

European Petroleum Survey Group



**Guidance Note Number 7, part 2**

**Coordinate Conversions and Transformations including Formulas**

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*Index to part 2*

**PREFACE**

Coordinate conversions and coordinate transformations

**1 MAP PROJECTIONS AND THEIR COORDINATE CONVERSION FORMULAS 5**

<b>1.1</b>	<b>INTRODUCTION</b>	<b>5</b>
<b>1.2</b>	<b>IDENTIFICATION OF MAP PROJECTION METHOD</b>	<b>6</b>
<b>1.3</b>	<b>MAP PROJECTION PARAMETERS</b>	<b>7</b>
<b>1.4</b>	<b>MAP PROJECTION FORMULAS</b>	<b>18</b>
1.4.1	LAMBERT CONIC CONFORMAL	18
1.4.1.1	Lambert Conic Conformal (2SP)	19
1.1.1.2	Lambert Conic Conformal (1SP)	20
1.1.1.3	Lambert Conic Conformal (West Orientated)	21
1.1.1.4	Lambert Conic Conformal (2 SP Belgium)	22
1.1.1.5	Lambert Conic Near-Conformal	23
1.1.2	KROVAK OBLIQUE CONFORMAL CONIC	25
1.1.3	MERCATOR	27
1.1.4	CASSINI-SOLDNER	29
1.1.5	TRANSVERSE MERCATOR	31
1.1.1.1	General Case	31
1.1.1.2	Transverse Mercator Zoned Grid System	34
1.1.1.3	Transverse Mercator (South Orientated)	35
1.1.6	OBLIQUE MERCATOR AND HOTINE OBLIQUE MERCATOR	35
1.1.7	STEREOGRAPHIC	40
1.1.1.1	Oblique and Equatorial Stereographic cases	40
1.1.1.2	Polar Stereographic	43
1.1.8	NEW ZEALAND MAP GRID	48
1.1.9	TUNISIA MINING GRID	49
1.1.10	AMERICAN POLYCONIC	50
1.1.11	LAMBERT AZIMUTHAL EQUAL AREA	50
1.1.1.1	Lambert Azimuthal Equal Area (Spherical)	51
1.1.12	ALBERS EQUAL AREA	51
1.1.13	EQUIDISTANT CYLINDRICAL	52
1.1.1.1	Pseudo Plate Carrée	53
1.1.14	BONNE	53
1.1.1.1	Bonne (South Orientated)	54
1.1.15	AZIMUTHAL EQUIDISTANT	54
1.1.15.1	Guam Projection	54

**2 FORMULAS FOR COORDINATE OPERATIONS OTHER THAN MAP PROJECTIONS 56**

<b>1.1</b>	<b>INTRODUCTION</b>	<b>56</b>
<b>1.2</b>	<b>COORDINATE CONVERSIONS OTHER THAN MAP PROJECTIONS</b>	<b>56</b>
1.2.1	GEOGRAPHIC/GEOCENTRIC CONVERSIONS	56
1.1.2	GEOGRAPHIC 3D TO 2D CONVERSIONS	58
<b>1.3</b>	<b>COORDINATE OPERATION METHODS THAT CAN BE CONVERSIONS OR TRANSFORMATIONS</b>	<b>59</b>
1.1.1	POLYNOMIAL TRANSFORMATIONS	59
1.1.1.1	General case	59
1.1.1.2	Polynomial transformation with complex numbers	64
1.1.1.3	Polynomial transformation for Spain	66
1.1.2	MISCELLANEOUS LINEAR COORDINATE OPERATIONS	67
1.1.1.1	Affine Parametric Transformation	67

1.1.1.2	Affine General Geometric Transformation	68
1.1.1.3	Affine Orthogonal Geometric Transformation	70
1.1.1.4	Similarity Transformation	71
<b>1.4</b>	<b>COORDINATE TRANSFORMATIONS</b>	<b>74</b>
1.4.1	OFFSETS - GENERAL	74
1.4.2	TRANSFORMATIONS BETWEEN VERTICAL COORDINATE REFERENCE SYSTEMS	75
1.4.2.1	Vertical Offset	75
1.4.2.2	Vertical Offset by Interpolation of Gridded Data	75
1.4.2.3	Vertical Offset and Slope	75
1.1.3	TRANSFORMATIONS BETWEEN GEOCENTRIC COORDINATE REFERENCE SYSTEMS	76
1.1.1.1	Geocentric Translations	77
1.1.1.2	Helmert 7-parameter transformations	77
1.1.1.3	Molodensky-Badekas 10-parameter transformation	80
1.1.4	TRANSFORMATIONS BETWEEN GEOGRAPHIC COORDINATE REFERENCE SYSTEMS	81
1.1.4.1	Transformations using geocentric methods	81
1.1.1.2	Abridged Molodensky transformation	83
1.1.1.3	Geographic Offsets	84
1.1.1.4	Geographic Offset by Interpolation of Gridded Data	85
1.1.5	GEOID MODELS	85
1.1.5.1	Geographic3D to GravityRelatedHeight	85
1.1.5.2	Geographic3D to Geographic2D+GravityRelatedHeight	86
1.1.5.3	Geographic2D with Height Offsets	86

## **Preface**

This document, EPSG Guidance note 7 – part 2, provides a detailed explanation of formulas necessary for executing coordinate conversions and transformations. Most of these conversions and transformations require parameters as arguments. The values for these parameters may be obtained from the EPSG geodetic parameter dataset. EPSG Guidance note 7 – part 1 provides

- a conceptual overview of coordinate reference systems and coordinate operations,
- details of how these are dealt with in the EPSG dataset,
- details of how the EPSG dataset is managed, and
- guidance on how to extract data from the dataset and on how to use it.

A **coordinate system** is a set of mathematical rules for specifying how coordinates are to be assigned to points. It includes the definition of the coordinate axes, the units to be used and the geometry of the axes. The coordinate system is unrelated to the Earth. A **coordinate reference system** (CRS) is a coordinate system related to the Earth through a **datum**. Colloquially the term coordinate system has historically been used to mean coordinate reference system.

Coordinates may be changed from one coordinate reference system to another through the application of a **coordinate operation**. Two types of coordinate operation may be distinguished:

- **coordinate conversion**, where no change of datum is involved and the parameters are chosen and thus error free.
- **coordinate transformation**, where the target CRS is based on a different datum to the source CRS. Transformation parameters are empirically determined and thus subject to measurement errors.

A projected coordinate reference system is the result of the application of a **map projection** to a geographic coordinate reference system. A map projection is a type of coordinate conversion. It uses an identified method with specific formulas and a set of parameters specific to that coordinate conversion method.

Map projection methods are described in section 1 below. Other coordinate conversions and transformations are described in section 2.

## 1 Map projections and their coordinate conversion formulas

### 1.1 Introduction

Setting aside the large number of map projection methods which may be employed for atlas maps, equally small scale illustrative exploration maps, and wall maps of the world or continental areas, EPSG provides reference parameter values for orthomorphic or conformal map projections which are used for medium or large scale topographic or exploration mapping. Here accurate positions are important and sometimes users may wish to scale accurate positions, distances or areas from the maps.

Small scale maps normally assume a spherical earth and the inaccuracies inherent in this assumption are of no consequence at the usual scale of these maps. For medium and large scale sheet maps, or maps and coordinates held digitally to a high accuracy, it is essential that due regard is paid to the actual shape of the Earth. Such coordinate reference systems are therefore invariably based on an ellipsoid and its derived map projections. The EPSG data set and this supporting conversion documentation considers only map projections for the ellipsoid.

Though not exhaustive the following list of named map projection methods are those which are most frequently encountered for medium and large scale mapping, some of them much less frequently than others since they are designed to serve only one particular country. They are grouped according to their possession of similar properties, which will be explained later. Except where indicated all are conformal.

Mercator		<i>Cylindrical</i>
	with one standard parallel	
	with two standard parallels	
Cassini-Soldner (N.B. not conformal)		<i>Transverse Cylindrical</i>
Transverse Mercator Group		<i>Transverse Cylindrical</i>
	Transverse Mercator (including south oriented version)	
	Universal Transverse Mercator	
	Gauss-Kruger	
	Gauss-Boaga	
Oblique Mercator Group		<i>Oblique Cylindrical</i>
	Hotine Oblique Mercator	
	Oblique Mercator	
	Laborde Oblique Mercator	
Lambert Conical Conformal		<i>Conical</i>
	with one standard parallel	
	with two standard parallels	
	one standard parallel with truncated formulas (N.B. not conformal)	
Stereographic		<i>Azimuthal</i>
	Polar	
	Oblique and equatorial	

## 1.2 Identification of Map Projection method

If a map or coordinate list is provided for which an EPSG listed coordinate reference system is clearly identifiable, then its name or code together with EPSG dataset version number will address the required parameters including the coordinate conversion parameter values. If the coordinate reference system is not listed it will be necessary to create a new coordinate reference system with its own coordinate conversion (parameter) values.

It may often happen that one is presented with a coordinate list or map for which the author or compiler has regrettably failed to provide any indication of parameter values or properties:- no projection name, no grid definition and no statement of ellipsoid or datum. On the map there may be no grid or graticule, or indeed neither.

In order to adequately relate the digital or displayed map data to other data it is necessary to establish the properties of the data or given map from what may be gleaned from their appearance and other information. Geographical coordinates without qualifying information do not allow identification of the coordinate reference system other than that it is a geographic one. Projected or map grid coordinates may, by virtue of the actual and relative magnitudes of the Easting and Northing and knowledge of where in the world they relate to, provide clues as to the map projection. For example eastings between say 150,000m and 850,000m, allied with 6 or 7 figure northings correlated with latitude *may* indicate a UTM grid zone.

If the map bears neither grid nor graticule it will be useless unless one can identify a number of the point features shown for which one already has coordinate data. One may then be able to superimpose and fit a rectangular grid at appropriate scale from which other coordinate data may be read. If the map carries a grid then the numerical labelling of the grid lines, the assumption that it will be conformal or orthomorphic, and prior knowledge of approximately where in the world it covers may give some indication of the type of projection, but this may not be totally definitive. If the map bears a graticule the nature of the graticule lines will give some indication of the type of projection used in its compilation. For example straight meridians and concentric parallels would suggest a conical projection or, less frequently, a polar azimuthal. If the former, and assuming that it will be orthomorphic, then it will either be with one standard parallel or two and these will have been selected in relation to the latitudinal extent of the area, very possibly those in general use for that state's mapping. If the parallels are equally spaced it will be a simple equidistant conical projection. However for large scale mapping purposes the requirement that it is conformal will dictate that the parallels will not be equally spaced and it is more than likely that it will be some form of Lambert projection with either one or two standard parallels. Unfortunately there is no easy way of detecting which, nor the values of the standard parallels. The country it comes from and its national mapping system, if known, may suggest what these are. The EPSG data set will assist but is not exhaustive.

