

Adaptive Composite Map Projections

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Abstract—All major web mapping services use the web Mercator projection. This is a poor choice for maps of the entire globe or areas of the size of continents or larger countries because the Mercator projection shows medium and higher latitudes with extreme areal distortion and provides an erroneous impression of distances and relative areas. The web Mercator projection is also not able to show the entire globe, as polar latitudes cannot be mapped. When selecting an alternative projection for information visualization, rivaling factors have to be taken into account, such as map scale, the geographic area shown, the map's height-to-width ratio, and the type of cartographic visualization. It is impossible for a single map projection to meet the requirements for all these factors. The proposed composite map projection combines several projections that are recommended in cartographic literature and seamlessly morphs map space as the user changes map scale or the geographic region displayed. The composite projection adapts the map's geometry to scale, to the map's height-to-width ratio, and to the central latitude of the displayed area by replacing projections and adjusting their parameters. The composite projection shows the entire globe including poles; it portrays continents or larger countries with less distortion (optionally without areal distortion); and it can morph to the web Mercator projection for maps showing small regions.

Index terms—Multi-scale map, web mapping, web cartography, web map projection, web Mercator, HTML5 Canvas.

1 INTRODUCTION

All major web-mapping frameworks, such as Google Maps or Microsoft's Bing Maps, use the web Mercator projection. The Mercator projection is a compromise for web maps that are based on pre-rendered raster images tiled together to compose the map. But for maps showing the entire globe or areas of the size of continents or larger countries (i.e., maps at small scales), the Mercator projection is an inappropriate choice because it generates the following problems:

- Enormous areal distortion at higher latitudes.
- Areas of features at different latitudes cannot be visually compared, as map-readers are not able to compensate for the areal distortion induced by the Mercator projection [1].
- Impossibility of showing the entire globe, as poles are placed at infinite distance from the equator.
- Some data visualization types are difficult to interpret. For example, choropleth or dot maps require an equal-area base [27].

A better map projection is needed for interactive small-scale maps, which allow the user to adjust scale and the geographic area displayed. The alternative projection must minimize space distortion and be applicable for all map scales, all geographic latitudes, and all map formats. Since a single map projection cannot meet all constraints, a composite of multiple map projections is proposed.

The main contribution of this paper is a composition schema involving multiple projections. Projection types and associated parameters are selected, such that the geometry of the map changes seamlessly without a visual discontinuity as the user changes scale or the central latitude. At small scales, the mapmaker can choose among different projections to adapt map geometry to a particular format or application. At large scales, the composite can be made compatible with existing mapping services by including the web Mercator projection. Compared to the static web Mercator projection, the adaptive composite projection offers the following benefits:

- The composite projection can optionally be made equivalent (that is, equal area) for all scales, resulting in a faithful representation of areas.
 - Polar views, that is, maps including the North or South Pole, are possible.
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- Higher latitudes do not suffer from awkward distortion.

This contribution fills a gap in the context of information visualization. While the information visualization community has drawn inspiration from cartographic techniques in the past for solving many difficult aspects in map and visualization design (e.g., color selection [36], [38], legend design ([9], flow mapping [35], road network visualization [14]), only little attention has been paid so far to the question of map projection selection for information visualization [26]. This seems unfortunate, as many infovis systems utilize maps to show, explore, and analyze geographic data. For these maps to be unambiguous and efficient to read, the choice of a projection is as relevant as the choice of a visualization technique, a color scheme or other visual variables.

The rest of this paper is structured as follows: Section 2 first discusses the Mercator projection and its problems for small-scale maps, then reviews the selection of map projections as recommended in cartographic literature, and finally defines assessment criteria for an alternative projection. Section 3 describes the adaptive composite map projection. It discusses (a) the projections and the transitions between projections for world and continental maps, (b) projections for large-scale maps in square, portrait and landscape format, and (c) the inclusion of the Mercator projection at largest scales. Section 4 describes a proof-of-concept implementation, and section 5 evaluates results. Section 6 completes the exposition with conclusions and future work.

2 MAP PROJECTIONS

Literately hundreds of map projections for transforming spherical or ellipsoidal coordinates to Euclidean space have been described. Due to this plethora of available options, selecting an appropriate projection is often a non-trivial problem, and there is no one-size-fits-all solution to it.

In 1569, Gerardus Mercator presented a cylindrical map projection that he devised for nautical navigation. The projection maps lines of constant angular direction or compass bearing, known as rhumb lines or loxodromes, as straight segments. As with all cylindrical projections, the parallels and meridians form a grid of straight and perpendicular lines. Mercator's projection is conformal (preserving angles and infinitesimal shapes). Size of large objects is increasingly distorted away from the equator, as scale increases towards the poles, where it is infinite (Figure 1).

In 2005, Google introduced their mapping service based on Mercator's projection. With its public API, Google Maps quickly became the leading mapping service, and its web Mercator projection the de-facto standard for web maps. The Mercator

projection is an acceptable compromise when a single projection is to be used for all scales and a wide latitude range. Strebe identifies the following advantages [31]: (a) The majority of maps are viewed at very large scales, where the relative area distortion is of less importance. Shapes look right at large scales, because the Mercator projection is conformal. If a single equal-area projection were used instead, some regions would inevitably be considerably sheared. (b) Because the Mercator projection is a cylindrical projection, north is always in upward direction on a map oriented north. This would not be the case on non-cylindrical projections. (c) Mercator's projection is the only one that is both cylindrical and conformal, which offers the additional benefit that directions are always the same regardless of what portion the user looks at.

