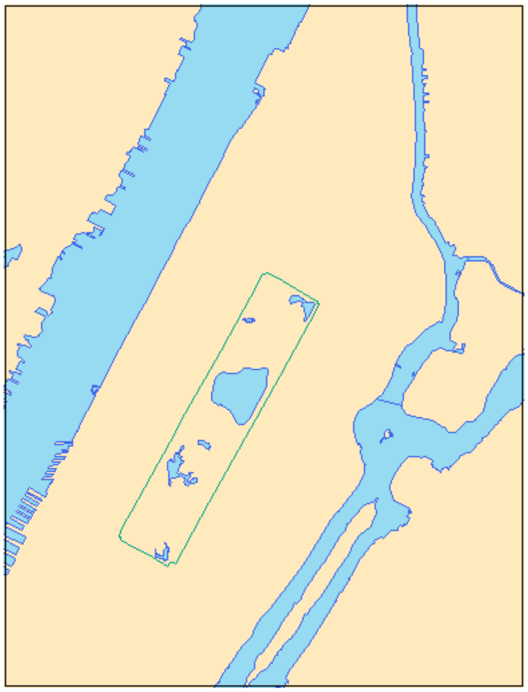

Fig. 11. Central Park on conformal projections.
Central Park in Manhattan, NY, as it appears on the Mercator, transverse Mercator, north polar stereographic and south polar stereographic projections, with appropriate parameters in each case. The shape is correct.

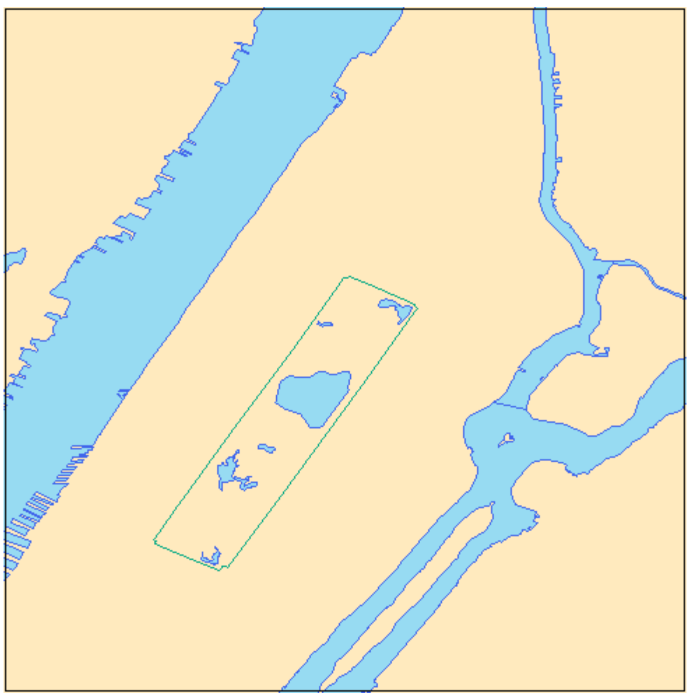

Fig. 12. Central Park on the Plate Carrée projection.
Central Park in Manhattan, NY, as it appears on the Plate Carrée projection, which is non-conformal. Note the shape distortion – elongation in the E-W direction – as compared to Fig. 11.

8 Map Projections for Specialized Geographic Analysis

There are some important map projections that have very particular uses and don't fall into one of the above sections. They are discussed here.

8.1 Gnomonic projection (great circles)

The gnomonic projection is used by maritime navigators to plot a great circle route from one port city across an ocean to another.

References for its procedure

- Snyder, pp. 164-168
- ESRI map projection codes 43047, 43147, and 43065

Properties

- In its most-used form, a spherical model of the Earth is assumed. Which radius for the sphere and whether/how to convert the geodetic latitude (*e.g.* latitude from the WGS 84 datum) to latitude on the sphere are the reasons for listing several ESRI codes for this projection.
- Perspective projection with the center of the Earth as the point from which the lines emanate
- Perspective projection with a chosen point on the sphere identified as the point of tangency of the image plane (map projection plane)
- Great circles are mapped to straight lines
- Neither conformal nor equal area
- See Fig. 13 for general appearance

Parameters

- The longitude and latitude of the point of tangency
- Scale reduction factor at the point of tangency

Indications for use

- When the great circle route is needed between two points on the globe
- Navigation at sea, where intermediate way points can be successfully calculated using a spherical model of the Earth, for example, the model whose radius is consistent with the conversion: One minute of great circle arc equals 1852 meters (the international nautical mile).
- Application of the procedures in The American Practical Navigator ("Bowditch") concerning the great circle route from one place to another

Appropriate applications

- Navigation
- Mission Planning
- Visualization
- Usable Scale: Medium and Small

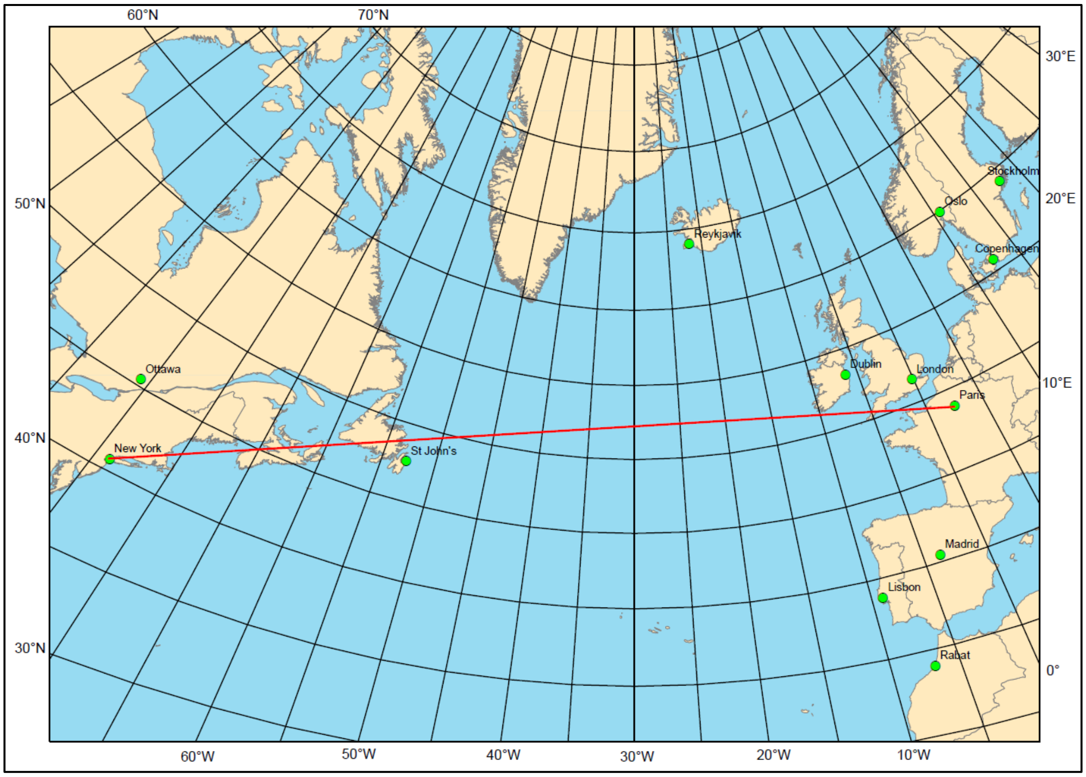

Fig. 13. North Atlantic as portrayed on the Gnomonic projection.
The center point of the projection is 30°W, 50°N. Great circles are represented as straight lines. The path in red from New York to Paris is a straight line.