If both meridians and parallels of latitude are straight it will be a cylindrical projection but of the normal and not the more frequent transverse or oblique variety (Figure 1 at end of section 1.3). Of the normal aspect cylindrical projections only the Mercator is conformal and it is not frequently used for topographic mapping though it is almost invariably used for the production of marine navigation charts.

If both parallels of latitude and meridians are curved the projection has numerous possibilities but a form of Transverse Mercator may well be the most likely. One may attempt to identify the projection by computing the grid values of some of the graticule intersections for several possible projections in turn, plotting these to a rounded value for the estimated scale of the map e.g. 1:50000 or 1:100000, and attempting to fit the overlaid grid plot on the graticule. Repeating this for a number of potential projections for the area may be successful in obtaining a reasonable fit. But bear in mind that paper stretch may slightly distort scale from the nominal scale of the map, and the scale factor used in the graticule to grid conversions is another variable which may take only slightly different values e.g. a Gauss-Kruger takes a central meridian scale factor of unity while a UTM (like Gauss-Kruger, a Transverse Mercator) takes 0.9996.

Digital cartographic techniques make it relatively easy to plot grid and graticule for different projections with different parameters onto transparencies for "trial and error" overlays. The process can be time consuming so it is preferable to make maximum use of the clues which one may infer from the appearance of the map as initially presented, - its origins, its national area, and the conventional projections used for that area.

### 1.3 Map Projection parameters

A map projection grid is related to the geographical graticule of an ellipsoid through the definition of a coordinate conversion method and a set of parameters appropriate to that method. Different conversion methods may require different parameters. Any one coordinate conversion method may take several different sets of associated parameter values, each set related to a particular map projection zone applying to a particular country or area of the world. Before setting out the formulas involving these parameters, which enable the coordinate conversions for the projection methods listed above, it is as well to understand the nature of the parameters.

The plane of the map and the ellipsoid surface may be assumed to have one particular point in common. This point is referred to as the **natural origin**. It is the point from which the values of both the geographical coordinates on the ellipsoid and the grid coordinates on the projection are deemed to increment or decrement for computational purposes. Alternatively it may be considered as the point which in the absence of application of false coordinates has grid coordinates of (0,0). For example, for projected coordinate reference systems using the Cassini-Soldner or Transverse Mercator methods, the natural origin is at the intersection of a chosen parallel and a chosen central meridian (see Figure 2 at end of section). The chosen parallel will frequently but not necessarily be the equator. For the stereographic projection the origin is at the centre of the projection where the plane of the map is imagined to be tangential to the ellipsoid.

Since the natural origin may be at or near the centre of the projection and under normal coordinate circumstances would thus give rise to negative coordinates over parts of the map, this origin is usually given false coordinates which are large enough to avoid this inconvenience. Hence each natural origin will normally have **False Easting, FE** and **False Northing, FN** values. For example, the false easting for the origins of all Universal Transverse Mercator zones is 500000m. As the UTM origin lies on the equator, areas north of the equator do not need and are not given a false northing but for mapping southern hemisphere areas the equator origin is given a false northing of 10,000,000m, thus ensuring that no point in the southern hemisphere will take a negative northing coordinate. Figure 4 illustrates the UTM arrangements.

These arrangements suggest that if there are false easting and false northing for the real or natural origin, there is also a **Grid Origin** which has coordinates (0,0). In general this point is of no consequence though its geographic position may be computed if needed. For example, for the WGS 84 / UTM zone 31N coordinate reference system which has a natural origin at 0°N, 3°E where false easting is 500000m E (and false northing is 0m N), the grid origin is at 0°N, 1°29'19.478"W. Sometimes however, rather than base the easting and northing coordinate reference system on the natural origin by giving it **FE** and **FN** values, it may be convenient to select a **False Origin** at a specific meridian/parallel intersection and attribute the false coordinates **Easting at False Origin, E<sub>F</sub>** and **Northing at False Origin, N<sub>F</sub>** to this. The related easting and northing of the natural origin may then be computed if required.

The natural origin will always lie on a meridian of longitude. Longitudes are most commonly expressed relative to the **Prime Meridian** of Greenwich but some countries, particularly in former times, have preferred to relate their longitudes to a prime meridian through their national astronomic observatory, usually sited in or near their capital city, e.g. Paris for France, Bogota for Colombia. The meridian of the projection zone origin is known as the **Longitude of Origin**. For certain projection types it is often

termed the **Central Meridian** or abbreviated as **CM** and provides the direction of the northing axis of the projected coordinate reference system.

Because of the steadily increasing distortion in the scale of the map with increasing distance from the origin, central meridian or other line on which the scale is the nominal scale of the projection, it is usual to limit the extent of a projection to within a few degrees of latitude or longitude of this point or line. Thus, for example, a UTM or other Transverse Mercator projection zone will normally extend only 2 or 3 degrees from the central meridian. Beyond this area another **zone** of the projection, with a new origin and central meridian, needs to be used or created. The UTM system has a specified 60 numbered zones, each 6 degrees wide, covering the ellipsoid between the 84 degree North and 80 degree South latitude parallels. Other Transverse Mercator projection zones may be constructed with different central meridians, and different origins chosen to suit the countries or states for which they are used. A number of these are included in the EPSG dataset. Similarly a Lambert Conic Conformal zone distorts most rapidly in the north-south direction and may, as in Texas, be divided into latitudinal bands.

In order to further limit the scale distortion within the coverage of the zone or projection area, some projections introduce a **scale factor** at the origin (on the central meridian for Transverse Mercator projections), which has the effect of reducing the nominal scale of the map here and making it have the nominal scale some distance away. For example in the case of the UTM and some other Transverse Mercator projections a scale factor of slightly less than unity is introduced on the central meridian thus making it unity on two meridians either side of the central one, and reducing its departure from unity beyond these. The scale factor is a required parameter whether or not it is unity and is usually symbolised as  $k_0$ .

Thus for projections in the Transverse Mercator group in section 1.1 above, the parameters which are required to completely and unambiguously define the projection method are:

- Latitude of natural origin
- Longitude of natural origin (the central meridian)
- Scale factor at natural origin (on the central meridian)
- False easting
- False northing

Since the UTM zones obey set rules, it is sufficient to state only the UTM zone number (or central meridian). The remaining parameters from the above list are defined by the rules.

It has been noted that the Transverse Mercator projection is employed for the topographical mapping of longitudinal bands of territories, limiting the amount of scale distortion by limiting the extent of the projection either side of the central meridian. Sometimes the shape, general trend and extent of some countries makes it preferable to apply a single zone of the same kind of projection but with its central line aligned with the trend of the territory concerned rather than with a meridian. So, instead of a meridian forming this true scale central line for one of the various forms of Transverse Mercator, or the equator forming the line for the Mercator, a line with a particular azimuth traversing the territory is chosen, and the same principles of construction are applied to derive what is now an Oblique Mercator. This projection is sometimes referred to as the Hotine Oblique Mercator after the British geodesist who set out its formulas for application to Malaysian Borneo (East Malaysia) and also West Malaysia. Laborde had previously developed the projection system for Madagascar, and Switzerland uses a similar system derived by Rosenmund.

More recently (1974) Lee has derived formulas for a minimum scale factor projection for New Zealand known as the New Zealand Map Grid. The line of minimum scale follows the general alignment of the two main islands. This resembles an Oblique Mercator projection in its effect, but is not strictly an Oblique Mercator. The additional mathematical complexity of the projection enables its derivation via an Oblique Stereographic projection, which is sometimes the way it is classified. Because of its unique formulation inclusion of the New Zealand Map Grid within international mapping software was sporadic;

as a consequence New Zealand has reverted to the frequently-encountered Transverse Mercator for its most recent mapping.

The parameters required to define an Oblique Mercator projection are:

- Latitude of projection centre (the origin point on the initial line)
- Longitude of projection centre
- Azimuth of initial line [at the projection centre]
- Scale factor on initial line [at the projection centre]
- Angle from Rectified to Skewed grid [at the natural origin]

and then either

- False easting (easting at the projection natural origin)
- False northing (northing at the projection natural origin)

or

- Easting at projection centre
- Northing at projection centre

The angle from rectified to skewed grid is normally applied at the natural origin of the projection, that is where the initial line of the projection intersects the aosphere. In some circumstances, for instance in the Alaskan panhandle State Plane zone, this angle is taken to be identical to the azimuth of the initial line at the projection centre. This results in grid and true north coinciding at the projection centre rather than at the natural origin as is more usual.

It is possible to define the azimuth of the initial line through the latitude and longitude of two widely spaced points along that line. This approach is not followed by EPSG.

For **Conical** map projections, which for the normal aspect may be considered as the projection of the ellipsoid onto an enveloping cone in contact with the ellipsoid along a parallel of latitude, the parallel of contact is known as a **standard parallel** and the scale is regarded as true along this parallel. Sometimes the cone is imagined to cut the ellipsoid with coincidence of the two surfaces along **two standard parallels**. All other parallels will be concentric with the chosen standard parallel or parallels but for the Lambert Conical Conformal will have varying separations to preserve the conformal property. All meridians will radiate with equal angular separations from the centre of the parallel circles but will be compressed from the 360 longitude degrees of the ellipsoid to a sector whose angular extent depends on the chosen standard parallel, - or both standard parallels if there are two. Of course the normal longitudinal extent of the projection will depend on the extent of the territory to be projected and will never approach 360 degrees.

As in the case of the Transverse Mercator above it is sometimes desirable to limit the maximum positive scale distortion for the one standard parallel case by distributing it more evenly over the extent of the mapped area. This may be achieved by introducing a scale factor on the standard parallel of slightly less than unity thus making it unity on two parallels either side of it. This achieves the same effect as choosing two specific standard parallels in the first place, on which the nominal scale will be preserved. The projection is then a Lambert Conical Conformal projection with two standard parallels. Although, strictly speaking, the scale on a standard parallel is always the nominal scale of the map and the scale factor on the one or two standard parallels should be unity, it is sometimes convenient to consider a Lambert Conical Conformal projection with one standard parallel yet which has a scale factor on the standard parallel of less than unity. This provision is allowed for by EPSG, where the single standard parallel is referred to as the **latitude of natural origin**. For an ellipsoidal projection the natural origin will fall slightly poleward of the mean of the latitudes of the two standard parallels.