Regardless of its advantages for large scales, the Mercator projection is not a good choice for maps at small and medium scales. This section identifies these problems, reviews principles for selecting map projections, and defines criteria for assessing the proposed adaptive composite projection.

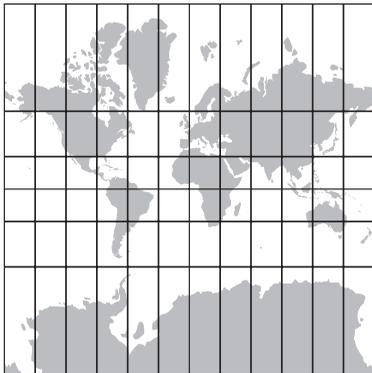


Fig. 1. Greenland takes as much area as Africa on the Mercator map, but is 14 times smaller in reality. Latitudes beyond $\pm 85^\circ$ are clipped.

2.1 Mercator Projection for World Maps

Academic cartographers have speculated about the existence of the Mercator Effect, which would cause a distorted cognitive map of the world (exaggerating the size of poleward areas), resulting from the continuing exposure to the Mercator projection (e.g., [23], [25]). While Chiodo [6] and Saarinen and colleagues [25] found distortion patterns in sketch maps of the world that seemed due to the Mercator projection, Battersby and Montello found no evidence of the Mercator Effect [2]. Battersby found in another study that people are quite capable in interpreting areas shown on maps, but are unable to compensate for areal distortions introduced by map projections, even if the distortion patterns are known [1]. This confirms MacEachren's observation that map-readers assume "relative size on the map corresponds to relative size in the world" ([17], p. 315). With a map projection introducing enormous areal distortion, readers are "likely to (mis)interpret the sign-vehicles to mean something that they do not [17]." Hence, areal distortion is a problem when map readers compare the size of areas at different latitudes. It is also a problem for various cartographic methods that require an equal-area base for visualization, for example, choropleth maps (showing values usually normalized by area by differently shaded areas) or dot maps (where the shown relative density of dots changes with areal distortion) [27]. These density techniques require an equal-area base both for calculation and visualization.

Accordingly, cartographers have warned for a long time against using Mercator's projection for maps at small scales [3], [19], [20], [22-24], [28], but the Mercator projection has been widely (mis)used in the past for world maps despite these warnings. In non-systematic surveys, it has been found on wall maps, free promotional maps, cheap atlases, encyclopedias and backdrops for evening news on major US TV channels (e.g., [23], [28]; for overviews [19], [20]).

The fact that poles are impossible to represent with the web Mercator projection is another major drawback. Since poles would

be placed at infinite distance from the equator, the web Mercator projection only stretches up to approximately 85° north and south.

To summarize, Mercator's projection is inappropriate for maps at small scales, where an alternative projection with less areal distortion should be applied.

2.2 Selecting a Map Projection

Several classifications and selection guidelines exist for map projections (e.g., [12], [16], [18], [29], [33], and for overviews [5], [7], [21]). Snyder has presented the most systematic and practical selection guideline, so far, for map projections [29]. Snyder suggests a hierarchical tree for different mapping purposes, organized according to the region of the world to be mapped, the projection property (e.g., equivalent, conformal, azimuthal), and other characteristics. This hierarchy can be converted to decision trees for interactive decision support systems [10], [15], [21].

While the selection process aims at finding the projection resulting in the map with the lowest distortion, there is also an esthetic criterion for the selection of map projections [27]. Personal taste and the projection's influence on the overall map design are additional major selection criteria. Werner and Gilmartin both showed that map readers prefer projections with an elliptical outline or pseudocylindrical projections (with straight parallels and curved meridians). Least preferred projections were cylindrical projections, as for example the Mercator projection [11], [37]. Gilmartin also found that more compact proportions are preferred [11].

The first level in Snyder's decision tree distinguishes between three categories of geographic extent: (1) maps showing the entire world, (2) maps showing areas of the size of a hemisphere, and (3) maps of a continent, ocean or smaller regions. For maps of the entire world or a hemisphere, the branches of the next level of the decision tree are properties such as conformality, equivalence, or equidistance.

World. For world maps, if equivalency and a standard aspect is required, Snyder recommends the following projections for uninterrupted maps: Hammer, Mollweide, Eckert IV or VI, McBryde or McBryde-Thomas variations, Boggs Eumorphic, Sinusoidal, or miscellaneous pseudocylindricals.

Hemisphere. For equivalent maps showing an area of the size of a hemisphere, Snyder recommends the Lambert azimuthal projection.

Smaller areas. For maps showing continents or smaller areas, the first level of the decision tree relates to the directional extent of the map. The four categories are (1) a predominant east-west extent (landscape format), (2) north-south extend (portrait format), (3) equal extent (square format) or (4) an oblique orientation of the major axis of the mapped area. For portrait and square formats, Snyder distinguishes between different locations (along equator, on pole or in between). The final level in the decision tree distinguishes between conformal and equivalent projections (Table 1 for equal-area projections).

Table 1. A portion of Snyder's selection guideline for continents and smaller areas. Only equal-area projections. (After [27]).

Level 1 Directional Extent	Level 2 Location	Level 3 Projection (equal-area only)
East-West	Along equator	Lambert cylindrical
	Away from equator	Albers conic
North-South	Anywhere	Lambert transverse cylindrical
Equal extent	Near poles	Lambert azimuthal polar
	Along equator	Lambert azimuthal equatorial
	Away from pole or equator	Lambert azimuthal oblique

Snyder's decision tree is not deterministic, and additional projection parameters, such as the standard parallels, must also be determined. These parameters are often selected by estimation [29].