8.2 Azimuthal equidistant projection (range rings)

The azimuthal equidistant projection is used by geographic information analysts to plot range rings, *i.e.* circles representing points that have the same distance from a chosen (center) point.

References for its procedure

- Snyder, pp. 191-202
- ESRI map projection codes 43032, and 43132

Properties

- For large areas of the Earth, a spherical model of the Earth is usually assumed. Which radius for the sphere and whether/how to convert the geodetic latitude (*e.g.* latitude from the WGS 84 datum) to latitude on the sphere are the reasons for listing several ESRI codes for this projection.
- Every point on the globe is plotted on the projection plane in this way: its distance and geodetic azimuth from a chosen point (center point) is used as the distance and map azimuth from this point on the projection plane
- If the center point is a Pole, this projection is the polar azimuthal equidistant projection of Section 6.6
- The point diametrically opposite the center point (antipodal point) is represented by a circle whose radius is half the circumference of the sphere
- Neither conformal, nor equal area
- Distortion increases with distance from the center point

Indications for use

- Range rings for continental or inter-continental distances. (Range rings for geographic analysis at the local and county level should be placed on an appropriate projection for large-scale mapping. See Section 7).
- Applications where a spherical model of the Earth is appropriate

Appropriate applications
- Mission Planning
- Visualization
- Usable Scale: Medium and Small

9 Map Projections for Tiled Raster Graphics

9.1 Guidance

Geographic information is offered in many formats, of which the largest distinction is, perhaps, vector *vice* raster. Within the raster category, the data may be tiled or untiled. Examples of tiled data are internet downloads to mobile devices. An example of untiled data is the scan and publication of an NGA standard product as a JPEG2000 file. If tiled, the raster data is organized by zoom level. Typically, there are twice as many tiles in each direction at succeeding zoom levels.

This document and the following listed document state NGA's recommendations for Tiled Raster Graphics.

- NGA.SIG.0014_1.0_PROJRAS, Map Projections for Tiled Raster Graphics, 2015-04-24

For their inclusion in the container format, GeoPackage, or for their delivery by a Web Mapping Tile Service, additional details about tiled raster graphics can be found in these documents:

- OGC GeoPackage Encoding Standard, OGC 12-128r10
- NSG GeoPackage Encoding Standard 2.1 Implementation Interoperability Standard
- OGC OpenGIS Web Map Tile Service Implementation Standard 07-057r7
- OGC Web Map Tile Service (WMTS) Simple Profile 13-082r2

A summary of the conclusions of NGA.SIG.0014 follows. Several options are offered, but the best option is to use Mercator between the latitudes of 66.65°S and 66.65°N, and to use Polar Stereographic between the latitudes 55°N and 90°N and between 55°S and 90°S. These latitude limits are approximate. See NGA.SIG.0014 for the exact tile boundaries. This combination will cover the whole world conformally in three pieces with appropriate overlap, and will avoid the extreme size distortions of Mercator near the Poles.

9.2 Mercator

The NSG Profile for GeoPackage (NGA.STND.0051_2.1_GEOPKG) allows the Mercator projection for tiled raster graphics. The Mercator projection was chosen for tiled raster graphics because it provides a near-global, seamless projection with north as vertical (aligned with map projection Y-axis), and is conformal. Conformality is important because the tiling scheme will have zoom levels down to very small portions of the earth.

The tiling scheme in NGA.SIG.0014 for Mercator ("World Mercator", EPSG::3395) is illustrated in Fig. 14 for zoom-level 2.

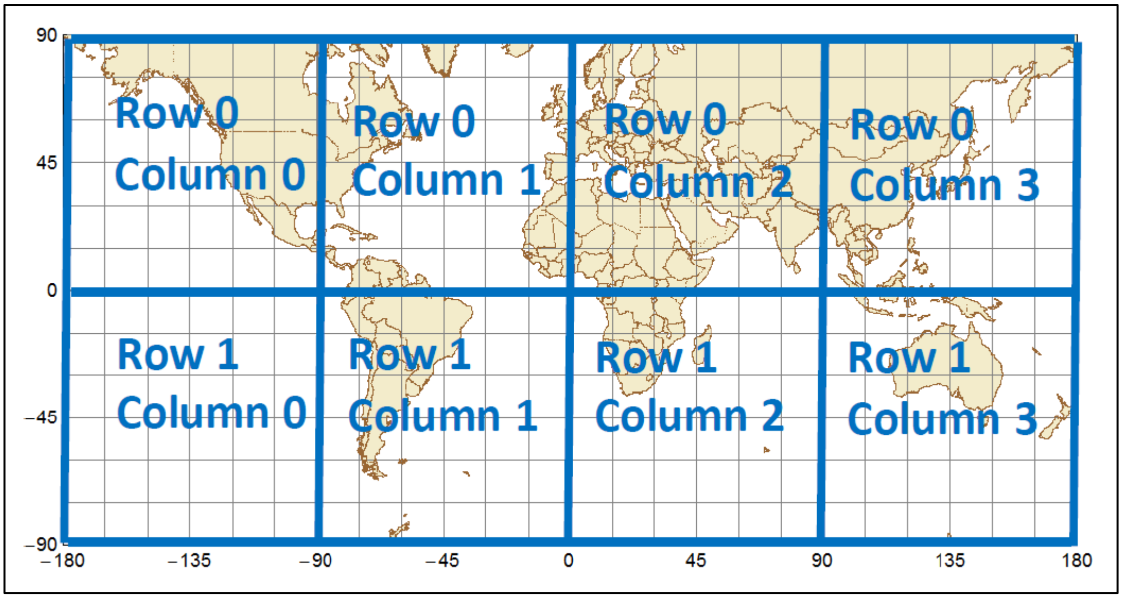

Fig. 14. Recommended tiling for Mercator.

The length of a degree of longitude on the Equator is the unit by which both the x- and y- axes are labeled in this diagram. EPSG::3395 uses meters for the x- and y- axes. The conversion formula is $180° = \pi\, a$, where $a = 6378137$ meters is the semi-major axis of the WGS 84 ellipsoid.

9.3 Polar stereographic

The NSG Profile for GeoPackage (NGA.STND.0051_2.1_GEOPKG) allows the polar stereographic projection for tiled raster graphics. The polar stereographic projection was chosen to fill the gap that is not covered by Mercator, namely the polar regions. The direction of north is consistent with the UPS grid. Conformality is chosen as a requirement because the tiling scheme will have zoom levels down to very small portions of the earth.