A **longitude of origin** or **central meridian** will again be chosen to bisect the area of the map or, more usually, the total national map area for the country or state concerned. Where this cuts the one standard parallel will be the natural origin of the projected coordinate reference system and, as for the Transverse Mercator, it will be given a **False easting and False northing** to ensure that there are no negative coordinates within the projected area (see Figure 5). Where two standard parallels are specified a false origin may be chosen at the intersection of a specific parallel with the central meridian. This point will be

given an **easting at false origin** and a **northing at false origin** to ensure that no negative coordinates will result. Figure 6 illustrates these arrangements.

It is clear that any number of Lambert projection zones may be formed according to which standard parallel or standard parallels are chosen and this is clearly exemplified by those which are used for many of the United States State Plane coordinate zones. They are normally chosen either, for one standard parallel, to approximately bisect the latitudinal extent of the country or area or, for two standard parallels, to embrace most of the latitudinal extent of the area. In the latter case the aim is to minimise the maximum scale distortion which will affect the mapped area and various formulas have been developed by different mathematicians to select the appropriate standard parallels to achieve this. Kavraisky was one mathematician who derived a recipe for choosing the standard parallels to achieve minimal scale distortion. But however the selection of the standard parallels is made the same projection formulas apply. Thus the parameters needed to specify a projection in the Lambert projection will be as follows:

For a Lambert Conical Conformal with one standard parallel (1SP),  
 Latitude of natural origin (the Standard Parallel)  
 Longitude of natural origin (the Central Meridian)  
 Scale factor at natural origin (on the Standard Parallel)  
 False easting  
 False northing

For a Lambert Conical Conformal with two standard parallels (2SP),  
 Latitude of false origin  
 Longitude of false origin (the Central Meridian)  
 Latitude of first standard parallel  
 Latitude of second standard parallel  
 Easting at false origin  
 Northing at false origin

where the order of the standard parallels is not material if using the formulas which follow.

The limiting case of the Lambert Conic Conformal having the apex of the cone at infinity produces a **cylindrical** projection, the Mercator. Here, for the single standard parallel case the latitude of natural origin is the equator. For the two standard parallel case the two parallels have equal latitude in the north and south hemispheres. In both one and two standard parallel cases, grid coordinates are for the natural origin at the intersection of the equator and the central meridian (see figure 1). Thus the parameters needed to specify a map projection using the Mercator map projection method will be:

For a Mercator with one standard parallel (1SP),  
 Latitude of natural origin (the Equator)  
 Longitude of natural origin (the Central Meridian)  
 Scale factor at natural origin (on the Equator)  
 False easting  
 False northing

For a Mercator with two standard parallels (2SP),  
 Latitude of first standard parallel  
 Longitude of natural origin (the Central Meridian)  
 False easting (grid coordinate at the intersection of the CM with the equator)  
 False northing

In the formulas that follow the absolute value of the first standard parallel must be used.

For **Azimuthal** map projections, which are only infrequently used for ellipsoidal topographic mapping purposes, the natural origin will be at the centre of the projection where the map plane is imagined to be

tangential to the ellipsoid and which will lie at the centre of the area to be projected. The central meridian will pass through the natural origin. This point will be given a False Easting and False Northing.

The parameters needed to specify the Stereographic map projection method are:

- Latitude of natural origin
- Longitude of natural origin (the central meridian for the oblique case)
- Scale factor at natural origin
- False easting
- False northing

TABLE 1.  
Parameters used in map projection conversions

Parameter Name	Symbol	Description
Angle from Rectified to Skew Grid	$\gamma_C$	The angle at the natural origin of an oblique projection through which the natural coordinate reference system is rotated to make the projection north axis parallel with true north.
Azimuth of initial line	$\alpha_C$	The azimuthal direction (north zero, east of north being positive) of the great circle which is the centre line of an oblique projection. The azimuth is given at the <i>projection centre</i> .
Central meridian		See <i>Longitude of natural origin</i>
Easting at false origin	$E_F$	The easting value assigned to the <i>false origin</i> .
Easting at projection centre	$E_C$	The easting value assigned to the <i>projection centre</i> .
False easting	FE	The value assigned to the abscissa (east or west) axis of the projection grid at the <i>natural origin</i> .
False northing	FN	The value assigned to the ordinate (north or south) axis of the projection grid at the <i>natural origin</i> .
False origin		A specific parallel/meridian intersection other than the <i>natural origin</i> to which the grid coordinates $E_F$ and $N_F$ , are assigned.
Grid origin		The point which has coordinates (0,0). It is offset from the <i>natural origin</i> by the <i>false easting</i> and <i>false northing</i> . In some projection methods it may alternatively be offset from the <i>false origin</i> by <i>Easting at false origin</i> and <i>Northing at false origin</i> . In general this point is of no consequence.
Initial longitude	$\lambda_1$	The longitude of the western limit of the first zone of a Transverse Mercator zoned grid system.
Latitude of 1st standard parallel	$\varphi_1$	For a conic projection with two standard parallels, this is the latitude of intersection of the cone with the ellipsoid that is nearest the pole. Scale is true along this parallel.
Latitude of 2nd standard parallel	$\varphi_2$	For a conic projection with two standard parallels, this is the latitude of intersection of the cone with the ellipsoid that is furthest from the pole. Scale is true along this parallel.
Latitude of false origin	$\varphi_F$	The latitude of the point which is not the natural origin and at which grid coordinate values easting at false origin and northing at false origin are defined.
Latitude of natural origin	$\varphi_O$	The latitude of the point from which the values of both the geographical coordinates on the ellipsoid and the grid coordinates on the projection are deemed to increment or decrement for computational purposes. Alternatively it may be considered as the latitude of the point which in the absence of application of false coordinates has grid coordinates of (0,0).
Latitude of projection centre	$\varphi_C$	For an oblique projection, this is the latitude of the point at which the azimuth of the central line is defined.

Parameter Name	Symbol	Description
Latitude of pseudo standard parallel	$\lambda_F$	Latitude of the parallel on which the conic or cylindrical projection is based. This latitude is not geographic, but is defined on the conformal sphere AFTER its rotation to obtain the oblique aspect of the projection.
Latitude of standard parallel	$\phi_F$	For polar aspect azimuthal projections, the parallel on which the scale factor is defined to be unity.
Longitude of false origin		The longitude of the point which is not the natural origin and at which grid coordinate values easting at false origin and northing at false origin are defined.
Longitude of natural origin	$\lambda_O$	The longitude of the point from which the values of both the geographical coordinates on the ellipsoid and the grid coordinates on the projection are deemed to increment or decrement for computational purposes. Alternatively it may be considered as the longitude of the point which in the absence of application of false coordinates has grid coordinates of (0,0). Sometimes known as "central meridian (CM)".
Longitude of origin	$\lambda_O$	For polar aspect azimuthal projections, the meridian along which the northing axis increments and also across which parallels of latitude increment towards the north pole.
Longitude of projection centre	$\lambda_C$	For an oblique projection, this is the longitude of the point at which the azimuth of the central line is defined.
Natural origin		The point from which the values of both the geographical coordinates on the ellipsoid and the grid coordinates on the projection are deemed to increment or decrement for computational purposes. Alternatively it may be considered as the point which in the absence of application of false coordinates has grid coordinates of (0,0). For example, for projected coordinate reference systems using the Transverse Mercator method, the natural origin is at the intersection of a chosen parallel and a chosen central meridian.
Northing at false origin	$N_F$	The northing value assigned to the false origin.
Northing at projection centre	$N_C$	The northing value assigned to the projection centre.
Origin		See <i>natural origin</i> , <i>false origin</i> and <i>grid origin</i> .
Projection centre		
Scale factor at natural origin	$k_O$	The factor by which the map grid is reduced or enlarged during the projection process, defined by its value at the <i>natural origin</i> .
Scale factor on initial line	$k_C$	The factor by which the map grid is reduced or enlarged during the projection process, defined by its value at the projection center.
Scale factor on pseudo standard parallel		The factor by which the map grid is reduced or enlarged during the projection process, defined by its value at the pseudo-standard parallel.
Spherical latitude of origin		The latitude of the point from which the values of both the geographical coordinates on the sphere and the grid coordinates on a spherical projection are deemed to increment or decrement for computational purposes.
Spherical longitude of origin		The longitude of the point from which the values of both the geographical coordinates on the sphere and the grid coordinates on a spherical projection are deemed to increment or decrement for computational purposes.
Zone width	W	The longitude width of a zone of a Transverse Mercator zoned grid system.

