CHAPTER FOUR

The Map Projections

4.1 Introduction

A map projection is a 2-D model whereby the curved surface of the Earth is portrayed on a flat map, or it's a systematic representation of all or part of the surface of a round body, especially the earth, on a plane. If one looks only at a small portion of the Earth's surface such as a city map, it appears that local features on the map correctly portray the same features as viewed by a person walking or driving in that area. However, when dealing with larger and larger portions of the Earth's surface, distortion and the challenge of true map representation grow exponentially.

The transformation from carved surface to a plane cannot be accomplished without distortion. If the map covers a large area of the earth's surface - e.g. a continent - distortions will be visually apparent. If the region covered by the map is small, distortions might be barely measurable using many projections, yet it can be serious with other projections.

Cartography is the science of making maps and includes various graphical portrayals of spatial data. Using cartographic definitions, a graticule is the grid-like appearance of parallels and meridians covering the Earth, and a map projection is defined as a systematic arrangement of the graticule on a flat surface. The challenge is going from a curved surface to a flat map without distorting any geometric element. It can't be done. Most people know that when you peel an orange (even children enjoy making those pieces as big as possible), the curved peel will not lay flat on a table unless one presses it flat. In so doing, the peel is distorted. Either the peel tears or other parts of the peel are artificially compressed in the process of being flattened. However, if one considers only a small portion of the orange peel, it appears to be smooth and flat even though it originated from a spherical "whole." So it is with the Earth. Small portions of the surface can be represented very well using the assumption that the Earth is flat. But, when dealing with larger and larger areas on the Earth, the inevitable distortions that occur between the curved surface and the flat map must be accommodated.

Maps range from simple to complex and serve many purposes. In some cases, a map communicates best by grossly distorting geometrical detail. In other cases, the geometrical detail of a map is the basis of its value to the user. Given that most spatial data are now digital and given further the proliferation of computerized data visualization tools, the opportunities for cartographers to develop creative and innovative representations of spatial data have become innumerable.

Thus, the earth, however, is sphere; and the maps are flat. As it is impossible to make a sheet of paper rest smoothly on a sphere, so it is impossible to make a correct map on a sheet of paper. It is for this reason that projections have become necessary. A casual inspection of a good atlas will show that there are several different kinds of projections. In some the lines of latitude and longitude are straight, in others curved, and yet again, the meridians may be straight and the parallels curved, or vice versa. By making these several variations, however, certain advantages may be obtained, so that particular countries are better represented on one projection than on another.

Although it is impossible to make a correct map of any part of the globe, it is by no means difficult to maintain certain definite qualities in a projection. These qualities may be enumerated as preservation of area; preservation of shape (orthomorphism); preservation of scale; preservation of bearing, and ease of drawing.

In order that a map may be equal in area with that part of the globe which it represents, shape must be neglected. A combination of true shape and correct area is impossible. But it is easy to make one surface equal in area to another if it does not matter how much shape is discounted. For example, a rectangle whose sides are 1m and 4m is of the same area as a square on a base 2m long. Again, two parallelograms on the same base and between the same parallels are equal in area. By calculation a circle may be made to enclose a space equal to the surface dimensions of a sphere or of a zone. Many similar examples might be given, but these are sufficient to show that the preservation of area alone is a simple matter.

4.2 Types of Projections

Projections can be divided into three types: Azimuthal (Zenithal) projections, Conical projections, and cylindrical projections.

4.2.1 Azimuthal or Zenithal Projections

These projections are made upon a plane tangent to the globe at any point. Usually the point is taken at one of the poles or at some place on the equator; it can, however, be taken at any other point, but, if it is, the projection is more difficult to make. So far projections have been assumed on a plane tangent at a pole. But when it is moved from a pole, the meridians and parallels no longer project into straight lines and circles. When the plane is tangent at a point on the equator, this is called the equatorial aspect; when the point of tangency is between pole and equator, what is called the oblique aspect - Figure (4.1). No matter how different the parallels and meridians may appear on these two aspects, the properties that pertain to the polar aspect apply just the same; e.g. azimuths (bearings) are true from the point of tangency, and if the parallels are so spaced to give equivalence of area or some other property in the polar aspect, a corresponding set of radiating straight lines and circles based on the point of tangency would have the same properties, and so also would the graticule itself despite the different appearance of the lines of latitude and longitude.