The tiling scheme in NGA.SIG.0014 for Polar Stereographic (UPS North, EPSG::32661) is illustrated in Fig. 15 for zoom-level 2:

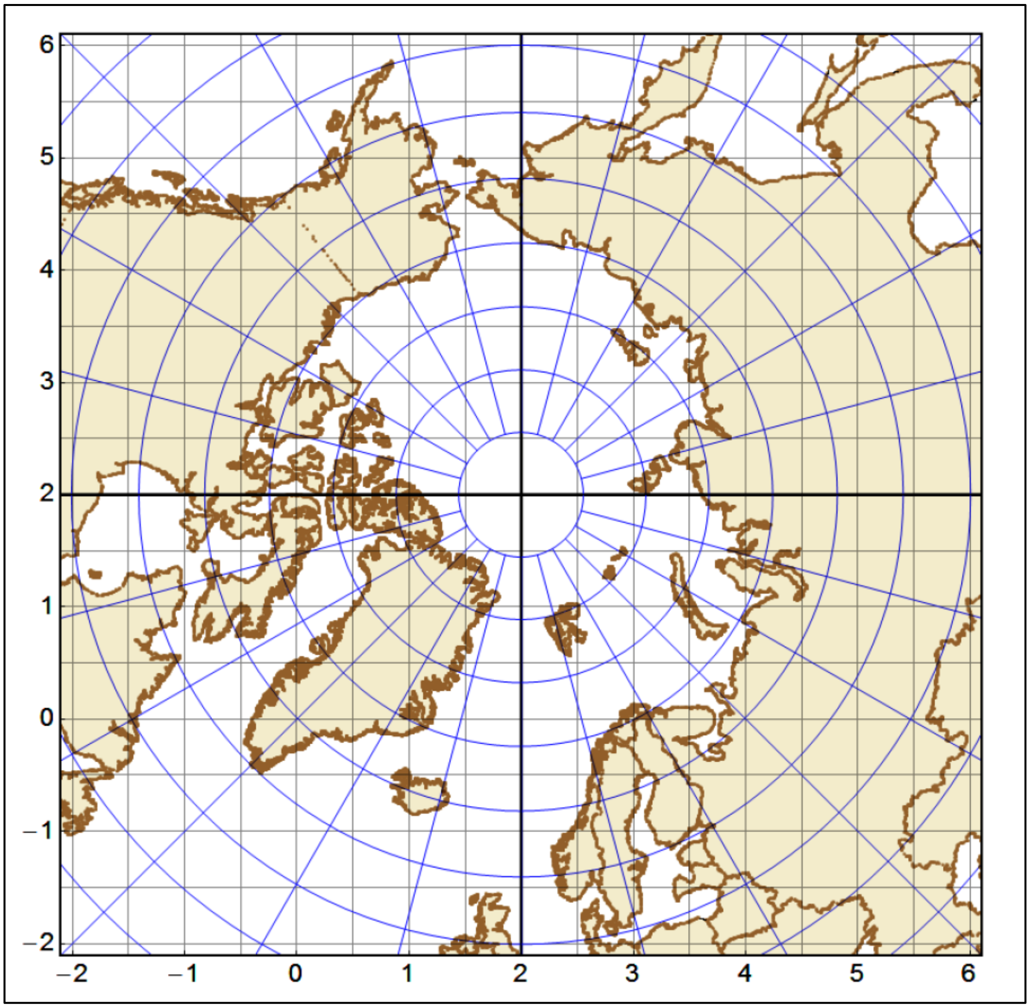

Fig. 15. Recommended tiling for north polar stereographic.
The outside square is the single tile for zoom level 2. Its center is the north Pole with UPS coordinates $(x, y) = (2\,000\,000, 2\,000\,000)$. Zoom level 3 is obtained by dividing it into 4 squares that abut each other along the 90°W, 0°E, 90°E, and 180°E meridians. The labels on the x- and y- axes are millions of meters, and UPS grid lines are shown every one half-million meters. Shown in blue are meridians at 15° intervals from the Prime Meridian and parallels at 5° intervals from 85°N. The southernmost parallel circle shown in full is 55°N.

9.4 Web Mercator

The NSG Profile for GeoPackage (NGA.STND.0051_2.1_GEOPKG) allows Mercator and Polar Stereographic projections, but not web Mercator, for tiled raster graphics. The NSG Profile recognizes that web Mercator is a de facto industry standard but does not provide for the implementation of it in tiled raster graphics. Instead it gives the following cautionary note (Section 7.1 of the NSG Profile):

> "Note: Web Mercator is a de facto standard used for web mapping applications. It is used by virtually all major online map providers, including Google Maps, Bing Maps, OpenStreetMap, Mapquest, Esri, Mapbox, and others. If using WMTS map data from a Volunteered Geographic Information (VGI) or commodity data source which is in the Web Mercator projection, it is highly recommended that your service warn users that this data is suitable for Visualization use cases only."

This document agrees with the recommendation of the NSG Profile regarding tiled raster graphics.

10 Map Projections for Data Transfer

10.1 Introduction

This section makes allowances for legacy products whose choice of map projection is not recommended but may be accepted as a means to transfer data. The systems and platforms that ingest this data are expected to convert it to an acceptable projection, or adopt other procedures that work around the defects of the projection.

10.2 The ARC System

The Equal **A**rc-Second **R**aster **C**hart/Map System (ARC System) is a set of map-projections used in many raster-graphic products of NGA. These products include ARC-Digitized Raster Graphics (ADRG), Compressed ARC-Digitized Raster Graphics (CADRG), Controlled Image Base (CIB), and, recently, an enhancement of CIB called the Enhanced Controlled Image Base (ECIB). All these products adopted the ARC System for the map-projection component of their specifications.

The non-polar portion of the ARC System consists of an equidistant-by-latitude cylindrical projection for each of eight latitude bands north of the Equator (and likewise, eight bands south of the Equator). The eight bands are defined by the nine latitudes 0°, 32°, 48°, 56°, 64°, 68°, 72°, 76°, and 80°. See Fig. 16. The equidistant-by-latitude cylindrical projection for each band is non-conformal and the plot of the ratio of North-South scale over East-West scale for all 8 bands combined is a broken curve that oscillates between 0.85 and 1.17, a significant departure from conformality (1.00). The NGA products listed above are large-scale topographic products, and the non-conformality applied to them by the ARC System is contrary to the recommendation of Section 7.

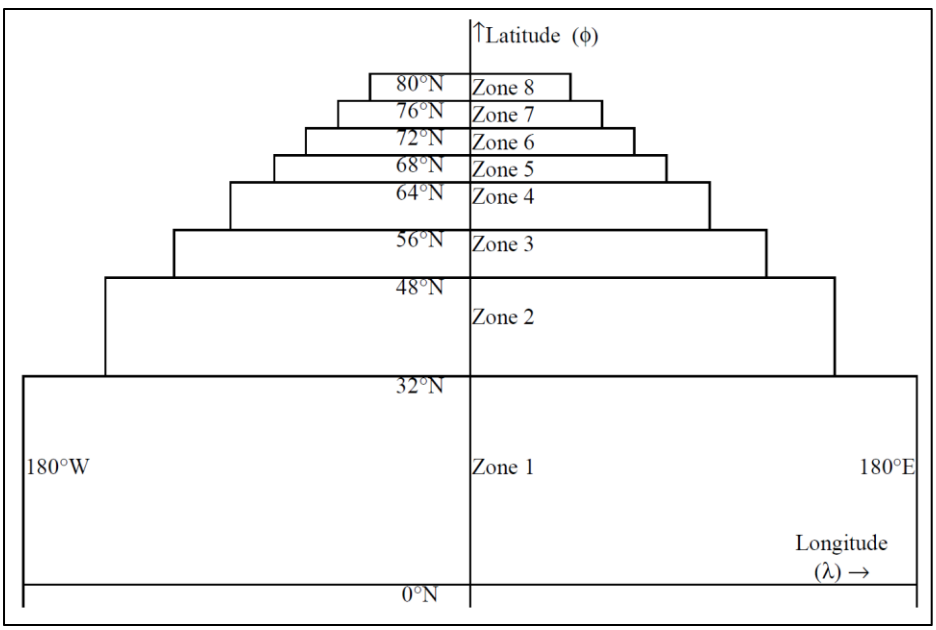

Fig. 16. Schematic for the non-polar portion of the ARC System.
The ARC System consists of bands of latitude, and for each band there is specified an equidistant-by-latitude projection.