**TABLE 2**  
**Ellipsoid parameters used in conversions and transformations**

In the formulas for map projections the basic ellipsoidal parameters are represented by symbols and derived as follows:

<b>Primary ellipsoid parameters</b>		
<b>Parameter Name</b>	<b>Symbol</b>	<b>Description</b>
semi-major axis	a	Length of the semi-major axis of the ellipsoid, the radius of the equator.
semi-minor axis	b	Length of the semi-minor axis of the ellipsoid, the distance along the ellipsoid axis between equator and pole.
inverse flattening	1/f	= a/(a – b)
<b>Derived ellipsoid parameters</b>		
<b>Parameter Name</b>	<b>Symbol</b>	<b>Description</b>
eccentricity	e	= $\sqrt{2f - f^2}$
flattening	f	= 1 / (1/f)
radius of curvature in the meridian	$\rho$	radius of curvature of the ellipsoid in the plane of the meridian at latitude $\phi$ , where $\rho = a(1 - e^2)/(1 - e^2 \sin^2 \phi)^{3/2}$
radius of curvature in the prime vertical	v	radius of curvature of the ellipsoid perpendicular to the meridian at latitude $\phi$ , where $v = a / (1 - e^2 \sin^2 \phi)^{1/2}$
second eccentricity	e'	= $\sqrt{[e^2 / (1 - e^2)]}$

**TABLE 3**  
**Summary of Coordinate Operation Parameters required for some Map Projections**

<u>Coordinate Operation Parameter Name</u>	<u>Coordinate Operation Method</u>								
	Mercator (1SP)	Mercator (2SP)	Cassini-Soldner	Transverse Mercator	Hotine Oblique Mercator	Oblique Mercator	Lambert Conical (1 SP)	Lambert Conical (2 SP)	Oblique Stereographic
Latitude of false origin								1	
Longitude of false origin								2	
Latitude of 1st standard parallel		1						3	
Latitude of 2nd standard parallel								4	
Easting at false origin								5	
Northing at false origin								6	
Latitude of projection centre					1	1			
Longitude of projection centre					2	2			
Scale factor on initial line					3	3			
Azimuth of initial line					4	4			

Angle from Rectified to Skewed grid					5	5			
Easting at projection centre						6			
Northing at projection centre						7			
Latitude of natural origin	1 =equator		1	1			1		1
Longitude of natural origin	2	2	2	2			2		2
Scale factor at natural origin	3			3			3		3
False easting	4	3	3	4	6		4		4
False northing	5	4	4	5	7		5		5

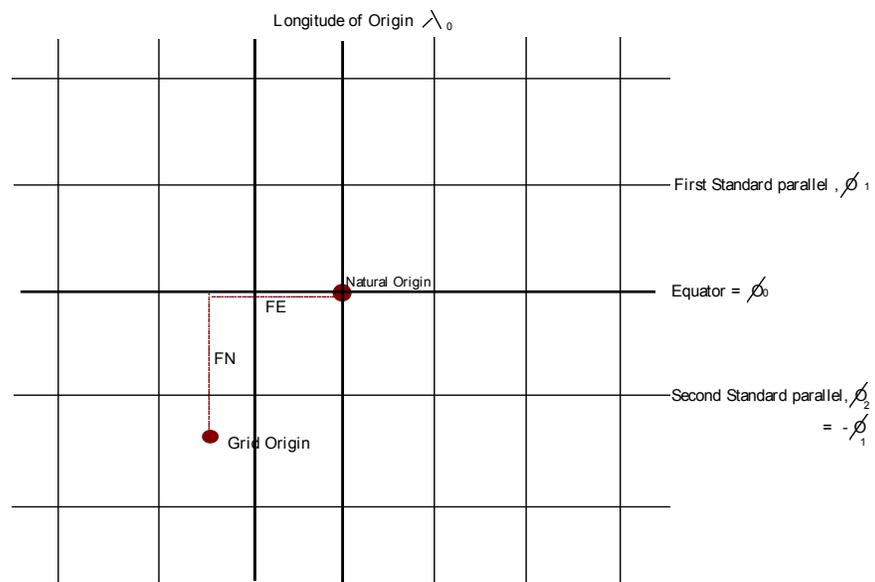


Figure 1. Key Diagram for Mercator Projection arrangements  
(One and two standard parallel cases)

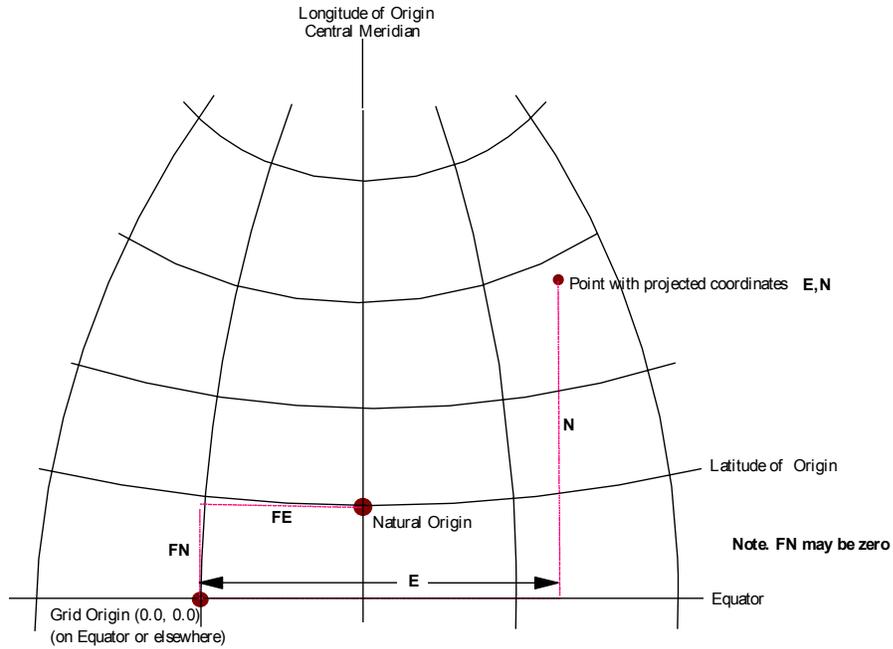


Figure 2. Key Diagram for Transverse Mercator Projection arrangements (N.Hemisphere)

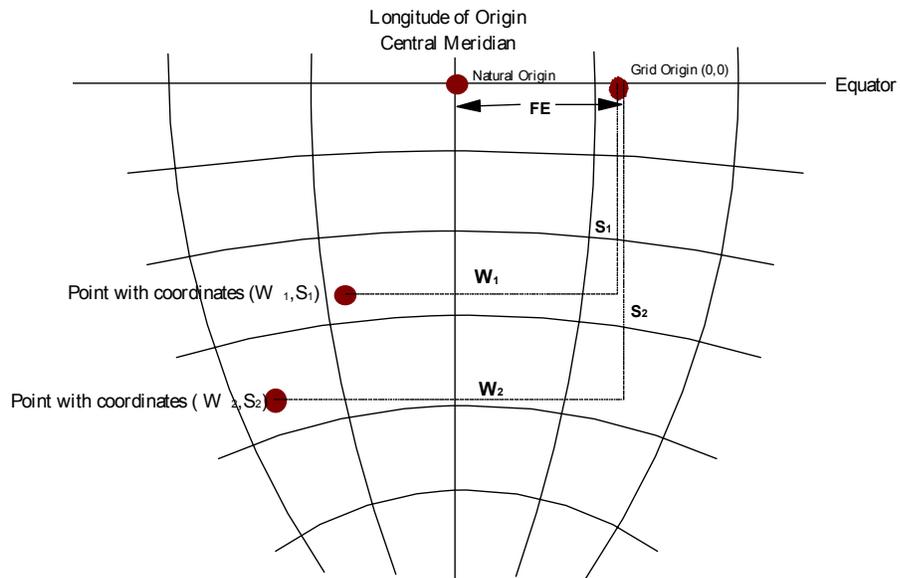


Figure 3. Key Diagram for South oriented Transverse Mercator Projection arrangements

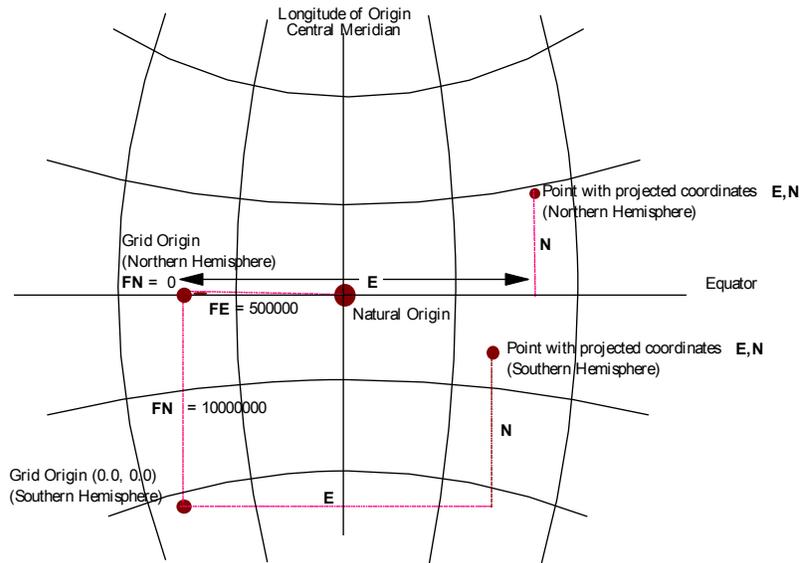


Figure 4. Key Diagram for Universal Transverse Mercator Projection arrangements (N and S hemisphere cases)

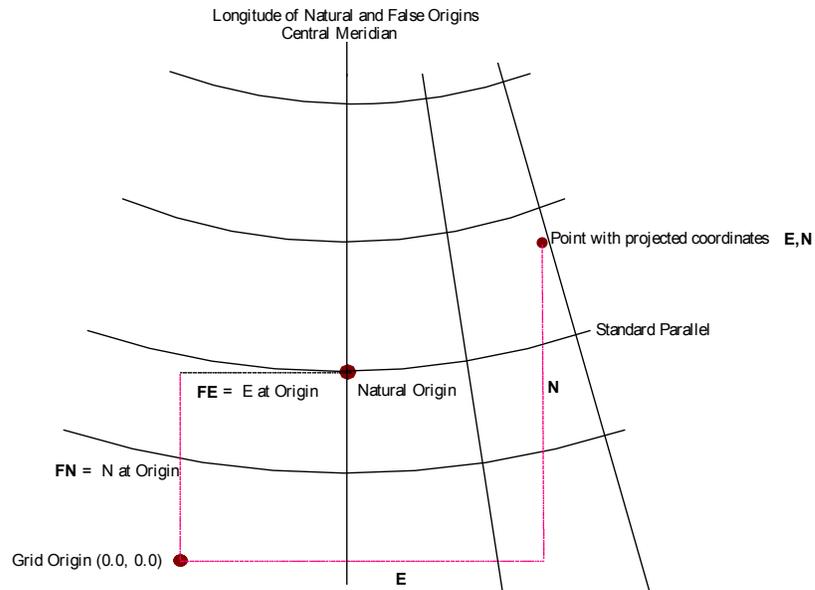


Figure 5. Key Diagram for Lambert Conical Conformal Projection with one standard parallel