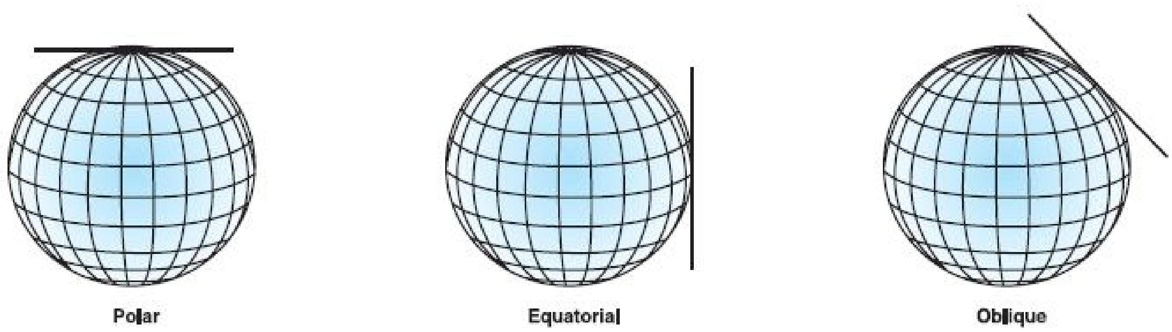

Figure (4.1) Azimuthal projection

A sub-division may be made into perspective and non-perspective zenithals. In the former the constructions are most easily visualized if one imagines a transparent globe, with the surface features painted on it, placed in various positions relative to a point of light. If the light be inside the earth - at the center - we have the Gnomonic; if at one end of a diameter, the stereographic; if at infinite distance away, the orthographic. In this last case all the rays are supposed to be parallel.

These three types of Azimuthal projections (Gnomonic, Stereographic, and Orthographic) are shown in the figure (4.2) and (4.3) below.