The polar portion of the ARC System consists of an equidistant-by-latitude polar azimuthal projection for the Arctic region and another such for the Antarctic. These also are non-conformal, contrary to the recommendation of Section 7.

For these reasons, the recommended application is mainly data transfer of legacy products. Additionally, mission planning and visualization are appropriate.

11 Recommended Map Projections

11.1 Background

Although no single projection is suitable for every possible application, interoperability requirements for the IC and DoD make the selection and application of map projections non-trivial. The overarching criteria used in determining the recommended map projections is the property of conformality. A map projection is conformal if it has any of these three properties: a) small areas are preserved in shape, b) angles of intersection are preserved between linear features, and c) the local scale function is independent of direction. See Section 4.4 for additional details.

11.2 Recommendations

To depict accurate geospatial data, traditional mapping products (hardcopy and softcopy), layered content (vector and raster), and systems with dynamic displays will best be served with conformal map projections that support global coverage at any scale.

To meet IC requirements, DoD military operations, and Safety of Navigation requirements, and to form the basis for a framework of interoperability for military mapping and GEOINT analysis, NGA recommends the following projections listed in Table 3. The recommendations are based upon the map projections recommended in NATO Standard, AGeoP-21 (see References).

Table 3 – Recommended map projections

Domain	Projection	Condition
General	Mercator	For use in dynamic systems where there is a requirement for conformal display at any scale at any location on the globe (except the poles). Mercator is not a good choice for accurate portrayals of lands or seas poleward of ±70° latitude.
	Polar Stereographic	For use in dynamic systems where there is a requirement for conformal display at any scale covering the polar areas, (poleward of ±70° latitude).
Land	Transverse Mercator	Transverse Mercator is appropriate for regions that are greater in N-S extent than in E-W extent. Large scale mapping in regions of longitudinal extent not greater than 6° has been the traditional (still valid) advice. Updated algorithms from NGA.SIG.0012_2.0.0_UTMUPS allow transverse Mercator to be used successfully for regions up to ±70° longitude departure from the central meridian.
	Lambert Conformal Conic	Lambert conformal conic is appropriate for regions that are greater in E-W extent than in N-S extent. It is used in some of the U.S. State Plane Coordinate systems.
	Polar Stereographic	Charts covering the pole or covering regions poleward of ±70° latitude
Sea	Mercator	Most nautical charts, especially, charts at scales smaller than 1:50,000
	Transverse Mercator	Charts at scales 1:50,000 or larger or charts belonging to regions that are poleward of ±70° latitude
	Lambert Conformal Conic	Charts poleward of ±70° latitude but not covering the pole
	Polar Stereographic	Charts covering the pole or covering regions poleward of ±70° latitude
Air	Lambert Conformal Conic	Charts at scales 1:500,000 and smaller (TPC, ONC, JNC, GNC) not covering the pole
	Transverse Mercator	Charts at scales 1:2,000,000 and smaller (JNC, GNC) that cover the pole have used transverse Mercator in the past. NGA recommends sun-setting the transverse Mercator projection for aeronautical products over the poles.
		Strip charts for flights beginning or terminating at or near the pole
	Polar Stereographic	The usual choice for small-scale charts that cover the pole. NGA recommends adopting the polar stereographic projection for aeronautical products over the poles.
Intelligence	Lambert Conformal Conic	Maps covering the middle latitudes with a greater extent east-west than north-south
	Transverse Mercator	Large scale maps, when the area of interest is within 15° of the central meridian

	Mercator	Maps of the equatorial region (within 15° north or south of the equator), nautical charts
	Polar Stereographic	Maps covering the polar areas
	Azimuthal Equidistant	Maps that depict range information, such as the range of an airplane or missile from a single point to any location on the map
	Albers Equal Area Conic	Maps that need to maintain accurate area measurements, such as population density or other proportional numeric attribute associated with an area
	Robinson Miller	World maps

12 Summary of Map Projections

12.1 Summary of map projection properties

Table 4 – Summary of map projection properties

	EPSG Codes		Map Projection Properties						
Map Projections	Operation Method	Projected CRS Example	Small Shapes, Local Angles, Local Scale Correct[1]	Areas Preserved	Distances from a Set Point True	Directions from a Set Point True[2]	True North is Vertical on Map	Seamless	Displays Entire Earth
Recommended Projections									
Lambert Conformal Conic	9801, 9802	3968	Yes	No	No	No	No	Yes	No
Mercator	9804, 9805, 1044	3395	Yes	No	No	No	Yes	Yes	No
Polar Stereographic	9810, 9829, 9830	3031	Yes	No	No	Yes	No	Yes	No
Transverse Mercator	9807	32720	Yes	No	No	No	No	Yes	No
Additional Projections									
Albers Equal Area Conic	9822	3338	No	Yes	No	No	No	Yes	No
Azimuthal Equidistant	None	None	No	No	Yes	Yes	No	Yes	Yes
Cylindrical Equidistant	1028	4087	No	No	No	No	Yes	Yes	Yes
Gnomonic	None	None	No	No	No	Yes	No	Yes	No
Miller	None	None	No	No	No	No	Yes	Yes	Yes
Multi-Equirectangular (ARC)	None	None	No	No	No	No	Yes	No	No
Orthographic	9840	None	No	No	No	No	No	Yes	No
Plate Carrée (“WGS 84”)	1029, 9825	4326	No	No	No	No	Yes	Yes	Yes
Robinson	None	None	No	No	No	No	No	Yes	Yes
Web Mercator	1024	3857	No	No	No	No	Yes	Yes	No

Footnotes
[1]Conformal
[2]Azimuthal

12.2 Summary of map projection usages

Table 5 – Summary of map projection usages

	Appropriate Applications				Suitable Mapping Uses	
Map Projections	**Navigation**	**Relative Positioning**	**Mission Planning**	**Visualization**	**Usable Scale[1]**	**Tiled Raster Graphics**
Recommended Projections						
Lambert Conformal Conic					All	
Mercator					All	
Polar Stereographic					All	
Transverse Mercator					All	
Additional Projections						
Albers Equal Area Conic					Med, Small	
Cylindrical Equidistant					Small, Global	
Gnomonic					Med, Small	
Miller					Global	
Multi-Equirectangular (ARC)					Large	
Orthographic					Small	
Plate Carrée (“WGS 84”)					Global	
Azimuthal Equidistant					Med, Small	
Robinson					Global	
Web Mercator					All	

Footnotes	Color Key
[1]Scales defined as:	**Recommended**
Large = Larger than 1:50,000	**Not recommended, potential risk**
Med = 1:50,001 to 1:500,000	**Discouraged, not appropriate**
Small = 1:500,001 to 1:5,000,000	
Global = Smaller than 1:5,000,000	

Note: Select a green, yellow, or red cell above to view an associated user scenario

12.3 Table 4 and Table 5 column definitions

The columns headings from the above tables are defined below for additional clarification.