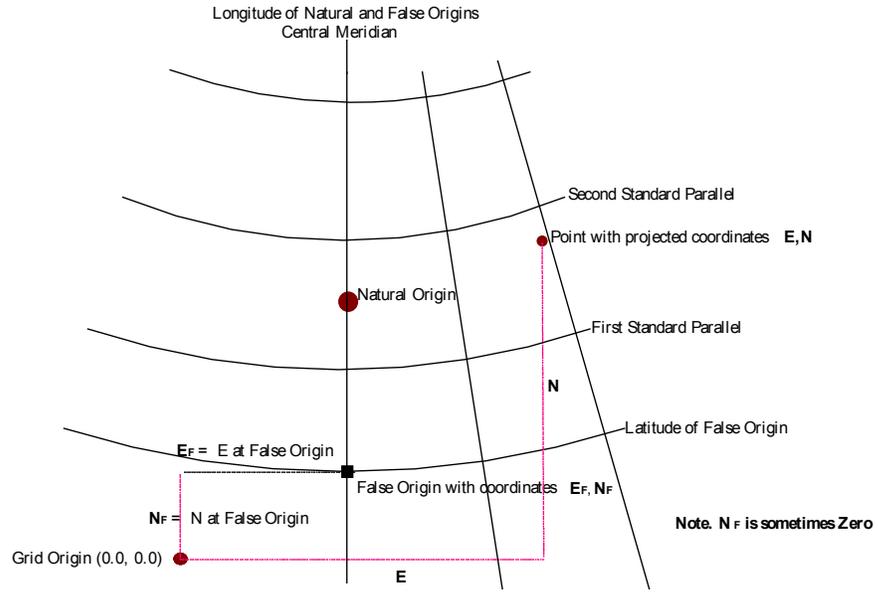


Figure 6. Key Diagram for Lambert Conical Conformal Projection with two standard parallels

## 1.4 Map Projection formulas

Only formulas for computation on the ellipsoid are considered. Projection formulas for the spherical earth are simpler but the spherical figure is inadequate to represent positional data with great accuracy at large map scales for the real earth. Projections of the sphere are only suitable for illustrative maps at scale of 1:1 million or less where precise positional definition is not critical.

The formulas which follow are largely adapted from "Map Projections - A Working Manual" by J.P.Snyder, published by the U.S. Geological Survey as Professional Paper No.1395<sup>1</sup>. As well as providing an extensive overview of most map projections in current general use, and the formulas for their construction for both the spherical and ellipsoidal earth, this excellent publication provides computational hints and details of the accuracies attainable by the formulas. It is strongly recommended that all those who have to deal with map projections for medium and large scale mapping should follow its guidance.

There are a number of different formulas available in the literature for map projections other than those quoted by Snyder. Some are closed formulas; others, for ease of calculation, may depend on series expansions and their precision will generally depend on the number of terms used for computation. Generally those formulas which follow in this chapter will provide results which are accurate to within a decimetre, which is normally adequate for exploration mapping purposes. Coordinate expression and computations for engineering operations are usually consistently performed in grid terms.

The importance of one further variable should be noted. This is the unit of linear measurement used in the definition of projected coordinate reference systems. For metric map projections the unit of measurement is restricted to this unit. For non-metric map projections the metric ellipsoid semi-major axis needs to be converted to the projected coordinate reference system linear unit before use in the formulas below. The relevant ellipsoid is obtained through the datum part of the projected coordinate reference system.

### Reversibility

Different formulas are required for forward and reverse map projection conversions: the forward formula cannot be used for the reverse conversion. However both forward and reverse formulas are explicitly given in the sections below as parts of a single conversion method. As such, map projection methods are described by EPSG as being reversible. Forward and reverse formulas for each conversion method use the projection parameters appropriate to that method with parameter values unchanged.

### 1.4.1 Lambert Conic Conformal

For territories with limited latitudinal extent but wide longitudinal width it may sometimes be preferred to use a single projection rather than several bands or zones of a Transverse Mercator. The Lambert Conic Conformal may often be adopted in these circumstances. But if the latitudinal extent is also large there may still be a need to use two or more zones if the scale distortion at the extremities of the one zone becomes too large to be tolerable.

Conical projections with one standard parallel are normally considered to maintain the nominal map scale along the parallel of latitude which is the line of contact between the imagined cone and the ellipsoid. For a one standard parallel Lambert the natural origin of the projected coordinate system is the intersection of the standard parallel with the longitude of origin (central meridian). See Figure 5 at end of section 1.3. To

8585

<sup>1</sup> This was originally published with the title "Map Projections Used by the US Geological Survey". In some cases the formulas given are insufficient for global use. In these cases EPSG has modified the formulas. Note that the origin of most map projections is given false coordinates (FE and FN or  $E_F$  and  $N_F$  or  $E_C$  and  $N_C$ ) to avoid negative coordinates. In the EPSG formulas these values are included where appropriate so that the projected coordinates of points result directly from the quoted formulas.

maintain the conformal property the spacing of the parallels is variable and increases with increasing distance from the standard parallel, while the meridians are all straight lines radiating from a point on the prolongation of the ellipsoid's minor axis.

Sometimes however, although a one standard parallel Lambert is normally considered to have unity scale factor on the standard parallel, a scale factor of slightly less than unity is introduced on this parallel. This is a regular feature of the mapping of some former French territories and has the effect of making the scale factor unity on two other parallels either side of the standard parallel. The projection thus, strictly speaking, becomes a Lambert Conic Conformal projection with **two** standard parallels. From the one standard parallel and its scale factor it is possible to derive the equivalent two standard parallels and then treat the projection as a two standard parallel Lambert conical conformal, but this procedure is seldom adopted. Since the two parallels obtained in this way will generally not have integer values of degrees or degrees minutes and seconds it is instead usually preferred to select two specific parallels on which the scale factor is to be unity, as for several State Plane Coordinate systems in the United States.

The choice of the two standard parallels will usually be made according to the latitudinal extent of the area which it is wished to map, the parallels usually being chosen so that they each lie a proportion inboard of the north and south margins of the mapped area. Various schemes and formulas have been developed to make this selection such that the maximum scale distortion within the mapped area is minimised, e.g. Kavraisky in 1934, but whatever two standard parallels are adopted the formulas are the same.

#### 1.4.1.1 Lambert Conic Conformal (2SP)

(EPSG coordinate operation method code 9802)

To derive the projected Easting and Northing coordinates of a point with geographical coordinates ( $\phi, \lambda$ ) the formulas for the Lambert Conic Conformal **two standard parallel case** (EPSG coordinate operation method code 9802) are:

$$\begin{aligned} \text{Easting, } E &= E_F + r \sin \theta \\ \text{Northing, } N &= N_F + r_F - r \cos \theta \end{aligned}$$

where  $m = \cos\phi / (1 - e^2 \sin^2\phi)^{0.5}$  for  $m_1, \phi_1$ , and  $m_2, \phi_2$  where  $\phi_1$  and  $\phi_2$  are the latitudes of the standard parallels  
 $t = \tan(\pi/4 - \phi/2) / [(1 - e \sin\phi) / (1 + e \sin\phi)]^{e/2}$  for  $t_1, t_2, t_F$  and  $t$  using  $\phi_1, \phi_2, \phi_F$  and  $\phi$  respectively  
 $n = (\ln m_1 - \ln m_2) / (\ln t_1 - \ln t_2)$   
 $F = m_1 / (n t_1^n)$   
 $r = a F t^n$  for  $r_F$  and  $r$ , where  $r_F$  is the radius of the parallel of latitude of the false origin  
 $\theta = n(\lambda - \lambda_F)$

The reverse formulas to derive the latitude and longitude of a point from its Easting and Northing values are:

$$\begin{aligned} \phi &= \pi/2 - 2 \operatorname{atan} \left\{ t \left[ \frac{1 - e \sin\phi}{1 + e \sin\phi} \right]^{e/2} \right\} \\ \lambda &= \theta'/n + \lambda_F \end{aligned}$$

where

$$\begin{aligned} r' &= \pm \left\{ (E - E_F)^2 + [r_F - (N - N_F)]^2 \right\}^{0.5}, \text{ taking the sign of } n \\ t' &= (r' / (aF))^{1/n} \\ \theta' &= \operatorname{atan} \left[ (E - E_F) / (r_F - (N - N_F)) \right] \end{aligned}$$

and  $n, F$ , and  $r_F$  are derived as for the forward calculation.

Note that the formula for  $\phi$  requires iteration. First calculate  $t'$  and then a trial value for  $\phi$  using

$\phi = \pi/2 - 2 \arctan t'$ . Then use the full equation for  $\phi$  substituting the trial value into the right hand side of the equation. Thus derive a new value for  $\phi$ . Iterate the process until  $\phi$  does not change significantly. The solution should quickly converge, in 3 or 4 iterations.

**Example:**

For Projected Coordinate Reference System: NAD27 / Texas South Central

Parameters:

Ellipsoid:	Clarke 1866	a = 6378206.400 metres	=	20925832.16 US survey feet
		1/f = 294.97870		
	then	e = 0.08227185		e <sup>2</sup> = 0.00676866

Latitude of false origin	$\phi_F$	27°50'00"N	=	0.48578331 rad
Longitude of false origin	$\lambda_F$	99°00'00"W	=	-1.72787596 rad
Latitude of 1st standard parallel	$\phi_1$	28°23'00"N	=	0.49538262 rad
Latitude of 2nd standard parallel	$\phi_2$	30°17'00"N	=	0.52854388 rad
Easting at false origin	$E_F$	2000000.00		US survey feet
Northing at false origin	$N_F$	0.00		US survey feet

Forward calculation for:

Latitude  $\phi = 28^\circ30'00.00''N = 0.49741884$  rad  
 Longitude  $\lambda = 96^\circ00'00.00''W = -1.67551608$  rad

first gives :

$m_1 = 0.88046050$        $m_2 = 0.86428642$   
 $t = 0.59686306$        $t_F = 0.60475101$   
 $t_1 = 0.59823957$        $t_2 = 0.57602212$   
 $n = 0.48991263$        $F = 2.31154807$   
 $r = 37565039.86$        $r_F = 37807441.20$   
 $\theta = 0.02565177$

Then Easting E = 2963503.91 US survey feet  
 Northing N = 254759.80 US survey feet

Reverse calculation for same easting and northing first gives:

$\theta' = 0.025651765$   
 $t' = 0.59686306$   
 $r' = 37565039.86$

Then Latitude  $\phi = 28^\circ30'00.000''N$   
 Longitude  $\lambda = 96^\circ00'00.000''W$

**1.4.1.2 Lambert Conic Conformal (1SP)**  
 (EPSG coordinate operation method code 9801)

The formulas for the two standard parallel can be used for the Lambert Conic Conformal single standard parallel case (EPSG coordinate operation method code 9801) with minor modifications. Then

$E = FE + r \sin\theta$

$N = FN + r_0 - r \cos\theta$ , using the natural origin rather than the false origin.

where

$n = \sin \phi_0$

$r = aFt^n k_0$  for  $r_0$ , and  $r$   
 $t$  is found for  $t_0$ ,  $\phi_0$  and  $t$ ,  $\phi$  and  $m$ ,  $F$ , and  $\theta$  are found as for the two standard parallel case.