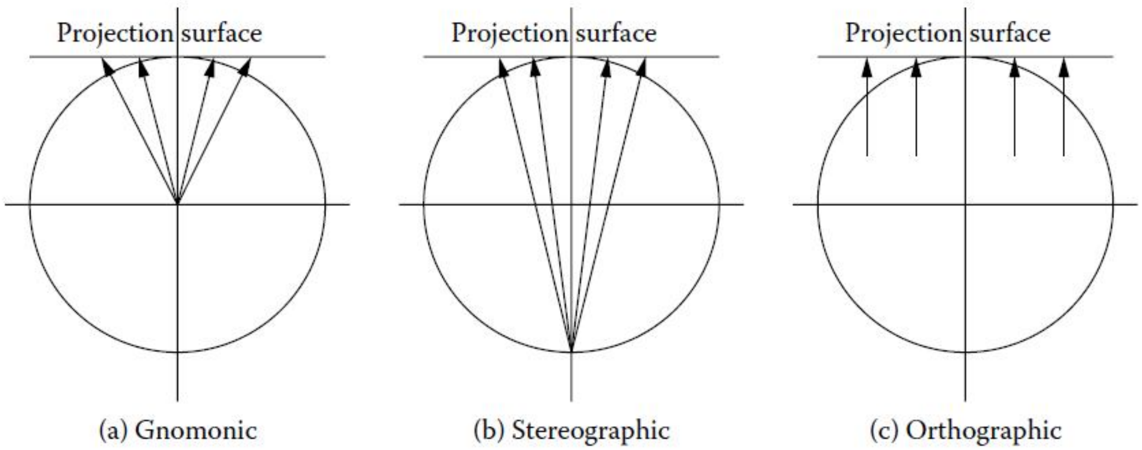

Figure (4.2) Projection lines of Gnomonic, Stereographic, and Orthographic

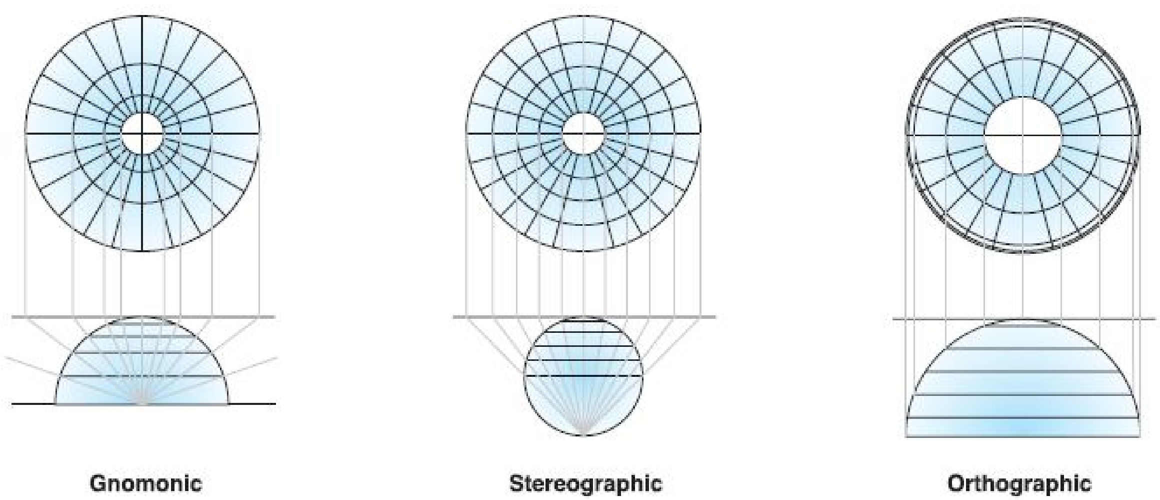

Figure (4.3) Gnomonic, Stereographic, and Orthographic

It is at once obvious that these are merely special cases; the source of light can be moved to any other position, as in the projections of La Hire, Sir H. James, Clarke, and others.

The non-geometrical zenithals include the zenithal equidistant and the zenithal equal-area. In the polar aspect of the former, the distances along the meridians are the same as on the globe, reduction being made for scale; and on the latter, the area between any two parallels is made the same as on a globe of corresponding scale. All zenithals possess the property of maintaining correct azimuths, or true bearings from the center of the map. This fact is most easily visualized in the polar cases, because the meridians all radiate out from the pole at their correct angular distance apart. The same property holds good if the plane on which the projection is constructed is tangent to the globe at any other point, but only in the polar case will the meridians correspond with the Azimuthal lines.

4.2.2 Conical Projections

A second type of projection can be made on a hollow cone set so as to touch the globe along any parallel of latitude between 0˚ and 90˚. The cone might also be tangent along any other small circle; but when the apex of the cone is not directly above one of the poles, the lines of latitude and longitude no longer project into circles and straight lines.

This group includes a large number of projections, several of which are in common use in atlases. The modifications which may b made are similar to those which are made in the zenithals and the cylindricals. There are both equal-area conical and orthomorphic conical as well as simple forms. All of them are very easy to draw and, as a class, they are suited to maps of countries in temperature latitudes which have not too great an extent in latitude.

As in the Azimuthal projections, the conical can be divided into three types depending on the way that the conic oriented when it is inserted into the earth, these types are equatorial, oblique, and transverse as shown in the figure (4.4) below.

Equatorial Oblique Transverse

Figure (4.4) Conical projection

4.2.2.1 The simple conic projection with one standard parallel

If a cone is placed over a sphere, it will touch it along one line. In the simple conic the pole of the cone is vertically above the pole of the globe and thus the two coincide (i.e. the globe and the cone) along a parallel of latitude. This is the standard parallel, and is divided truly. A central meridian is drawn to represent the meridian which runs through the center of the country to be mapped. The parallels are spaced along it at their true distances apart, reduction being made for scale.