2.3 Quality Criteria

A projection for web mapping services has to satisfy criteria related to distortion, the shape of the graticule (the grid of lines of latitude and longitude), esthetics, and map navigation.

Distortion. Depending on the map's purpose and its type of visualization, the projection should minimize distortion of area, angles, shapes, directions, distances, etc. For a general-purpose mapping service, an equal-area projection is an appropriate default because many thematic maps require equal area geometry to show phenomena in correct proportion per unit area [27]. Conformality (the preservation of angles) is a rare requirement for world maps at small scales [5], and at large scales conformality is less relevant as virtual rulers can compensate for distorted angles and distances, or a conformal projection, such as the Mercator projection can be included in the composite.

Graticule border and shape. The shape of the graticule (the lines of constant latitude and longitude) should meet the following requirements:

- Assuming an inward pointing border or an otherwise uncommonly shaped border might be visually distracting, such borders should be avoided.
- For all projections suggested by selection guidelines mentioned above, the equator is shown as a straight line when the map is centered on it.
- Rectangular straight lines facilitate the comparison of latitudinal or longitudinal positions. For this reason, cylindrical projections are often used for maps at large scales near the equator, and pseudocylindrical projections (with straight parallels and curved meridians) for world maps [29].
- For polar views, straight meridians should be used to facilitate the comparison of directions relative to the pole [18].

Esthetics. The choice of projection is also a question of esthetics and design, particularly for world maps. For example, projections with elliptical outlines are generally preferred over those with rectangular shapes [11], [37]. Many authors include selection criteria, such as symmetry, ratio of axes or the shape of outlines, parallels and meridians (e.g., [7]). The globe may graphically well fit with available screen space with one projection, but not with another. The composite should therefore offer alternative small-scale projections with differently shaped graticules and aspect ratios.

Map navigation. When the user changes map scale or the geographical area displayed, geometry has to be projected on the fly at responsive frame rates. The morphing should not result in sudden visual discontinuities while map scale changes or while the geographic area is repositioned. This criterion excludes from the outset interrupted projections that reduce distortion by creating one or more lobes by cutting the graticule along specific meridians, which results in a non-continuous map space. Examples of interrupted projections include the interrupted Goode homolosine, or the class of myriahedral projections developed by van Wijk [34].

3 THE ADAPTIVE COMPOSITE MAP PROJECTION

Following Snyder's selection guideline, the composite map projection combines various projections. The default projections are the Hammer projection for equal-area world maps (third map in Fig. 2), Lambert's azimuthal equal-area projection for showing an area of the size of a hemisphere (first map in Fig. 2), and the projections in Table 1 for smaller areas. If desired, the map can morph into the conformal web Mercator projection at large scales.

If equivalency is not required, an alternative compromise projection can be selected for showing the entire globe. Compromise projections are neither conformal nor equivalent, but tend to show continents with less shape distortion. Snyder recommends the

pseudocylindrical Robinson projection, or—if a rectangular graticule is required—the Miller cylindrical projection [29]. A recently developed alternative to Robinson's is the Natural Earth projection with similar distortion properties (bottom of Figure 4) [32].

The selected projections are parameterized for a visually seamless transition between the different projections. Parameters depend on map scale, the latitude of the central point, and the height-to-width ratio of the map. To allow for interactive map scrolling, the center of the map is adjusted by transforming the central spherical longitude and latitude on the globe before projecting to Euclidean space [29].

3.1 Projections for World and Hemispherical Views

For equivalent maps, Snyder recommends the Lambert azimuthal projection for maps showing an area of the extent of a hemisphere. This is the projection included in the suggested composite.

Of the several equal-area projections suggested by Snyder for world maps, the Hammer projection has the interesting property of being convertible into Lambert's azimuthal projection. In 1892, Hammer transformed the Lambert azimuthal to obtain his equal-area projection [13], following a method introduced by Aitoff in 1889 [30]. Hammer's projection is therefore also called Hammer-Aitoff. To construct his projection, Hammer stretches the central hemisphere of the equatorial aspect of Lambert's azimuthal projection along the abscissa by a factor of 2, and doubles the value of each meridian, resulting in Equation 1 (after [4]).

$$x = \frac{B\sqrt{2} \cos \phi \sin(\lambda/B)}{\eta}, y = \frac{\sqrt{2} \sin \phi}{\eta}, \eta = \sqrt{1 + \cos \phi \cos(\lambda/B)} \quad (1)$$

In Equation 1, x and y are the projected coordinates, λ and ϕ are spherical longitude and latitude, and B is a coefficient larger than 1. Hammer sets $B = 2$, resulting in an ellipsoidal outline with a height-to-width ratio of 1:2 and bent parallels. With the limiting case $B = 1$, Lambert's azimuthal projection is obtained. As B increases, parallels are becoming flatter (Figure 2). The variant with $B = 4$ is the Eckert-Greifendorff projection [4]. When B is made infinity Siemon's quartic authalic projection with straight parallels is obtained [30]. All projections are equal-area.

In the suggested composite projection, the default for showing the entire globe is Hammer's projection with $B = 2$. As the user enlarges this global map towards a map showing an area of the size of a hemisphere, B is linearly reduced with scale and ends in the azimuthal projection at a certain scale limit. This scale limit was chosen at 1.5. This scale value is relative to the scale of a world map using the Hammer projection that vertically fills the available canvas space. Hence a scale value of 1.5 results in a map with 75% of its vertical extent visible on the canvas.