12.3.1 Column definitions for Table 4

Operation Method: The code assigned to the map projection formulas by the International Association of Oil and Gas Producers (IOGP) [formerly the European Petroleum Survey Group (EPSG)].

Projected CRS Example: An example of the code assigned by EPSG for a projected CRS. A projected CRS is the combined specification of map projection formulas, map projection parameters, and geodetic datum.

Small Shapes, Local Angles, Local Scale Correct: Indicates whether the map projection is conformal.

Areas Preserved: Indicates whether the area of a polygon on the map is correct.

Distances from a Set Point True: Indicates whether the map projection contains a set point from which the distance to any other point is correct.

Directions from a Set Point True: Indicates whether the map projection contains a set point from which the starting azimuth of the shortest path to any other point is correct.

True North is Vertical on Map: Indicates whether true North points straight up (vertical) on the screen/paper.

Seamless: Indicates whether there are any seams (multiple map projections pieced together).

Displays Entire Earth: Indicates whether the entire Earth can be made visible on one map.

12.3.2 Column definitions for Table 5

Navigation: Indicates whether the map projection can be used for land, sea, and air navigation provided that its sources, content, scale, and usage adhere to Navigation doctrine.

Relative Positioning: Indicates whether the map projection can be used for relative positioning, *i.e.* the determination of the coordinates of a point by applying range and bearing measurements relative to a point whose coordinates are known. This is to be done for short distances using map projection coordinates within the principles of plane geometry, rather than geodetic coordinates within the algorithms for geodesics.

Mission Planning: Indicates whether the map projection can be used for land, sea, air, and intelligence mission planning purposes.

Visualization: Indicates whether the map projection can be used to visualize data to support land, sea, air, and intelligence mission planning.

Usable Scale: Indicates the scales for which the map projection is best suited.

Tiled Raster Graphics: Indicates whether the projection is suitable for Tiled Raster Graphics as outlined by the NGA Standard Implementation Guidance (NGA.SIG.0014_1.0_PROJRAS).

13 User Scenarios

13.1 Introduction

The following Epics and User Scenarios tie to "Table 5 – Summary of Map Projection Usages" in Section 12. Each Epic describes a broad situation and then the Scenarios provide an outcome based solely upon a chosen map projection. The Scenarios only provide one instance of usage and do not attempt to cover all possible situations or applications. The "Green Cells", "Yellow Cells", and "Red Cells" in the User Scenarios below refer to the cells found in Table 5.

13.2 Navigation

Epic 1 – Create a product that can be used for NGA Safety of Navigation purposes.

User Scenario 1.1 - Green Cells A GEOINT Analyst constructs a custom coastal chart using a map projection shown as a Green Cell. The specific map projection is indicated in the margin notes/metadata to allow any customer who sees the chart to know how it is projected. The ship successfully completes its navigation mission without incident.

User Scenario 1.2 - Yellow Cells A GEOINT Analyst constructs a custom coastal chart using a map projection shown as a Yellow Cell. The specific map projection is indicated in the margin notes/metadata to allow any customer who sees the chart to know how it is projected. The customer is not well versed in map projections and does not notice that there is a mismatch between the chart and NGA standard products. The ship barely avoids a hazard, but successfully completes its navigation mission. The cause of the near collision was due to using a slightly non-conformal map projection.

User Scenario 1.3 - Red Cells A GEOINT Analyst constructs a custom coastal chart using a map projection shown as a Red Cell. The specific map projection is indicated in the margin notes/metadata to allow any customer who sees the chart to know how it is projected. The customer is not well versed in map projections and does not notice that there is a mismatch between the chart and NGA standard products. The ship collides with a hazard causing major damage and complete mission failure. It was determined the collision was the result of using a severely non-conformal map projection.

13.3 Relative positioning

Epic 2 – Provide a Cross Country Mobility map to travel between two points across a country.

User Scenario 2.1 - Green Cells Team A and Team M have an operational support mission and need to mobilize from their respective bases and complete a time dependent, simultaneous rendezvous at a specific location. A mission planner prepares a cross country mobility graphic using a Green Cell map projection and distributes it to both Teams. Team A's mission requires an East-West route to get to the destination, but Team M's mission requires a North-South route. Since both Teams have a conformal map projection, the East-West and North-South scales are consistent and each team's departure times are calculated correctly. The mission is a success as both Teams arrive simultaneously at the specific location.

User Scenario 2.2 - Yellow Cells Team A and Team M have an operational support mission and need to mobilize from their respective bases and complete a time dependent, simultaneous rendezvous at a specific location. A mission planner prepares a cross country mobility graphic using a Yellow Cell map projection and distributes it to both Teams. Team A's mission requires an East-West route to get to the destination, but Team M's mission requires a North-South route. Due to the small distortion induced by the non-conformality of the projection, Team A's departure time is miscalculated, whereas Team M's departure time is correctly calculated. Team A then arrives shortly after the predetermined time at the specific location, nearly causing a mission failure. Team M arrives at the correct time, unsupported by Team A for a short time.

User Scenario 2.3 - Red Cells Team A and Team M have an operational support mission and need to mobilize from their respective bases and complete a time dependent simultaneous rendezvous at a specific location. A mission planner prepares a cross country mobility graphic using a Red Cell map projection and distributes it to both Teams. Team A's mission requires an East-West route to get to the destination, but Team M's mission requires a North-South route. Due to the distortion induced by the non-conformality of the projection, Team A's departure time is miscalculated, whereas Team M's departure time is correctly calculated. Team A then arrives significantly after the predetermined time at the specific location, thereby not lending support to Team M and causing a mission failure.

13.4 Mission planning

Epic 3 – Provide a map product that shows the local streets of a city for situational awareness.

User Scenario 3.1 - Green Cells A GEOINT Analyst has a requirement to provide a customer a map of a foreign city to use in mission planning. The customer understands the product is not suitable for making measurements (distances, angles, etc.) and can only be used for general planning purposes. Any map projection chosen by the GEOINT Analyst will suit the needs of the customer due to the scale requirements and usage of the product.

User Scenario 3.2 - Yellow Cells NONE

User Scenario 3.3 - Red Cells NONE

13.5 Visualization

Epic 4 – Provide a map product that shows the jurisdictions of agencies around the world.

User Scenario 4.1 - Green Cells An analyst has a requirement to provide a customer a map of the whole world to show which agencies are responsible for various portions of the world. The customer understands the product is not suitable for making measurements (distances, angles, etc.) and can only be used for general visualization purposes. Any map projection chosen by the analyst will suit the needs of the customer due to the scale requirements and use case of the product.

User Scenario 4.2 - Yellow Cells NONE

User Scenario 4.3 - Red Cells NONE

13.6 Tiled raster graphics

Epic 5 - Manage an application and associated data that displays tiled raster graphics in a zoom level interface, commonly called a pyramid of tiles.

User Scenario 5.1 - Green Cells A developer has a requirement to build an app for a hand-held device to display image tiles. The map projection chosen for the app is shown as a Green Cell. The displayed tiles are compatible with NGA standard products (adjusting for scaling) and result in a properly functioning app.

User Scenario 5.2 - Yellow Cells A developer has a requirement to build an app for a hand-held device to display image tiles. The map projection chosen for the app is shown as a Yellow Cell in order to display commercial data. The displayed tiles are not compatible with NGA standard products. The developer then redesigns the app to use a Green Cell map projection and combines it with a pre-process that converts the commercial data to the Green Cell projection ("tiled image converter"). After the redesign, the displayed tiles are compatible with NGA standard products.