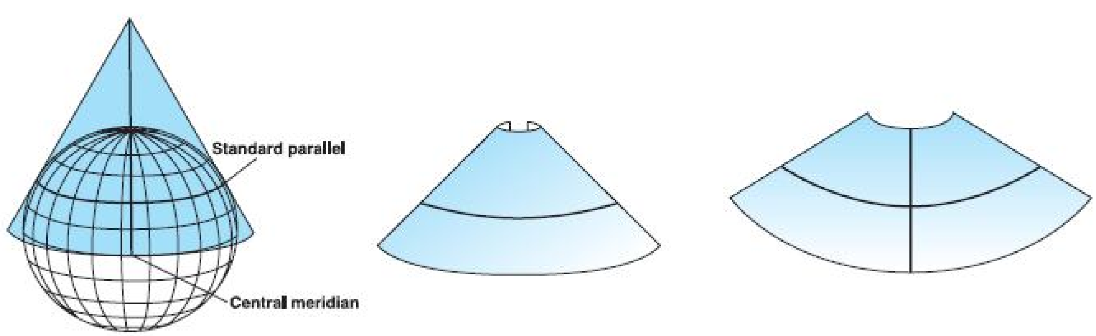

Figure (4.5) The simple conic projection

4.2.2.2 The conical with two standard parallels

In the usual form of the simple conic one parallel is made correct to scale. If, by slight modifications, we can have two parallels correct to scale as well as all the meridians, we have made a distinct advance, and have obtained a projection which is capable of wider application.

Any two parallels may be chosen as standards. Naturally they will vary according to the map. Their choice, however, depends on the most economic distribution of error for the whole map.

This projection has often been called the secant conic. This description is misleading. A secant of a circle is any straight line cutting the circumference at two points. If we were to make a true secant conic projection we should, therefore, make the distance between the standard parallels equal to the secant distance between them. As it is, we make use of the arc distance, so that the parallels are the same distance apart on the projection as on the globe, reduction being made for scale.

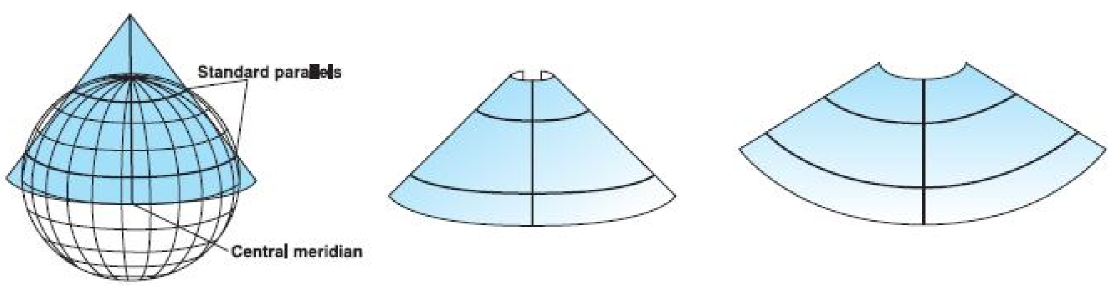

Figure (4.6) The conical with two standard parallels

4.2.3 Cylindrical Projections

A cylinder of paper can wrapped round a globe so as to touch it along the equator. If the source of light is central, the meridians will become straight lines on the paper spaced just as they are on the equator, and the parallels will be circles of the same length as the equator, but increasing rapidly in distance from one another towards the poles. The cylinder could also touch the globe along any other great circle, but if so the lines of latitude and longitude will be curves difficult to define in simple terms.

Projections on a circumscribed cylinder are frequently used in atlases. Most of them, however, are conventional or non-geometrical projections. If one were to make a perspective cylindrical projection, the exaggeration would be very great indeed, in fact, the same as in a Gnomonic. Cylindrical projections can also have tangent or secant cases.

As in the two previous types, there are normal, transverse, and oblique cylindrical projections - Figure (4.7).