If a pseudocylindrical world projection is required, the equivalent quartic authalic projection can be used (equations in [30]). Equal-area morphing towards this projection is possible by adjusting the B coefficient with scale (Figure 2).

If the Hammer or quartic authalic projection is replaced by another projection, linear interpolation could be used to morph the alternative projection into the Lambert azimuthal projection. This consists in converting longitude and latitude with the selected projection to X_w / Y_w , and with the Lambert azimuthal to X_L / Y_L . The final coordinate then results from a weighted mean of the two coordinates pairs, with the weight linearly proportional to map scale. However, this approach is not recommended as it overly bends parallels, adds considerable shape distortion, and, due to the spherical shape of the azimuthal graticule, folds graticule lines (Figure 3). A better approach is to interpolate the small-scale world projection with a customized Hammer projection that adjusts the B coefficient between 1 and infinity. This is illustrated in Figure 4, where the Natural Earth projection is interpolated with a continuously modified Hammer projection. The linear interpolation weight is $1/B$. It is to be noted that with this interpolation method, the resulting projection is not equal-area, though one projection is equal-area.

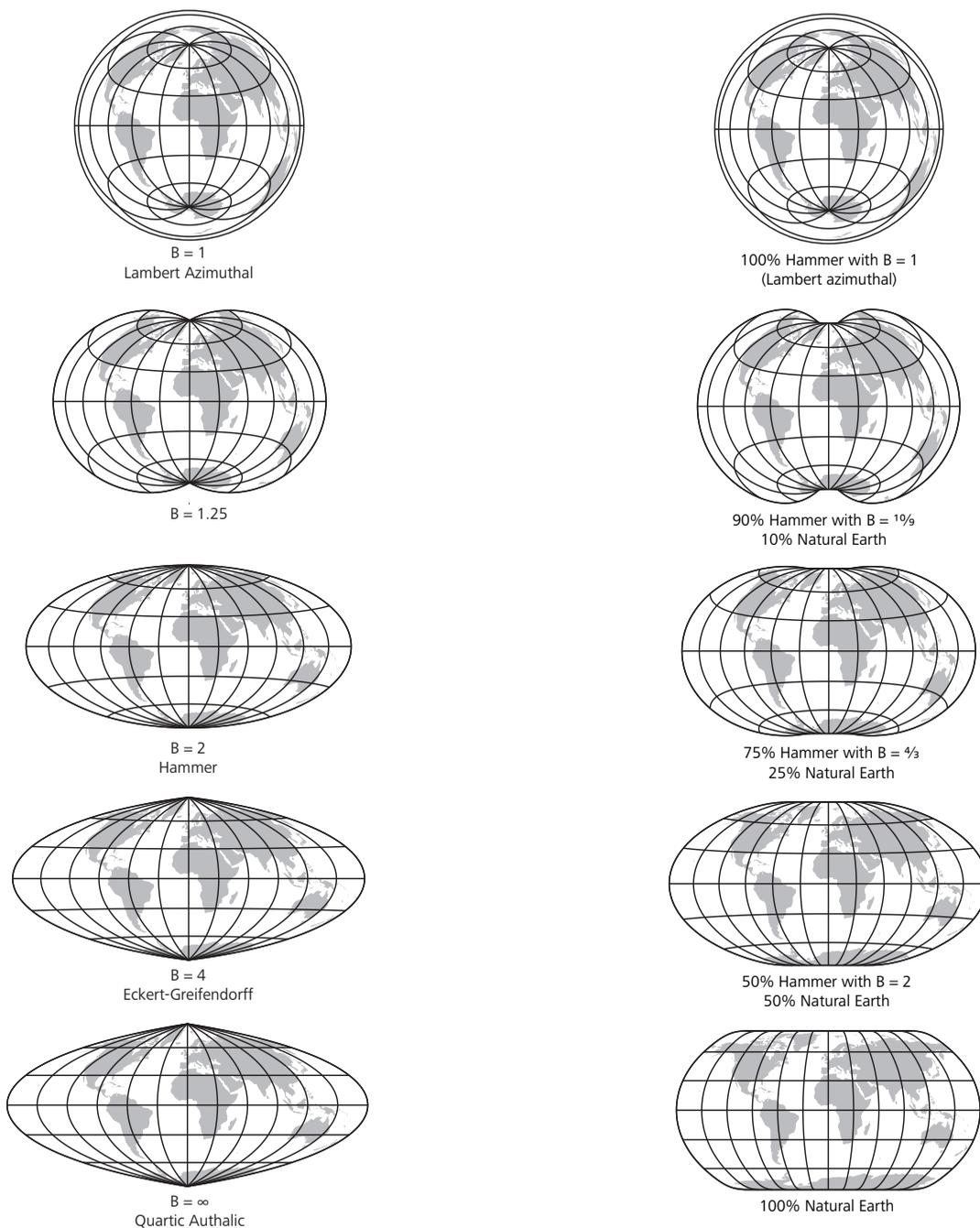


Fig. 2. Customizing the Hammer projection ($B = 2$) for equal-area morphing towards the Lambert azimuthal projection ($B < 2$) and towards a pseudocylindrical (straight parallels) projection ($B > 2$).