User Scenario 5.3 - Red Cells A developer has a requirement to build an app for a hand-held device to display image tiles. The map projection chosen for the app is shown as a Red Cell. The developer tests the app with NGA standard data. Because there is no conversion of the data, the image tiles do not display correctly. The developer needs to redesign the app to work with NGA standard data.

Appendix A – UTM Squares and Choice of Projection

Introduction

This appendix suggests a method by which cartographers and GIS analysts can ascertain how much validity adheres to the map projection they have chosen for their large-scale product or large-scale analytical work. In brief, the procedure is to overlay a UTM grid on the map or GIS layer they have created and see how the squares of the UTM grid are portrayed. If the UTM grid squares are actually portrayed as squares on the map or GIS layer, then the choice of map projection was valid, with a caveat to be stated later. If the UTM grid squares are some other shape, not square, then the choice of map projection should be reconsidered. The reconsideration could lead to choosing another map projection in agreement with this SIG, or it could mean keeping the map projection and providing an analytical justification that the lack-of-validity uncovered is inconsequential to the purposes of the map or GIS layer.

This ideas in this appendix appeared earlier as NGA GEOINT Note:
http://intel.nga.ic.gov/products/2017/6/21/NGAGN-604850R1-17/Overview.html

This appendix is organized as follows:

- The procedure to be followed
- Examples:
    - Mogadishu, Somalia as portrayed on:
        - Zone 1 of the ARC System
        - Web Mercator (EPSG:3857)
    - Barrow, Alaska as portrayed on:
        - Mercator projection
        - Plate Carrée projection
- Why the UTM grid system is recommended for this analysis
- Limitations of the UTM system for this analysis

The procedure

The UTM system divides the world into 60 zones by longitude as described in various NGA documents, such as NGA.STND.0037. Zone 1 is from 180°W to 174°W. Zone 2 is from 174°W to 168°W, *etc*. The zone to use should be the one that includes the area-of-interest (AoI) or includes a majority of the AoI. If the AoI is north of 84°N or south of 80°S, the algorithm for UTM found in NGA document NGA.SIG.0012_2.0.0_UTMUPS might be necessary.

Let the cartographer or analyst overlay the UTM grid on the proposed/finished map/GIS-layer as a temporary expedient. Grid spacing of 1000m (1 km) or 10,000m (10km) is typical. The enabling software must be capable of converting the grid lines' coordinates from their native UTM values to latitude/longitude and then to the map projection coordinates of the chosen (candidate) map projection.

The UTM grid lines, as portrayed by the above procedure, will create quadrilateral shapes of some kind by their intersections. Squares are good; rectangles, parallelograms and other shapes are red flags, *i.e.* indications of the need for reconsideration.

At this point, the visual appearance of the portrayed UTM grid squares might be enough. If quantitative analysis is needed, lengths and angles pertaining to the UTM "square" (now quadrilateral) should be obtained. In other words, assuming the cartographic/GIS software has such tools, the lengths of the sides of the UTM "square" and the angles of intersection of its sides can be measured as items belonging to the map projection plane. If the map projection is conformal, and the AoI is small enough, the sides of the portrayed UTM square should be equal, and meet at right angles, same as they do on the Earth.

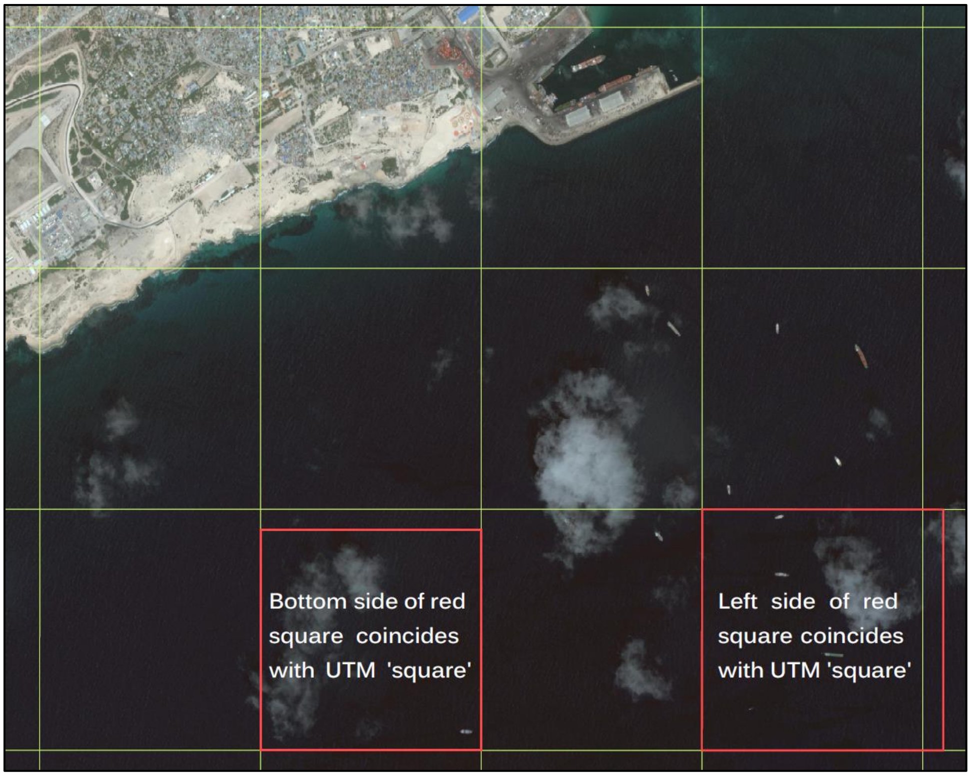

Fig. 17. Mogadishu on Zone 1 of the ARC System

UTM grid lines (green) and perfect squares (red) are overlaid on an image of Mogadishu, Somalia (45°E, 2°N) to show the effect of the non-conformality of Zone 1 of the ARC System. The aspect ratio of the UTM grid squares as portrayed is incorrect. This may be stated in two ways. In the example on the left, the UTM squares are shown to be too tall for their width, while in the example on the right, the UTM squares are shown to be too narrow for their height.

Example 1 – Mogadishu on Zone 1 of the ARC System

In Fig. 17. the city of Mogadishu, Somalia (45°E, 2°N) is portrayed on Zone 1 of the Equal Arc Second Raster/Chart System (the ARC System, for short). This is an instance of the equidistant-by-latitude cylindrical projection (ESRI::102421), with standard parallel 22.94791772°N.

This projection is not conformal, and not recommended for large-scale work. One result of the non-conformality is that the scale cannot be stated as a single scale-bar or a single ratio. The north-south scale is different than the east-west scale. If Fig. 17. were to be printed so that the 1000mE on the UTM grid became 5.0 cm on paper, then (rounding to 3 significant digits), the east-west scale would be 1:20,000, but the north-south scale would be 1:18,300.