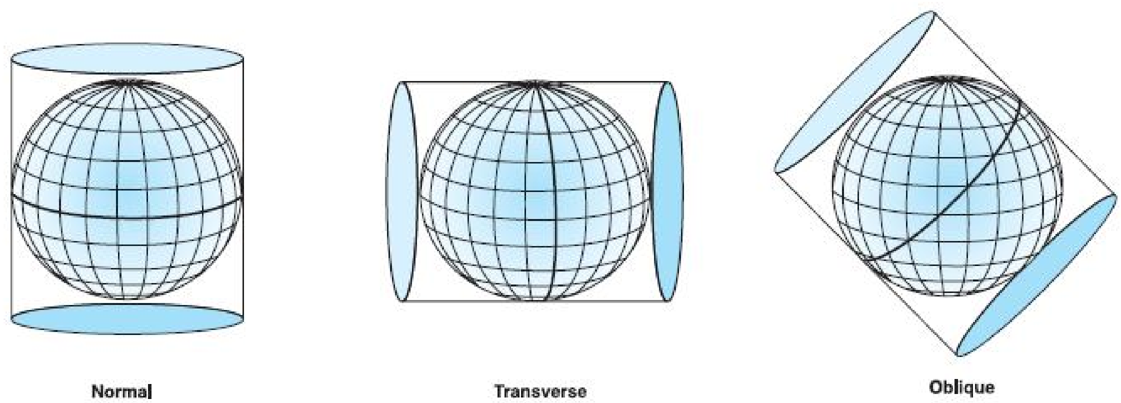

Figure (4.7) Cylindrical Projection

The cylinder need not touch the equator; it may encircle the globe along any great circle. A transverse Mercator is constructed on this principle. However, directly some slight calculations are employed in the equatorial case, useful modifications can be made. If the area between any two lines of latitude is preserved correctly, we have the cylindrical equal-area; if the exaggeration of the longitude scale is made to increase in the same proportion as the latitude scale, we have the Mercator or cylindrical orthomorphic projection.

These are the two commonest types, but the simple cylindrical in which the true spacing of the parallels is maintained, and the carte parllelogrammatique in which the scale along two parallels is correct, have some slight theoretical interest. They are in fact, the equivalents of the simple conic and the conic with two standards parallels.

4.2.3.1 The Simple Cylindrical Projection or Plate Carree

This is the cylindrical projection which corresponds to the simple conic and the zenithal equidistant. The meridians in each case are divided as on the globe, so that the parallels are their correct distance apart. In the simple cylindrical all that is necessary is to find the length of a meridian, divide it correctly, and draw the equator at right angles to it and, of course, twice it length. The other parallels are straight lines parallel to the equator and of the same length as the equator. The meridians are all straight lines perpendicular to the equator and spaced along it at their proper intervals. Thus the graticule forms a series of squares.

This projection is of little value; it is neither equal-area nor orthomorphic. Moreover, since the ninetieth parallel north or south latitude is, on the projection, the same length as the equator, it has all the disadvantages without any of the advantages of the other cylindrical projections. The scale is true along all the meridians and along the equator. The Plate Carree can be developed in an oblique form.

4.2.3.2 The Transverse Cylindrical or Cassini's Projection

This is in part a form of cylindrical projection; the cylindrical is supposed tangent to the globe along the central meridian of the area to be mapped. In order to make the map, first choose a central meridian and fix on some point for the center of the map.

4.2.3.3 The Cylindrical Equal-area Projection

In this projection, one of Lambert's, the meridian and parallels are straight lines and perpendicular one to another. But the area between any two parallels is made equal to the corresponding area on the globe.

4.2.3.4 The Cylindrical Equal-area Projection with two Standards parallels

In this projection, two parallels are chosen as standards and are divided truly. The area, however, between any parallel and the equator is to remain equal to the corresponding area on the globe.

4.2.3.5 Mercator's Projection

The Mercator projection is one of the most common cylindrical projections, and the equator is usually its line of tangency. Meridians are geometrically projected onto the cylindrical surface, and parallels are mathematically projected, producing graticular angles of 90 degrees. The cylinder is cut along any meridian to produce the final cylindrical projection. The meridians are equally spaced, while the spacing between parallel lines of latitude increases toward the poles. This projection is conformal and displays true direction along straight lines.

Mercator projection is properly the best known of all projections, because it is used for navigation purposes and also in nearly all atlases for maps of the world, and for wall-maps. Although it has certain great merits, it is largely responsible for many geographical misconceptions, e.g. the misleading appearance of the polar areas. These areas are greatly exaggerated when shown on this projection; this great increase in north and south latitudes apparently extends the size of the Antarctic continent enormously in comparison with equatorial regions.

Although Mercator is the most suitable projection for navigational purposes, the sailing routes themselves are not easily plotted on it, and difficulties are likely to arise unless the user of the map fully understands its limitations. On the projection all parallels are of the same length as the equator, and consequently the latitude scale increases with increasing distance from the equator. In fact, a separate scale line is necessary for each parallel. On the other hand, owing to the convergence of the meridians on the globe at the poles, the shortest distance between any two points due east and west of one another, and which are not on the equator, is not along the parallel of latitude passing through them, but is to the north of that line in the northern hemisphere and to the south of it in the southern hemisphere.