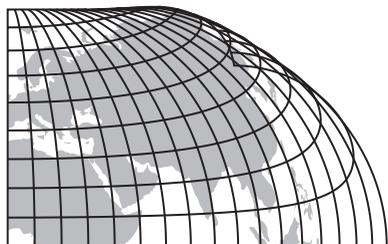


Fig. 3. Interpolating Natural Earth (50%) and Lambert azimuthal projections (50%) results in a curvy and folded graticule.

To center the map on a specific geographic location, the globe is rotated before the spherical coordinates are projected to Euclidean space. The globe is rotated around its vertical axis by adding the cen-

Fig. 4. The Natural Earth projection (non-equal area) interpolated with a continuously modified Hammer projection.

tral longitude value to each spherical coordinate. This rotation does not generate any unusual representation of the continents, as we are all accustomed to seeing maps not centered on the Greenwich Meridian. The vertical rotation requires basic spherical trigonometry [29] and can result in unusual-looking continental outlines. Figure 5 shows an example of a map that depicts about one half of the landmasses with uncommon orientation and distortion. Areas that are considerably rotated or moved to the edges of this map visually stand out, as they do not correspond with our familiar mental image of the world ([5], p. 82). However, such oblique aspects may offer new perspectives on the arrangement and association of spatial information, especially when mapping circumpolar phenomena. If the map's focus is on equatorial latitudes, the vertical rotation of poles can optionally be limited—or if parallels are required to be shown as straight lines in overview world maps, vertical polar rotation can be made impossible. If vertical rotation is prevented for

world maps, special care is taken at slightly larger scales, where the customized Hammer projection is used, to limit rotation such that the upper indentation of the graticule is placed at the upper border of the map (Figure 6). This hides the unusual indentation caused by the customized Hammer projection when a *B* coefficient between 1 and 2 is used (Figure 2, second map). This spiky dent might be confusing and graphically unpleasing. At scales showing smaller sections of the globe, the poles can be moved to the center of the map (as in Figure 7, top left), but not beyond, as this would generate confusing south-oriented maps, and cause difficulty for spatial navigation.

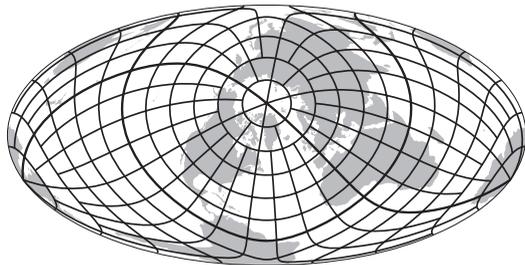


Fig. 5. Rotated world maps show landmasses placed at the border of the graticule with unusual distortion patterns. South America is crushed, Australia is split, and Japan is upside down (Hammer projection centered on 50°W / 70°N).

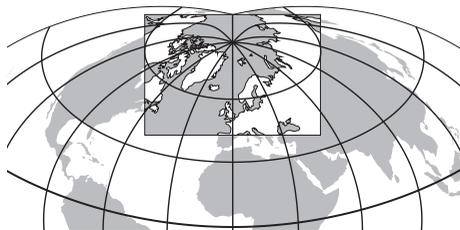


Fig. 6. Polar rotation is limited such that the polar indentation of the modified Hammer projection remains invisible. The rectangle is the area shown on the map (customized Hammer projection with $B = 1.45$).

3.2 Projections for Smaller Areas

For maps showing geographic regions of the size of continents or smaller areas, Snyder’s first level in the decision tree is the height-to-width ratio of the area mapped (left column in Table 1). This section discusses the composite’s projections and transitions for square, landscape and portrait formats at larger scales.

3.2.1 Square format maps

The Lambert azimuthal projection is used for square format maps throughout all scales and for all latitudes because azimuthal projections minimize distortion for regions with no predominant length in one direction (Figure 7). The Lambert azimuthal is also the projection used for maps at smaller scales showing areas of the size of a hemisphere. Hence, only the longitude and the latitude of the projection center have to be adjusted as the user re-centers the map. This can be achieved by either applying a transformation on the sphere, or, in order to increase computational efficiency, an “oblique” equation including the transformation [29].

3.2.2 Landscape format maps

For equal-area maps in landscape format, Snyder suggests three different projections (Figure 8). The Lambert azimuthal projection is well suited for polar areas, as it shows all meridians as straight lines radiating from the pole. For areas close to the equator, the Lambert cylindrical is used in the normal aspect with the cylinder touching the globe along the equator. The Lambert cylindrical shows meridians and parallels forming a regular grid of straight lines. Considering that on most web maps the graticule is not visible, straight parallels will likely help users compare north-south and east-

west relationships. The Albers conic is appropriate for intermediate latitudes because angular distortion is small and meridians are shown as straight radiating lines and parallels as concentric arcs. Its projection cone is oriented such that the axis aligns with the rotation axis of the globe.

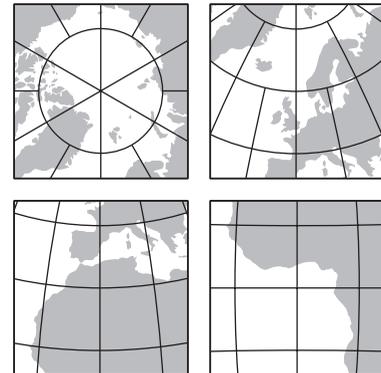


Fig. 7. Square format transition between polar, oblique (here at 60°N and 30°N) and equatorial aspects of the Lambert azimuthal projection.