The reverse formulas for  $\phi$  and  $\lambda$  are as for the two standard parallel case above, with  $n$ ,  $F$  and  $r_0$  as before and

$$\theta' = \text{atan}\{(E - FE)/[r_0 - (N - FN)]\}$$

$$r' = \pm\{(E - FE)^2 + [r_0 - (N - FN)]^2\}^{1/2}$$

$$t' = (r'/(ak_0F))^{1/n}$$

**Example:**

For Projected Coordinate Reference System: JAD69 / Jamaica National Grid

Parameters:

Ellipsoid:	Clarke 1866	$a = 6378206.400$ metres	$1/f = 294.97870$
	then	$e = 0.08227185$	$e^2 = 0.00676866$
Latitude of natural origin	$\phi_0$	18°00'00"N	= 0.31415927 rad
Longitude of natural origin	$\lambda_0$	77°00'00"W	= -1.34390352 rad
Scale factor at natural origin	$k_0$	1.000000	
False easting	FE	250000.00	metres
False northing	FN	150000.00	metres

Forward calculation for:

Latitude  $\phi = 17^\circ55'55.80''N = 0.31297535$  rad  
 Longitude  $\lambda = 76^\circ56'37.26''W = -1.34292061$  rad

first gives

$m_0 = 0.95136402$        $t_0 = 0.72806411$   
 $F = 3.39591092$        $n = 0.30901699$   
 $r = 19643955.26$        $r_0 = 19636447.86$   
 $\theta = 0.00030374$        $t = 0.728965259$

Then Easting  $E = 255966.58$  metres  
 Northing  $N = 142493.51$  metres

Reverse calculation for the same easting and northing first gives

$\theta' = 0.000303736$   
 $t' = 0.728965259$   
 $m_0 = 0.95136402$   
 $r' = 19643955.26$

Then Latitude  $\phi = 17^\circ55'55.80''N$   
 Longitude  $\lambda = 76^\circ56'37.26''W$

**1.4.1.3 Lambert Conic Conformal (West Orientated)**

(EPSG coordinate operation method code 9826)

In older mapping of Denmark and Greenland the Lambert Conic Conformal is used with axes positive north and **west**. To derive the projected Westing and Northing coordinates of a point with geographical coordinates ( $\varphi, \lambda$ ) the formulas are as for the standard Lambert Conic Conformal (1SP) case above (EPSG coordinate operation method code 9801) except for:

$$W = FE - r.\sin(\theta)$$

In this formula the term FE retains its definition, i.e. in the Lambert Conic Conformal (West Orientated) method it increases the Westing value at the natural origin. In this method it is effectively false westing (FW).

The reverse formulas to derive the latitude and longitude of a point from its Westing and Northing values are as for the standard Lambert Conic Conformal (1SP) case except for:

$$\theta' = \text{atan}[(FE - W) / \{r_0 - (N - FN)\}]$$

$$r' = +/-[(FE - W)^2 + \{r_0 - (N - FN)\}^2]^{0.5}$$

**1.4.1.4 Lambert Conic Conformal (2 SP Belgium)**

(EPSG coordinate operation method code 9803)

In 1972, in order to retain approximately the same grid coordinates after a change of geodetic datum, a modified form of the two standard parallel case was introduced in Belgium. In 2000 this modification was replaced through use of the regular Lambert Conic Conformal (2 SP) map projection with appropriately modified parameter values.

In the 1972 modification the formulas for the regular Lambert Conic Conformal (2SP) case given above are used except for:

$$\text{Easting, } E = E_F + r \sin(\theta - a)$$

$$\text{Northing, } N = N_F + r_F - r \cos(\theta - a)$$

and for the reverse formulas

$$\lambda = [(\theta' + a)/n] + \lambda_F$$

where  $a = 29.2985$  seconds.

**Example:**

For Projected Coordinate Reference System: Belge 1972 / Belge Lambert 72

Parameters:

Ellipsoid:	International 1924	$a = 6378388$ metres	$1/f = 297.0$
	then	$e = 0.08199189$	$e^2 = 0.006722670$

Latitude of false origin	$\varphi_F$	90°00'00"N	=	1.57079633 rad
Longitude of false origin	$\lambda_F$	4°21'24.983"E	=	0.07604294 rad
Latitude of 1 <sup>st</sup> standard parallel	$\varphi_1$	49°50'00"N	=	0.86975574 rad
Latitude of 2 <sup>nd</sup> standard parallel	$\varphi_2$	51°10'00"N	=	0.89302680 rad
Easting at false origin	$E_F$	150000.01	metres	
Northing at false origin	$N_F$	5400088.44	metres	

Forward calculation for:

$$\begin{aligned} \text{Latitude } \varphi &= 50^\circ 40' 46.4610''\text{N} &= 0.88452540 \text{ rad} \\ \text{Longitude } \lambda &= 5^\circ 48' 26.533''\text{E} &= 0.10135773 \text{ rad} \end{aligned}$$

first gives :

$$\begin{array}{ll}
 m_1 = 0.64628304 & m_2 = 0.62834001 \\
 t = 0.35913403 & t_F = 0.00 \\
 t_1 = 0.36750382 & t_2 = 0.35433583 \\
 n = 0.77164219 & F = 1.81329763 \\
 r = 5248041.03 & r_F = 0.00 \\
 \theta = 0.01953396 & a = 0.00014204
 \end{array}$$

Then Easting E = 251763.20 metres  
 Northing N = 153034.13 metres

Reverse calculation for same easting and northing first gives:

$$\begin{array}{ll}
 \theta' = 0.01939192 \\
 t' = 0.35913403 \\
 r' = 5248041.03
 \end{array}$$

Then Latitude  $\phi = 50^{\circ}40'46.4610''N$   
 Longitude  $\lambda = 5^{\circ}48'26.533''E$

**1.4.1.5 Lambert Conic Near-Conformal**

(EPSG coordinate operation method code 9817)

The Lambert Conformal Conic with one standard parallel formulas, as published by the Army Map Service, are still in use in several countries. The AMS uses series expansion formulas for ease of computation, as was normal before the electronic computer made such approximate methods unnecessary. Where the expansion series have been carried to enough terms the results are the same as the above formulas to the centimetre level. However in some countries the expansion formulas were truncated to the third order and the map projection is not fully conformal. The full formulas are used in Libya but from 1915 for France, Morocco, Algeria, Tunisia and Syria the truncated formulas were used. In 1943 in Algeria and Tunisia, from 1948 in France, from 1953 in Morocco and from 1973 in Syria the truncated formulas were replaced with the full formulas.

To compute the Lambert Conic Near-Conformal the following formulas are used. First compute constants for the projection:

n	=	$f / (2 - f)$
A	=	$1 / (6 \rho_0 v_0)$ where $\rho_0$ and $v_0$ are computed as in table 2 in section 1.3 above.
A'	=	$a [ 1 - n + 5 (n^2 - n^3) / 4 + 81 (n^4 - n^5) / 64 ] * \pi / 180$
B'	=	$3 a [ n - n^2 + 7 (n^3 - n^4) / 8 + 55 n^5 / 64 ] / 2$
C'	=	$15 a [ n^2 - n^3 + 3 (n^4 - n^5) / 4 ] / 16$
D'	=	$35 a [ n^3 - n^4 + 11 n^5 / 16 ] / 48$
E'	=	$315 a [ n^4 - n^5 ] / 512$
$r_0$	=	$k_0 v_0 / \tan \phi_0$
$s_0$	=	$A' \phi_0 - B' \sin 2\phi_0 + C' \sin 4\phi_0 - D' \sin 6\phi_0 + E' \sin 8\phi_0$
		where in the first term $\phi_0$ is in degrees, in the other terms $\phi_0$ is in radians.

Then for the computation of easting and northing from latitude and longitude:

s	=	$A' \phi - B' \sin 2\phi + C' \sin 4\phi - D' \sin 6\phi + E' \sin 8\phi$
		where in the first term $\phi$ is in degrees, in the other terms $\phi$ is in radians.

m	=	$[s - s_0]$
M	=	$k_0 (m + Am^3)$ (see footnote <sup>2</sup> )
r	=	$r_0 - M = r_0 - [k_0 (m + Am^3)] = r_0 - \{k_0 ([s - s_0] + A[s - s_0]^3)\}$
$\theta$	=	$(\lambda - \lambda_0) \sin \varphi_0$
and		
E	=	$FE + r \sin \theta$
N	=	$FN + M + r \sin \theta \tan (\theta / 2) = FN + \{k_0 ([s - s_0] + A[s - s_0]^3)\} + r \sin \theta \tan (\theta / 2)$

The reverse formulas for  $\varphi$  and  $\lambda$  from E and N are:

$\theta'$	=	$\text{atan} \{(E - FE) / [r_0 - (N - FN)]\}$
$r'$	=	$(E - FE) / \sin \theta'$
$M'$	=	$r' - r_0$
$\varphi$	=	$\varphi_0 + [(r' - r_0) / M_s]$ which to solve requires $M_s$ (being investigated!).
Then		
$\lambda$	=	$\lambda_0 + \theta' / \sin \varphi_0$ where $\lambda_0$ and $\lambda$ are in radians

where  $\varphi_0$  and  $\varphi$  are in degrees and with  $r_0$  as for the forward formulas above.

$M_s = M$  per second of arc =  $M / ((\varphi - \varphi_0) * 3600)$  which is circular!