It is impossible to map a complete hemisphere on a Gnomonic chart, whereas the whole world, with the exception of very high latitudes, can be shown a Mercator map. This limitation may be overcome to some extent by developing the Gnomonic as on a circumscribed cube, but the calculations are long and it is not very convenient to have to plot sailing courses over different faces of the cube. In contrast to this, Mercator's projection is extremely simple to construct from tables; all that is necessary is to draw straight lines at their correct distances apart. Lastly, the fact that Mercator has come into such very wide use through navigation gives it an enormous pull over any other; it has had the momentum of a start.

The principle of the construction of Mercator's projection is simple, but the crux of the problem is so to space the parallels that at any point the scale is the same along meridian and parallel, so that orthomorphism is obtained. The projection is often called the cylindrical orthomorphic.

4.2.3.6 The oblique Mercator projection

The main characteristics of the Oblique Mercator Projection can be summarized as follows:

- It is an oblique cylindrical projection.
- It is a conformal projection.
- The two meridians 180˚ apart are straight lines.
- Other meridians and parallels are complex curves.
- The scale will be true along the chosen central line.
- Scale becomes infinite 90˚ from the central meridian.
- It is mainly used for areas with greater extent in an oblique direction.

4.2.3.7 The Transverse Mercator Projection

In the ordinary development of the Mercator projection, the cylinder on which the projection is made touches the globe along the equator. In the transverse case the cylinder touches the globe along any meridian. The meridians of the normal case appear as horizontal straight lines and the parallels as vertical lines. It will be noticed also that the vertical meridian of the transverse case is the equator of the normal projection. Moreover, the numbers of the new meridians are the complements of the numbers of the parallel in the original graticule; the same relation holds between the parallels in the transverse case and the meridians in the normal.

4.3 Universal Transverse Mercator (UTM)

The UTM is simply a transverse Mercator projection to which specific parameters, such as central meridians, have been applied. In other words, the Universal Transverse Mercator (UTM) is a grid-based method of specifying locations on the surface of the Earth that is a practical application of a 2-dimensional Cartesian coordinate system. It is a horizontal position representation, i.e. it is used to identify locations on the earth independently of vertical position, but differs from the traditional method of latitude and longitude in several respects.

The Universal Transverse Mercator coordinate system was developed by the United States Army Corps of Engineers in the 1940s. The system was based on an ellipsoidal model of Earth. For areas within the conterminous United States, the Clarke 1866 ellipsoid was used. For the remaining areas of Earth, including Hawaii, the International Ellipsoid was used. Currently, the WGS84 ellipsoid is used as the underlying model of Earth in the UTM.

Prior to the development of the Universal Transverse Mercator coordinate system, several European nations demonstrated the utility of grid-based conformal maps by mapping their territory during the interwar period. Calculating the distance between two points on these maps could be performed more easily in the field (using the Pythagorean Theorem) than was otherwise possible using the trigonometric formulas required under the graticule-based system of latitude and longitude. In the post-war years, these concepts were extended into the Universal Transverse Mercator / Universal

Polar Stereographic (UTM/UPS) coordinate system, which is a global (or universal) system of grid-based maps.

The transverse Mercator projection is a variant of the Mercator projection, which was originally developed by the Flemish geographer and cartographer Gerardus Mercator, in 1569. This projection is conformal, so that it preserves angles and approximates shape but invariably distorts distance and area. UTM involves non-linear scaling in both Eastings and Northings to ensure the projected map of the ellipsoid is conformal.

The UTM divides the surface of Earth between 80°S and 84°N latitude into 60 zones, each 6° of longitude in width and centered over a meridian of longitude. Zone 1 is bounded by longitude 180° to 174° W and is centered on the 177th West meridian. Zone numbering increases in an eastward direction.

Each of the 60 longitude zones in the UTM system is based on a transverse Mercator projection, which is capable of mapping a region of large north-south extent with a low amount of distortion. By using narrow zones of 6° (up to 800 km) in width, and reducing the scale factor along the central meridian by only 0.0004 to 0.9996 (a reduction of 1:2500), the amount of distortion is held below 1 part in 1,000 inside each zone. Distortion of scale increases to 1.0010 at the outer zone boundaries along the equator.