The Albers conic projection has two standard parallels along which there is no areal, angular or scale distortion. Their location should be selected to minimize overall scale and angular distortion. Rules of thumb as well as more advanced methods exist for placing the standard parallels [18], [29]. For the composite map projection, standard parallels are placed at a distance of 1/6 of the height (in spherical coordinates) from the upper and lower map borders [8].

Lambert’s azimuthal and cylindrical projections are limiting forms of the Albers conic projection. The cylindrical form is obtained when the two standard parallels are placed on the equator. If the two standard parallels of the conic are placed on a pole, the Albers conic converts to the polar aspect of the Lambert azimuthal. Hence, by adjusting the position of the two standard parallels, seamless transitions between the three projections are possible, and for all cases the map is equal area (Figure 8).



Fig. 8. Landscape format transition between polar Lambert azimuthal (top left), Albers conic (top right and lower left) and Lambert cylindrical projections (lower right) by adjusting standard parallels of the conic.

Figure 9 illustrates the selection of projections. Latitude of the map center increases with the ordinate; map scale increases along the abscissa. Scale values are relative to the scale of a world map (using the small-scale projection) that vertically fills the available canvas space. For example, a scale value of 2 results in a map with 50% of its vertical extension visible on the canvas. Thick lines separate composited projections. Dashed lines separate scale and latitude ranges where parameters of a projection are interpolated. For example, the Lambert cylindrical is applied when the latitude of the central point of the map is close to the equator. Standard parallels are moved from the equator to their default position for the conic projection. In Figure 9 the area of standard parallels interpolation is labeled with “Albers conic with adjusted standard parallels” near the equator and delimited with a dashed line. This interpolation is carried out for a central latitude range between 15° and 22°.

The same method is applied when transitioning to the Lambert azimuthal projection near poles. Standard parallels are gradually

moved from the default position for the conic towards the poles. The default central latitude limits for this interpolation are 60° and 75°. Additionally, the 75°-latitude limit for this transition (represented as horizontal line in Figure 9 at 75°) is adjusted such that the azimuthal projection is always used when the pole is visible in the map. This adjustment is necessary because the conic projection shows poles as circular lines (Figure 10). Such a polar line would be confusing because a visual interruption would appear when scrolling the mapped area from the equator to a pole. The thin curved line in Figure 9 indicates the latitude of the central point of the map for which the pole line of the Albers conic projection would be shown. The default 75°-latitude limit is moved towards the equator for small scales along this curved line. To compute the limiting values, equations for the oblique Albers conic are used with both standard parallels set to the poles. The latitude of the origin of this coordinate system (which will appear in the center of the map) is moved towards the equator until the pole appears on the border of the map. The calculated latitude of the origin replaces the default limit.

wedge. To compensate for the necessary translation, the globe is rotated along the central meridian before the projection is applied. The rotation re-centers the map on the original central latitude. For a seamless transition between the conic and the azimuthal, the azimuthal has to be transformed in the same way. The Euclidean translation, the spherical rotation, and the flattening of the cone are linearly proportional to map scale for both the azimuthal and the conic projection. The transformation is applied in a bandwidth around a threshold defining the transition between the two projections (the shaded area in Figure 9). The resulting maps in this transition zone are equivalent, but show more angular distortion than maps using projection with standard aspects, as indicated by Tissot's indicatrices along the lower border of Figure 11. The bandwidth around the threshold should therefore be minimized, but a narrow bandwidth would generate an eye-catching discontinuity, as parallels show some jittering when scale is gradually enlarged. Hence, the bandwidth is a compromise between these two opposed constraints. A scale factor of approximately 4 with a transition zone between around 3 and 6 has resulted in a visually acceptable transition.

Near the equator, an equal-area transition between the azimuthal for medium scales and the cylindrical for large scales can only be realized via a conic. A translation and a rotation as outlined above are applied. If a conic projection is used for maps centered on the equator, the equator appears as a bent line, which might be contrary to what map readers are used to. If a straight equator line is preferred, the transition zone can be narrowed to a triangle with one tip on the equator, shown as the lower tip of the shaded area in Figure 9. This narrowed transition introduces a slight visual discontinuity when the map is centered on the equator and the

scale factor transitions the tip of the triangle. Parallels suddenly change between slightly curved (azimuthal projection) and straight lines (cylindrical projection) when transitioning the tip.

Near poles, Lambert's azimuthal is used with an oblique aspect for medium scales and with a polar aspect for large scales. For a seamless transition between the two, the point of tangency ϕ_0 is linearly interpolated with scale.