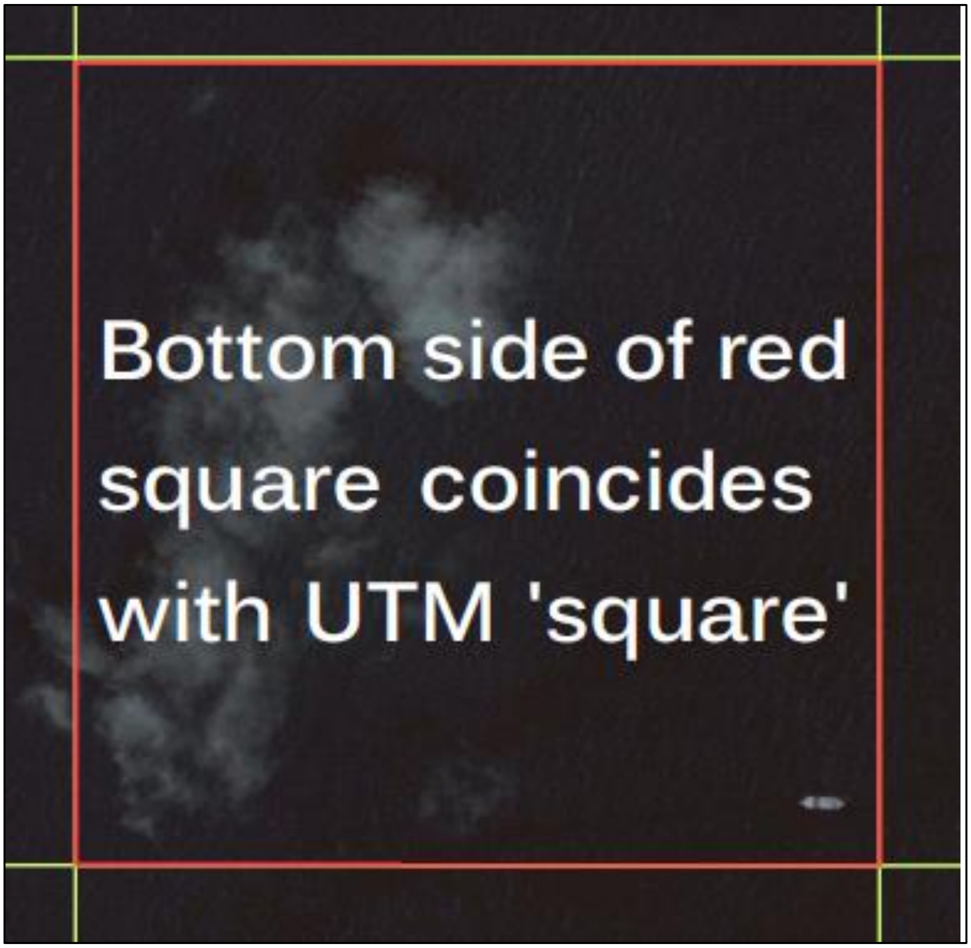

Fig. 18. Mogadishu on web-Mercator.

UTM grid lines (green) and a perfect square (red) are overlaid on an image of Mogadishu, Somalia (45°E, 2°N, off-shore) to show the effect of the non-conformality of the web Mercator projection. The UTM square, as portrayed on Web-Mercator, is slightly too tall for its width.

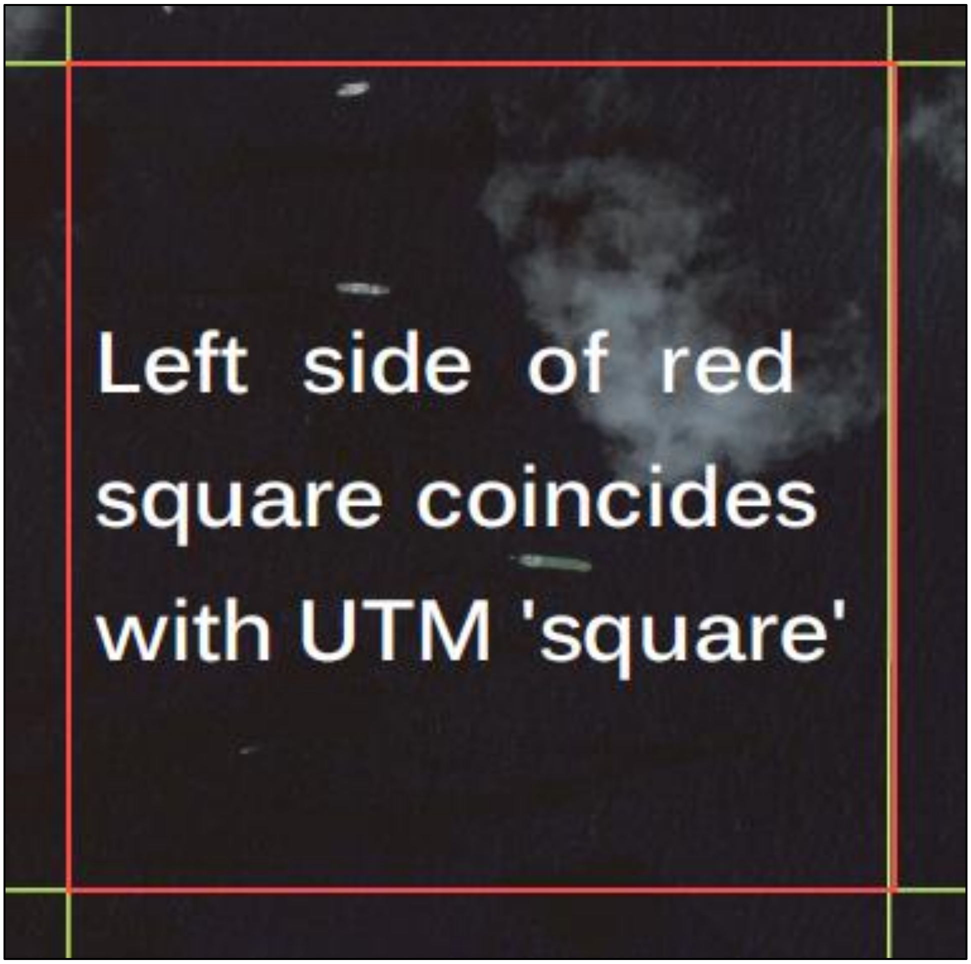

Fig. 19. Mogadishu on web-Mercator (continued).
UTM grid lines (green) and a perfect square (red) are overlaid on an image Mogadishu, Somalia (45°E, 2°N, off-shore) to show the effect of the non-conformality of the web Mercator projection. The UTM square, as portrayed on Web-Mercator, is slightly too narrow for its height.

Example 2 – Mogadishu on the Web Mercator projection

In Fig. 18. and Fig. 19., an area offshore of Mogadishu, Somalia (45°E, 2°N) is portrayed on the web Mercator projection (EPSG::3857) with overlays of UTM grid squares (1000mE by 1000mN) taken from UTM zone 38. Web Mercator is not conformal but fails to be so by a small amount, which these figures show.

If the graphics in Fig. 18. and Fig. 19. were printed so that the 1000mE on the UTM grid became 5.0 cm on paper, then the east-west scale would be 1:20,000 but the north-south scale would be 1:19,860. As a consequence, intervals of 1000mN on the UTM grid would print at 5.03 cm, not 5.00 cm as, perhaps, expected. The plastic overlays for finding UTM coordinates between printed UTM lines will not work perfectly when the UTM grid squares are distorted this way.

The effect of the non-conformality is compounded when larger UTM squares are considered. An interval of 10,000mE (*eastings*) on the grid would print at 50.00 cm on paper, but an interval of 10,000mN (*northings*) would print at 50.30 cm. The discrepancy is 0.30 cm or 3 mm on paper, and corresponds to 60 meters on the ground (rounded) at either ratio, 1:20,000 or 1:19,860.