In each zone, the scale factor of the central meridian reduces the diameter of the transverse cylinder to produce a secant projection with two standard lines, or lines of true scale, located approximately 180 km on either side of, and approximately parallel to, the central meridian (ArcCos 0.9996 = 1.62° at the Equator). The scale factor is less than 1 inside these lines and greater than 1 outside of these lines, but the overall distortion of scale inside the entire zone is minimized.

Distortion of scale increases in each UTM zone as the boundaries between the UTM zones are approached. However, it is often convenient or necessary to measure a series of locations on a single grid when some are located in two adjacent zones. Around the boundaries of large scale maps (1:100,000 or larger) coordinates for both adjoining UTM zones are usually printed within a minimum distance of 40 km on either side of a zone boundary. Ideally, the coordinates of each position should be measured on the grid for the zone in which they are located, but because the scale factor is still relatively small near zone boundaries, it is possible to overlap measurements into an adjoining zone for some distance when necessary.

Each zone is segmented into 20 latitude bands. Latitude bands are not a part of UTM, but rather a part of Military Grid Reference System (MGRS). They are however sometimes used. Each latitude band is 8 degrees high, and is lettered starting from "C" at 80°S, increasing up the English alphabet until "X", omitting the letters "I" and "O" (because of their similarity to the numerals one and zero). The last latitude band, "X", is extended an extra 4 degrees, so it ends at 84°N latitude, thus covering the northernmost land on Earth. Latitude bands "A" and "B" do exist, as do bands "Y" and Z". They cover the western and eastern sides of the Antarctic and Arctic regions respectively. A convenient mnemonic to remember is that the letter "N" is the first letter in the northern hemisphere, so any letter coming before "N" in the alphabet is in the southern hemisphere, and any letter "N" or after is in the northern hemisphere.

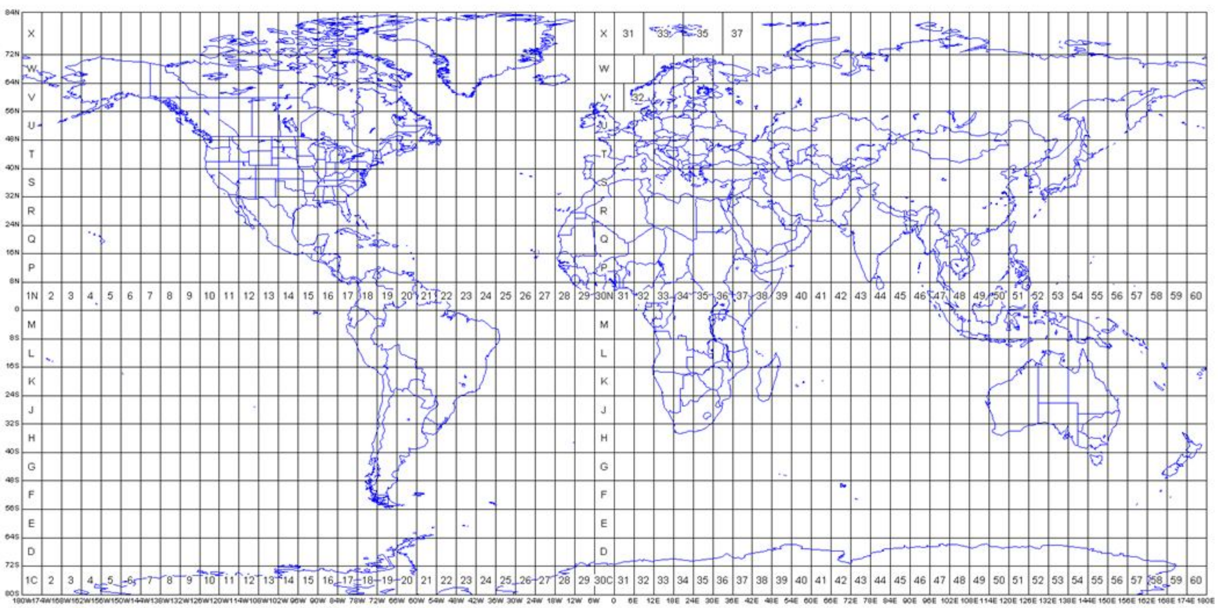

Figure (4.8): UTM zones and bands

The combination of a zone and a latitude band defines a grid zone. The zone is always written first, followed by the latitude band. For example, a position in Khartoum, Sudan, would find itself in zone 36 and latitude band "P", thus the full grid zone reference is "36P". The grid zones serve to delineate irregular UTM zone boundaries. They also are an integral part of the military grid reference system.