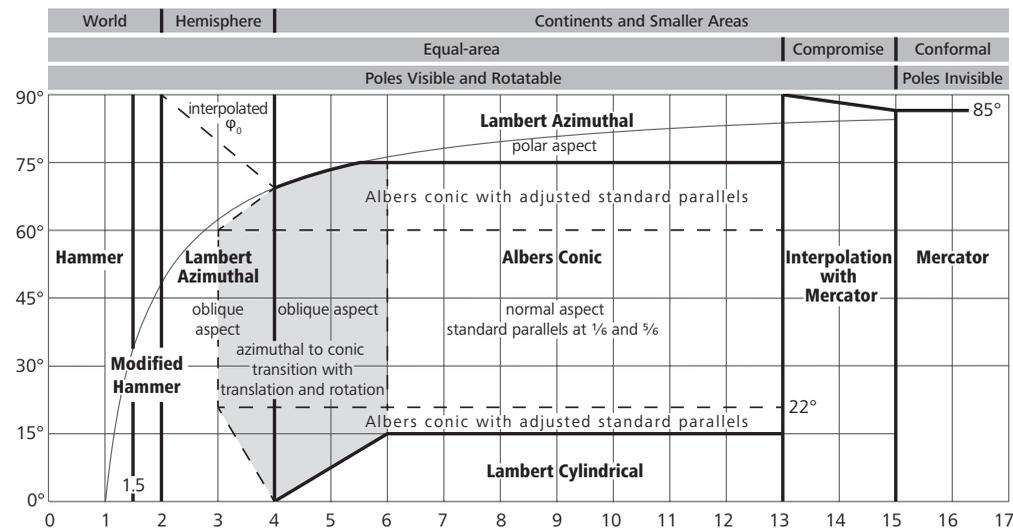


Fig. 9. Projection selection for maps in landscape format. Scale along abscissa; central latitude along the ordinate. The diagram is mirrored for the southern hemisphere.

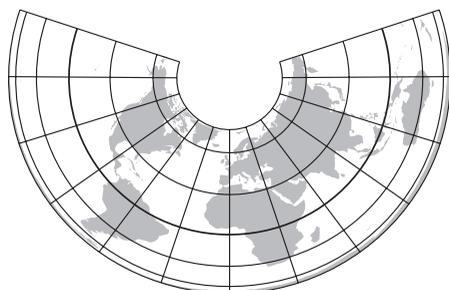


Fig. 10. The Albers conic projection shows poles as circular lines. Only a section centered on northern Africa is shown in the map.

When the user changes the scale of the map (moving along the abscissa in Figure 9), a transition between the Albers conic for large scales and the Lambert azimuthal for smaller scales is required. An Albers conic projection with an oblique aspect and a flattened cone is used for the transition. The axis of the cone is gradually shifted from the normal vertical position (coinciding with the globe's rotation axis) towards the latitude of the map center, as the area displayed in the map is enlarged. The cone is also gradually ablated until it is completely flat and the Albers' conic projection has morphed into Lambert's azimuthal projection. With such a flat cone, the border of the graticule is interrupted by a wedge-shaped intersection that is visible on the map when the cone is almost, but not entirely, flat (Figure 11). To hide the wedge, the map does not display the area in the center of the graticule, but an area adjacent to the tip of the

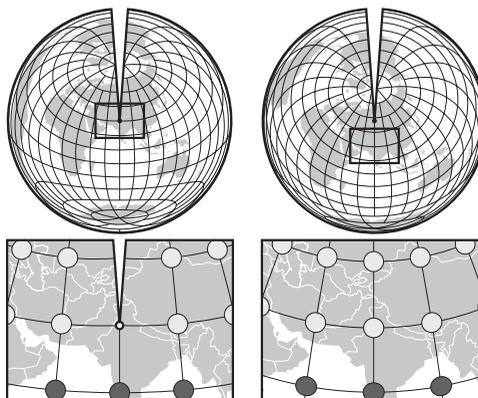


Fig. 11. The central part of an Albers conic map with a nearly flat cone has a wedge-shaped interruption (left), which is compensated with a vertical shift and a spherical rotation in opposite direction (right). Dark Tissot indicatrices (projections of infinitesimal circles) show more angular shearing along the lower border of the map on the right.

3.2.3 Portrait Format Maps

For portrait format maps, Snyder recommends the transverse Lambert cylindrical projection (Figure 12). With the transverse aspect, the cylinder's axis lies in the equatorial plane and the line of tangency between the cylinder and the globe follows the map's central meridian. An equal-area transition between the large-scale cylindrical and the medium-scale azimuthal projections can be achieved via an intermediate Albers conic projection, involving a translation and rotation, as for the transition in landscape format.

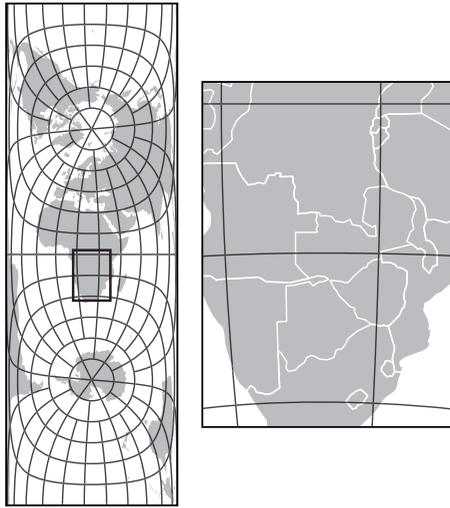


Fig. 12. Portrait format maps use the transverse Lambert cylindrical equal-area projection: the entire graticule (left) and the section shown in the map (right). Here centered on 15°S / 25°E.

3.3 Transition to the Web Mercator Projection

The conic, cylindrical and azimuthal projections described in the previous section can be morphed to the web Mercator projection, if compatibility with existing mapping services is required. The transition from an equivalent to a conformal projection uses linear interpolation with the interpolation factor linearly proportional to map scale. The outlines of the resulting graticules have unusual shapes, changing with central latitude and the relative contribution of the two projections. Since the map only shows a small central section, the outline remains invisible (Figure 13).

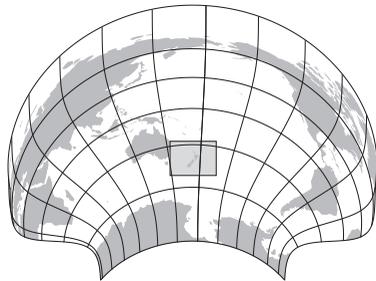


Fig. 13. Interpolating Albers conic (70%) and Mercator (30%). The shaded rectangle indicates the area shown on the map.