**Example:**

For Projected Coordinate Reference System: Deir ez Zor / Levant Zone

Parameters:

Ellipsoid:	Clarke 1880 (IGN)	a = 6378249.2 metres	1/f = 293.46602
	then	b = 6356515.000	n = 0.001706682563

Latitude of natural origin	$\varphi_0$	34°39'00"N	=	0.604756586 rad
Longitude of natural origin	$\lambda_0$	37°21'00"E	=	0.651880476 rad
Scale factor at natural origin	$k_0$	0.99962560		
False easting	FE	300000.00	metres	
False northing	FN	300000.00	metres	

Forward calculation for:

Latitude	$\varphi$	=	37°31'17.625"N	=	0.654874806 rad
Longitude	$\lambda$	=	34°08'11.291"E	=	0.595793792 rad

first gives :

A	=	$4.1067494 * 10^{-15}$	A'	=	111131.8633
B'	=	16300.64407	C'	=	17.38751
D'	=	0.02308	E'	=	0.000033
$s_0$	=	3835482.233	$r_0$	=	9235264.405
s	=	4154101.458	m	=	318619.225
M	=	318632.72	r	=	8916631.685
$\theta$	=	-0.03188875			

Then	Easting	E	=	15707.96 metres (c.f. E = 15708.00 using full formulas)
	Northing	N	=	623165.96 metres (c.f. N = 623167.20 using full formulas)

8585

<sup>2</sup> This is the term that is truncated to the third order. To be equivalent to the Lambert Conic Conformal (1SP) it would be  $M = k_0 (m + Am^3 + Bm^4 + Cm^5 + Dm^6)$ . B, C and D are not detailed here.

Reverse calculation for same easting and northing first gives:

$$\begin{aligned}\theta' &= -0.03188875 \\ r' &= 8916631.685 \\ M' &= 318632.72\end{aligned}$$

$$\begin{aligned}\text{Then Latitude } \varphi &= 37^{\circ}31'17.625''\text{N} \\ \text{Longitude } \lambda &= 34^{\circ}08'11.291''\text{E}\end{aligned}$$

### 1.4.2 Krovak Oblique Conformal Conic

(EPSG coordinate operation method code 9819)

The normal case of the Lambert Conformal conic is for the axis of the cone to be coincident with the minor axis of the ellipsoid, that is the axis of the cone is normal to the ellipsoid at a geographic pole. For the Oblique Conformal Conic the axis of the cone is normal to the ellipsoid at a defined location and its extension cuts the minor axis at a defined angle. This map projection is used in the Czech Republic and Slovakia under the name ‘Krovak’ projection. The map projection method is similar in principle to the Oblique Mercator (see section 1.4.5). The geographic coordinates on the ellipsoid are first reduced to conformal coordinates on the conformal (Gaussian) sphere. These spherical coordinates are then projected onto the oblique cone and converted to grid coordinates. The pseudo standard parallel is defined on the conformal sphere after its rotation, to obtain the oblique aspect of the projection. It is then the parallel on this sphere at which the map projection is true to scale; on the ellipsoid it maps as a complex curve. A scale factor may be applied to the map projection to increase the useful area of coverage.

The defining parameters for the Krovak oblique conformal conic map projection are:

- $\varphi_C$  = latitude of projection centre
- $\lambda_C$  = longitude of projection centre
- $\alpha_C$  = (true) azimuth of initial line passing through the projection centre  
= co-latitude of the cone axis at point of intersection with the ellipsoid
- $\varphi_1$  = latitude of pseudo standard parallel
- $k_C$  = scale factor on pseudo standard parallel
- $E_C$  = Easting at projection centre
- $N_C$  = Northing at projection centre

From these the following constants for the projection may be calculated :

$$\begin{aligned}A &= a (1 - e^2)^{0.5} / [ 1 - e^2 \sin^2 (\varphi_C) ] \\ B &= \{ 1 + [e^2 \cos^4 \varphi_C / (1 - e^2)] \}^{0.5} \\ \gamma_O &= \text{asin} [\sin (\varphi_C) / B] \\ t_O &= \tan(\pi / 4 + \gamma_O / 2) \cdot [ (1 + e \sin (\varphi_C)) / (1 - e \sin (\varphi_C)) ]^{e.B/2} / \tan(\pi / 4 + \varphi_C / 2)^B \\ n &= \sin (\varphi_1) \\ r_O &= k_C A / \tan (\varphi_1)\end{aligned}$$

To derive the projected Easting and Northing coordinates of a point with geographical coordinates ( $\varphi, \lambda$ ) the formulas for the oblique conic conformal are:

$$\begin{aligned}\text{Easting: } E &= E_C + r \cos \theta \\ \text{Northing: } N &= N_C + r \sin \theta\end{aligned}$$

where

$$U = 2 (\text{atan} \{ t_O \tan^B(\varphi / 2 + \pi / 4) / [(1 + e \sin (\varphi)) / (1 - e \sin (\varphi))]^{e.B/2} \} - \pi / 4)$$

$$\begin{aligned}
 V &= B (\lambda_C - \lambda) \\
 S &= \text{asin} [ \cos (\alpha_C) \sin (U) + \sin (\alpha_C) \cos (U) \cos (V) ] \\
 D &= \text{asin} [ \cos (U) \sin (V) / \cos (S) ] \\
 \theta &= n D \\
 r &= r_0 \tan^n (\pi / 4 + \varphi_1 / 2) / \tan^n (S/2 + \pi / 4)
 \end{aligned}$$

Note that the terms Easting and Northing here refer to the two map grid coordinates. Their actual geographic direction depends upon the azimuth of the centre line.

The reverse formulas to derive the latitude and longitude of a point from its Easting and Northing values are:

$$\varphi_j = 2 ( \text{atan} \{ t_0^{-1/B} \tan^{1/B} (U'/2 + \pi / 4) [(1 + e \sin (\varphi_{j-1})) / (1 - e \sin (\varphi_{j-1}))]^{e/2} \} - \pi / 4)$$

where  $j=1,2$  and the latitude is found by iteration.

$$\lambda = \lambda_C - V' / B$$

where

$$\begin{aligned}
 r' &= [(E - E_C)^2 + (N - N_C)^2]^{0.5} \\
 \theta' &= \text{atan} [(E - E_C) / (N - N_C)] \\
 D' &= \theta' / \sin (\varphi_1) \\
 S' &= 2 * \{ \text{atan} [(r_0 / r')^{1/n} \tan(\pi / 4 + \varphi_1 / 2)] - \pi / 4 \} \\
 U' &= \text{asin} ( \cos (\alpha_C) \sin (S') - \sin (\alpha_C) \cos (S') \cos (D') ) \\
 V' &= \text{asin} ( \cos (S') \sin (D') / \cos (U') )
 \end{aligned}$$

For Projected Coordinate Reference System: S-JTSK (Ferro) / Krovak

N.B. Krovak projection uses Ferro as the prime meridian. This has a longitude with reference to Greenwich of 17 degrees 40 minutes West. To apply the formulas the defining longitudes must be corrected to the Greenwich meridian.

Parameters:

Ellipsoid:	Bessel 1841	a = 6377397.155metres	1/f = 299.15281
	then	e = 0.081696831	e <sup>2</sup> = 0.006674372

Latitude of projection centre	$\varphi_C$	49°30'00"N	=	0.863937979 rad
Longitude of projection centre	$\lambda_C$	42°30'00" East of Ferro		
Longitude of Ferro is		17°40'00" West of Greenwich		
$\lambda_C$ relative to Greenwich:		24°50'00"	=	0.433423431 rad
Azimuth of initial line	$\alpha_C$	30°17'17.3031"		
Latitude of pseudo standard parallel	$\varphi_1$	78°30'00"N		
Scale factor on pseudo standard parallel	$k_0$	0.9999		
Easting at projection centre	$E_C$	0.00		metres
Northing at projection centre	$N_C$	0.00		metres

Projection constants:

$$\begin{aligned}
 A &= 6380703.611 & B &= 1.000597498 \\
 \gamma_0 &= 0.863239103 & t_0 &= 1.003419164 \\
 n &= 0.979924705 & r_0 &= 1298039.005
 \end{aligned}$$

Forward calculation for:

$$\begin{aligned}
 \text{Latitude } \varphi &= 50^\circ 12' 32.4416'' \text{N} &= & 0.876312566 \text{ rad} \\
 \text{Longitude } \lambda &= 16^\circ 50' 59.1790'' \text{E} &= & 0.294083999 \text{ rad}
 \end{aligned}$$

first gives :

$$\begin{aligned} U &= 0.875596949 \\ V &= 0.139422687 \\ S &= 1.386275049 \\ D &= 0.506554623 \\ \theta &= 0.496385389 \\ r &= 1194731.014 \end{aligned}$$

$$\begin{aligned} \text{Then "Easting"} \quad E &= 1050538.643 \text{ metres} \\ \text{"Northing"} \quad N &= 568990.997 \text{ metres} \end{aligned}$$

where "Easting" increases southwards and "Northing" increases westwards.

Reverse calculation for the same "Easting" and "Northing" gives

$$\begin{aligned} r' &= 1194731.014 \\ \theta' &= 0.496385389 \\ D' &= 0.506554623 \\ S' &= 1.386275049 \\ U' &= 0.875596949 \\ V' &= 0.139422687 \end{aligned}$$

Then by iteration

$$\begin{aligned} \phi_1 &= 0.876310601 \text{ rad} \\ \phi_2 &= 0.876312560 \text{ rad} \\ \phi_3 &= 0.876312566 \text{ rad} \end{aligned}$$

$$\begin{aligned} \text{Latitude} \quad \phi &= 0.876312566 \text{ rad} &= 50^\circ 12' 32.4416'' \text{N} \\ \text{Longitude} \quad \lambda &= 0.294083999 \text{ rad} &= 16^\circ 50' 59.1790'' \text{E} \end{aligned}$$

### 1.4.3 Mercator

(EPSG coordinate operation method codes 9804 and 9805)

The Mercator map projection is a special limiting case of the Lambert Conic Conformal map projection with the equator as the single standard parallel. All other parallels of latitude are straight lines and the meridians are also straight lines at right angles to the equator, equally spaced. It is the basis for the transverse and oblique forms of the projection. It is little used for land mapping purposes but is in almost universal use for navigation charts. As well as being conformal, it has the particular property that straight lines drawn on it are lines of constant bearing. Thus navigators may derive their course from the angle the straight course line makes with the meridians.

In the few cases in which the Mercator projection is used for terrestrial applications or land mapping, such as in Indonesia prior to the introduction of the Universal Transverse Mercator, a scale factor may be applied to the projection. This has the same effect as choosing two standard parallels on which the true scale is maintained at equal north and south latitudes either side of the equator.

The formulas to derive projected Easting and Northing coordinates are:

For the two standard parallel case,  $k_0$ , the scale factor at the equator or natural origin, is first calculated from

$$k_0 = \cos\phi_1 / (1 - e^2 \sin^2\phi_1)^{0.5}$$

where  $\varphi_1$  is the absolute value of the first standard parallel (i.e. positive).