A note of caution, A method also is used that simply adds N or S following the zone number to indicate North or South hemisphere (the easting and northing coordinates along with the zone number supplying everything necessary to locate a position except which hemisphere). However, this method has caused some confusion since, for instance, "50S" can mean southern hemisphere but also grid zone "50S" in the northern hemisphere.

Because latitude band "S" is in the northern hemisphere, a designation such as "38S" is ambiguous. The "S" might refer to the latitude band (32°N –

40°N) or it might mean "South". It is therefore important to specify which convention is being used, e.g., by spelling out the hemisphere, "North" or "South", had been avoided in y=0 ,y=10000 from the equater.

These grid zones are uniform over the globe, except in two areas. On the southwest coast of Norway, grid zone 32V (9° of longitude in width) is extended further west, and grid zone 31V (3° of longitude in width) is correspondingly shrunk to cover only open water. Also, in the region around Svalbard, the four grid zones 31X (9° of longitude in width), 33X (12° of longitude in width), 35X (12° of longitude in width), and 37X (9° of longitude in width) are extended to cover what would otherwise have been covered by the seven grid zones 31X to 37X. The three grid zones 32X, 34X and 36X are not used.

A position on the Earth is referenced in the UTM system by the UTM zone, and the easting and northing coordinate pair. The easting is the projected distance of the position and westward from the central meridian, while the northing is the projected distance of the point north from the equator (in the northern hemisphere). Eastings and Northings are measured in meters. The point of origin of each UTM zone is the intersection of the equator and the zone's central meridian. In order to avoid dealing with negative numbers, the central meridian of each zone is given a "false easting" value of 500,000 meters. Thus, anything west of the central meridian will have an Easting less than 500,000 meters. For example, UTM Eastings range from 167,000 meters to 833,000 meters at the equator (these ranges narrow towards the poles). In the northern hemisphere, positions are measured northward from the equator, which has an initial "northing" value of 0 meters and a maximum "northing" value of approximately 9,328,000 meters at the 84th parallel - the maximum northern extent of the UTM zones. In the southern hemisphere, Northings decrease as you go southward from the equator, which is given a "false northing" of 10,000,000 meters so that no point within the zone has a negative northing value.

4.4 The Scale Factor

The origins of scale factors having been fully expounded, it simply remains to define them more specifically, thus:

$$F = {}^{G}/_{S}$$

Where F: Local scale factor (L.S.F).

G: Grid distance.

S: Distance on the spheroid at M.S.L.

A semi-rigorous formula for F may be deducted as follows. Scale error (S.E) is the difference between the scale factor at any point F and that at the central meridian F_0, and varies as the square of the distance from the central meridian. Thus:

$$S.E = K(\Delta E)^2$$

Where ΔE is the difference in Eastings of the point in question and the central meridian.

i.e. ΔE= (E-500000)m.

$\therefore F = F_0 + S.E$

F_0 is the L.S.F at the central meridian and equals 0.99960127.

$F = 0.99960127 + K(\Delta E)^2$.

Considering a point 180000m east or west of the central meridian, its value for F is unity, thus:

$1 = 0.99960127 + K(180000)^2$

$\therefore K = 1.228 \times 10^{-4}$

And hence:

$$F = 0.99960127 + [1.228 \times 10^{-4} \times (E - 500000)^2]$$

It's recommended that for every accurate work the L.S.F should be computed at each end of the line and in the middle, and the mean value obtained from Simpson's rule. However, for all practical purposes it is sufficient to compute the L.S.F at the middle point of the line.

It is very important to realize that the scale factor relates only to distances on the spheroid at M.S.L and grid distances on the projection. Thus, horizontal distances on the ground must first be reduced to their equivalent at M.S.L before the application of L.S.F to convert them to grid distances.