4 PROTOTYPE

A proof-of-concept implementation of the composite adaptive map projection was created in JavaScript and HTML5 Canvas, using vector data. GPU-accelerated raster projection [29] could alternatively be achieved with WebGL. The user can adjust map scale, the area displayed in the map, and the map's height-to-width ratio. All transitions are included. In our implementation, the transition between the azimuthal and the transverse cylindrical for portrait formats currently uses a non-equal-area arithmetic mean (between relative scale values of 4 and 6), which will be replaced with a transition via an Albers conic as described in Section 3.2.2.

Map geometry in spherical coordinates is stored in JavaScript structures, and projected before the map is drawn. A continuously smooth interactive response has been achieved with geometry consisting of 100,000 vertices with current web browsers on a 2.5 GHz Intel Core 2 Duo computer. With the present prototype, the time required for rasterizing geometry with HTML5 Canvas is considerably longer than the time for projecting geometry, especially when drawing filled polygons or text labels.

For landscape format maps, parameter values used for the prototype can be extracted from Figure 9. A map is in landscape format if height / width < 8 / 10; in portrait format if height / width > 10 / 8; and in square format otherwise. It is to be noted that the map author can adjust these default parameters, as well as the parameters reported in Figure 9 or in the text (such as the latitude and scale values for transitioning between projections). The proposed values have been established by visual inspection.

5 EVALUATION

Distortion. Minimizing distortion was the main goal when designing the adaptive composite projection. By swapping projections and adjusting their parameters, distortion is greatly reduced compared to static projections. Equal-area maps can be made for all scales with small angular shearing, a problem afflicting static equal-area maps along peripheral areas [31]. If equivalency is not required, various compromise projections can substitute for the Hammer projection at small scales to minimize shearing.

Graticule border and shape. The customized Hammer (Figure 6), the Albers conic (Figure 10), and the interpolated Mercator (Figure 13) have graticules with unusual and potentially disturbing outlines. With the measures described, these outlines do not appear on the map.

With Lambert's cylindrical and azimuthal projections, the graticule consists of rectangular straight lines along the equator, and straight meridians at poles. If an equal-area pseudocylindrical projection is needed, the Hammer projection can morph into the quartic authalic.

Esthetics. More esthetic compromise projections or projections with different aspect ratios can replace the default Hammer projection if equivalency is not required.

Map navigation. Projections seamlessly morph map space as the user adjusts map scale and the geographic area. With the discussed composition schema, a visual discontinuity appears in landscape format maps centered on the equator at the scale separating azimuthal and cylindrical projections (the equatorial tip of the shaded area in Figure 9). A sudden visual discontinuity also occurs when the map's height-to-width ratio changes continuously, which occurs, for example, when the aspect ratio of a browser window with an embedded map is changed.

As a preliminary step to a formal evaluation of the presented approach, the proof-of-concept implementation has been shown to about 90 people, mainly cartographers and experts in information visualization and geographic information science. Reception was generally very positive, particularly by cartographers, who are for the most part well aware of the problems associated with the use of the web Mercator projection for small-scale maps.

6 CONCLUSION

Composite map projections combine several projections that are optimized for a particular range of scale, geographic latitude and a map format. Composited projections are continuously adapted, such that geographic space seamlessly morphs as the user changes map scale or the area displayed. Projections with different distortion characteristics can be combined, including the web Mercator projection for showing small regions. Geographic space is represented with considerably less areal distortion than with the standard static web Mercator projection.

Some maps require non-equal area projections to best portray a phenomenon. For example, equidistance from a point or a line,

correct scale along meridians, or straight great circle routes may be required for mapping specialized topics. For some cases, the schema proposed in this work can be generalized to these requirements. An example is a scalable map requiring equidistance along meridians. For this case, Snyder recommends the azimuthal equidistant projection for showing the entire world or a hemisphere [29]. By analogy to the composite proposed in this work, the azimuthal equidistant can be combined with the equidistant variants of the conic and cylindrical projections for larger scales. As for the equal-area variants, the azimuthal and the cylindrical equidistant are special cases of the conic equidistant. (The equidistant cylindrical is commonly called Plate Carrée or geographic projection; equations for all projections can be found in [29]). It remains to be explored how other specialized projections can be composited to adaptive projections.

The main benefits of the proposed adaptive composite projection compared to the web maps using Mercator raster tiles are the fact that areas are displayed true to scale. This is an important factor at small and medium scales where areas at very different latitudes can be compared. At large scales the equal-area property is sometimes less relevant. The fact that the globe can be rotated and the poles shown as in Figure 5 can potentially offer new insights on the arrangement of geographic features, especially when mapping phenomena associated with polar areas, such as circumpolar bird migration, global warming, or melting ice sheets.

Experience gained with the described proof-of-concept implementation shows that on-the-fly projection of vector and raster data for web maps is feasible and interactive response rates can be achieved with current web browsers. The biggest weakness of the proposed composite projection might be the fact that existing tile-based web mapping systems have to be redesigned, components for storing, visualizing, transferring and caching vector map data have to be developed. Also, the proposed projection scheme is only useful when the information is truly multi-scale, that is, in some cases the user is unlikely to gain additional information when zooming in or out in a relatively coarse single-scale data set. A static map image might be more appropriate in these cases.

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