The effect of the non-conformality is present at every scale. Zooming-in to a smaller portion of the Earth does not mitigate. If, instead of the above, the map was 10x larger (with, perhaps, an AoI that was 10x smaller), and it was **100 m** grid lines that were drawn, and **100mE** on the UTM grid that was printed at 5.00 cm on paper, the scale discrepancy would be the same, relatively. An interval of 100mN on the UTM grid would be portrayed as 5.03 cm on paper, not 5.00 cm as perhaps expected.

A cartographer or GIS analyst who is interested to use a non-conformal projection for large scale work must know or discover what departure from conformality can be accepted. A useful quantification of the departure from conformality is the ratio m of the north-south scale over the east-west scale. In the above example, as first stated, we had:

$$m = \frac{\frac{1}{19860}}{\frac{1}{20000}} = 1.007$$

For the case that the map is 10x larger, the calculation for m would give the same value:

$$m = \frac{\frac{1}{1986}}{\frac{1}{2000}} = 1.007$$

For web-Mercator in general, the quantity m is latitude-dependent, and latitudes near zero are the worst cases.

Example 3 – Barrow, Alaska on the Mercator projection

In Fig. 20, the city of Barrow, Alaska is portrayed on the Mercator projection (EPSG::3395). The Mercator projection is conformal, but there is another problem. Because the projection is conformal, the individual UTM 1000m squares are properly portrayed as squares, but because the latitude is so far north, the UTM 1000m squares increase in size, going north, combining to create a small distortion of the UTM 10,000m square.

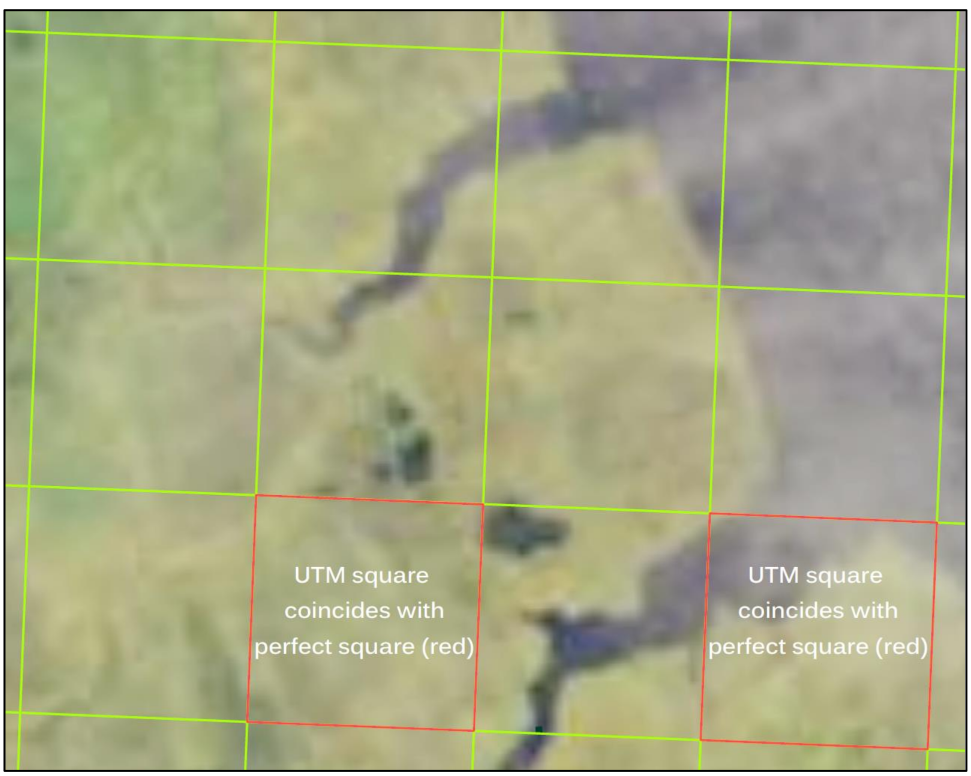

Fig. 20. Barrow, AK, on Mercator.

UTM grid lines (green) and a perfect square (red) are overlaid on an image of Barrow, Alaska using the Mercator projection. At this scale – 1000mE on the UTM grid in the middle of the AoI equals 5.00 cm on paper – the UTM 1000m squares coincide with the squares drawn in red.

The UTM 1000m squares depicted in Fig. 20. belong to the larger UTM 10,000m square whose southwest corner is 580,000mE by 7910,000mN. Let an actual square on the projection plane be drawn using the SW and SE corners of the larger UTM square as its baseline. Then both the NW and NE corners of the larger UTM square will lie outside the actual square drawn. They will lie outside by 1 mm horizontally and 1 mm vertically when printed at the scale 1000mE equals 5.00 cm at the middle of the AoI, *i.e.* at 7915,000mN on the UTM grid. These amounts can be substantiated by the GEOTRANS software.

Example 4 – Barrow, Alaska on the Plate Carrée projection

In Fig. 21, the city of Barrow, Alaska is portrayed on the Plate Carrée projection, also known as "geographics", or "unprojected". In essence, the map projection is $x =$ longitude and $y =$ latitude. This is a poor choice generally and an especially poor choice at high latitudes, such as for Barrow, AK. Because grid North (defined by the $+y$ direction of the UTM coordinates) is at an angle to true North in this case, the UTM squares are distorted into parallelograms.

Fig. 21. Barrow, AK on Plate Carrée.

UTM grid lines (green) and perfect squares (red) are overlaid on an image of Barrow, Alaska, using the Plate Carrée projection. The severe distortion due to this projection is apparent.

Summary of examples

A review of the examples in this Appendix is given in Table 6 – Examples.

Table 6 – Examples of UTM squares on choices of projection

#	Map projection	City	Comments
1	Equidistant (equi-rectangular)	Mogadishu	Significantly non-conformal.
2	Web-Mercator	Mogadishu	Non-conformal by a small amount.
3	Mercator	Barrow	Conformal, but size-distortion at high latitudes affects larger UTM squares.
4	Plate Carrée	Barrow	Severely non-conformal.

The above are examples where the choice of map projection is not ideal. Where possible, an appropriate conformal projection should be used instead.

Why the UTM system is a successful measuring tool

This appendix employs the UTM grid system as a measuring tool for the desired analysis. It is a successful tool for this, because it divides the world into 60 longitudinal strips, and gives each strip (zone) its own map projection coordinates (grid coordinates). In doing so, the problem of managing the distortions for the whole world in one map are avoided. Within the longitudinal strip, the distortion is well managed: one meter on the UTM grid is the same as one meter on the WGS 84 ellipsoid model of the Earth to within one part per thousand.

The UTM system is available for any part of the world. This includes the Poles and polar areas if the algorithms in NGA.SIG.0012_2.0.0_UTMUPS are implemented.

Limitations of the UTM system as a measuring tool

This appendix employs the UTM grid system as a measuring tool for the desired analysis. As stated above, one meter on the UTM grid agrees with one meter on the WGS 84 ellipsoid model of the Earth to within one part per thousand, while staying within a $6°$ wide zone of longitude. It is possible to design grid coordinates for smaller areas that have better agreement with the ellipsoid. For example, the state of Nevada is entirely within UTM zone 11, but the State Plane Coordinates for Nevada divide it into three zones – East, Central, and West – for better agreement with the ellipsoid.