Then, for both one and two standard parallel cases,

$$E = FE + ak_0 (\lambda - \lambda_0)$$

$$N = FN + ak_0 \ln \left\{ \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) \left[ \frac{1 - e \sin \varphi}{1 + e \sin \varphi} \right]^{(e^2/2)} \right\}$$

where symbols are as listed above and logarithms are natural.

The reverse formulas to derive latitude and longitude from E and N values are:

$$\varphi = \chi + \left( \frac{e^2}{2} + \frac{5e^4}{24} + \frac{e^6}{12} + \frac{13e^8}{360} \right) \sin(2\chi)$$

$$+ \left( \frac{7e^4}{48} + \frac{29e^6}{240} + \frac{811e^8}{11520} \right) \sin(4\chi)$$

$$+ \left( \frac{7e^6}{120} + \frac{81e^8}{1120} \right) \sin(6\chi) + \left( \frac{4279e^8}{161280} \right) \sin(8\chi)$$

where  $\chi = \pi/2 - 2 \operatorname{atan} t$

$$t = B^{(FN-N)/(ak_0)}$$

B = base of the natural logarithm, 2.7182818...

and for the 2 SP case,  $k_0$  is calculated as for the forward transformation above.

$$\lambda = [(E - FE)/ak_0] + \lambda_0$$

**Examples:**

**1. Mercator (with two standard parallels) (EPSG coordinate operation method code 9805)**

For Projected Coordinate Reference System: Pulkovo 1942 / Mercator Caspian Sea

Parameters:

Ellipsoid:	Krassowski 1940	a = 6378245.0 metres		1/f = 298.3
	then	e = 0.08181333		e <sup>2</sup> = 0.00669342

Latitude of 1 <sup>st</sup> standard parallel	$\varphi_0$	42°00'00"N	=	0.73303829 rad
Longitude of natural origin	$\lambda_0$	51°00'00"E	=	0.89011792 rad
False easting	FE	300000.00	metres	
False northing	FN	300000.00	metres	

then scale factor at natural origin  $k_0$  (at latitude of natural origin at 0°N) = 0.74426089.

Forward calculation for:

Latitude  $\varphi = 53^\circ 00' 00.00''\text{N} = 0.9250245 \text{ rad}$   
 Longitude  $\lambda = 53^\circ 00' 00.00''\text{N} = 0.9250245 \text{ rad}$

gives Easting E = 165704.29 metres  
 Northing N = 5171848.07 metres

Reverse calculation for same easting and northing first gives:

t = 0.33639129  
 $\chi = 0.92179596$

Then Latitude  $\varphi = 53^\circ 00' 00.000''\text{N}$   
 Longitude  $\lambda = 53^\circ 00' 00.000''\text{E}$

**2. Mercator (1SP) (EPSG coordinate operation method code 9804)**

For Projected Coordinate Reference System: Makassar / NEIEZ

Parameters:

Ellipsoid:	Bessel 1841	a = 6377397.155metres	1/f = 299.15281
	then	e = 0.081696831	

Latitude of natural origin	$\phi_0$	0°00'00"N	=	0.0 rad
Longitude of natural origin	$\lambda_0$	110°00'00"E	=	1.91986218 rad
Scale factor at natural origin	$k_0$	0.997		
False easting	FE	3900000.00	metres	
False northing	FN	900000.00	metres	

Forward calculation for:

$$\begin{aligned} \text{Latitude } \phi &= 3^{\circ}00'00.00''\text{S} = -0.05235988 \text{ rad} \\ \text{Longitude } \lambda &= 120^{\circ}00'00.00''\text{E} = 2.09439510 \text{ rad} \end{aligned}$$

$$\begin{aligned} \text{gives Easting } E &= 5009726.58 \text{ metres} \\ \text{Northing } N &= 569150.82 \text{ metres} \end{aligned}$$

Reverse calculation for same easting and northing first gives:

$$\begin{aligned} t &= 1.0534121 \\ \chi &= -0.0520110 \end{aligned}$$

$$\begin{aligned} \text{Then Latitude } \phi &= 3^{\circ}00'00.000''\text{S} \\ \text{Longitude } \lambda &= 120^{\circ}00'00.000''\text{E} \end{aligned}$$

**1.4.4 Cassini-Soldner**

(EPSG coordinate operation method code 9806)

The Cassini-Soldner projection is the ellipsoidal version of the Cassini projection for the sphere. It is not conformal but as it is relatively simple to construct it was extensively used in the last century and is still useful for mapping areas with limited longitudinal extent. It has now largely been replaced by the conformal Transverse Mercator which it resembles. Like this, it has a straight central meridian along which the scale is true, all other meridians and parallels are curved, and the scale distortion increases rapidly with increasing distance from the central meridian.

The formulas to derive projected Easting and Northing coordinates are:

$$\text{Easting, } E = FE + v[A - TA^3/6 - (8 - T + 8C)TA^5/120]$$

$$\text{Northing, } N = FN + M - M_0 + v \tan \phi [A^2/2 + (5 - T + 6C)A^4/24]$$

$$\begin{aligned} \text{where } A &= (\lambda - \lambda_0) \cos \phi \\ T &= \tan^2 \phi \\ C &= e^2 \cos^2 \phi / (1 - e^2) \\ v &= a / (1 - e^2 \sin^2 \phi)^{0.5} \end{aligned}$$

and M, the distance along the meridian from equator to latitude  $\phi$ , is given by

$$\begin{aligned} M = a [ &1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots ] \phi - (3e^2/8 + 3e^4/32 + 45e^6/1024 + \dots) \sin 2\phi \\ &+ (15e^4/256 + 45e^6/1024 + \dots) \sin 4\phi - (35e^6/3072 + \dots) \sin 6\phi + \dots ] \end{aligned}$$

with  $\phi$  in radians.

$M_0$  is the value of  $M$  calculated for the latitude of the chosen origin. This may not necessarily be chosen as the equator.

To compute latitude and longitude from Easting and Northing the reverse formulas are:

$$\begin{aligned}\varphi &= \varphi_1 - (v_1 \tan \varphi_1 / \rho_1) [D^2/2 - (1 + 3T_1)D^4/24] \\ \lambda &= \lambda_0 + [D - T_1 D^3/3 + (1 + 3T_1)T_1 D^5/15] / \cos \varphi_1\end{aligned}$$

where

$$\begin{aligned}v_1 &= a / (1 - e^2 \sin^2 \varphi_1)^{0.5} \\ \rho_1 &= a(1 - e^2) / (1 - e^2 \sin^2 \varphi_1)^{1.5} \\ \varphi_1 &\text{ is the latitude of the point on the central meridian which has the same Northing as the point whose coordinates are sought, and is found from:}\end{aligned}$$

$$\begin{aligned}\varphi_1 &= \mu_1 + (3e_1/2 - 27e_1^3/32 + \dots) \sin 2\mu_1 + (21e_1^2/16 - 55e_1^4/32 + \dots) \sin 4\mu_1 \\ &\quad + (151e_1^3/96 + \dots) \sin 6\mu_1 + (1097e_1^4/512 - \dots) \sin 8\mu_1 + \dots\end{aligned}$$

where

$$\begin{aligned}e_1 &= [1 - (1 - e^2)^{0.5}] / [1 + (1 - e^2)^{0.5}] \\ \mu_1 &= M_1 / [a(1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots)] \\ M_1 &= M_0 + (N - FN) \\ T_1 &= \tan^2 \varphi_1 \\ D &= (E - FE) / v_1\end{aligned}$$

**Example**

For Projected Coordinate Reference System: Trinidad 1903 / Trinidad Grid

Parameters:

Ellipsoid:	Clarke 1858	a = 20926348 ft	=	31706587.88 Clarke's links
		b = 20855233 ft		
	then	1/f = 294.2606764		e <sup>2</sup> = 0.006785146

Latitude of natural origin	$\varphi_0$	10°26'30"N	=	0.182241463 rad
Longitude of natural origin	$\lambda_0$	61°20'00"W	=	1.91986218 rad
False easting	FE	430000.00		Clarke's links
False northing	FN	325000.00		Clarke's links

Forward calculation for:

$$\begin{aligned}\text{Latitude } \varphi &= 10^\circ 00' 00.00'' \text{N} &= 0.17453293 \text{ rad} \\ \text{Longitude } \lambda &= 62^\circ 00' 00.00'' \text{W} &= -1.08210414 \text{ rad}\end{aligned}$$

first gives :

$$\begin{aligned}A &= -0.01145876 & C &= 0.00662550 \\ T &= 0.03109120 & M &= 5496860.24 \\ v &= 31709831.92 & M_0 &= 5739691.12\end{aligned}$$

$$\begin{aligned}\text{Then Easting } E &= 66644.94 \text{ Clarke's links} \\ \text{Northing } N &= 82536.22 \text{ Clarke's links}\end{aligned}$$

Reverse calculation for same easting and northing first gives:

$$\begin{aligned}e_1 &= 0.00170207 & D &= -0.01145875 \\ T_1 &= 0.03109544 & M_1 &= 5497227.34 \\ v_1 &= 31709832.34 & \mu_1 &= 0.17367306 \\ \varphi_1 &= 0.17454458 & \rho_1 &= 31501122.40\end{aligned}$$

$$\text{Then Latitude } \varphi = 10^\circ 00' 00.000'' \text{N}$$

Longitude  $\lambda = 62^{\circ}00'00.000''W$

### 1.4.5 Transverse Mercator

#### 1.4.5.1 General Case

(EPSG coordinate operation method code 9807)

The Transverse Mercator projection in its various forms is the most widely used projected coordinate system for world topographical and offshore mapping. All versions have the same basic characteristics and formulas. The differences which distinguish the different forms of the projection which are applied in different countries arise from variations in the choice of values for the coordinate conversion parameters, namely the latitude of the natural origin, the longitude of the natural origin (central meridian), the scale factor at the natural origin (on the central meridian), and the values of False Easting and False Northing, which embody the units of measurement, given to the origin. Additionally there are variations in the width of the longitudinal zones for the projections used in different territories.

The following table indicates the variations in the coordinate conversion parameters which distinguish the different forms of the Transverse Mercator projection and are used in the EPSG Transverse Mercator map projection operations:

TABLE 2  
**Transverse Mercator**

<b>Coordinate Operation Method Name</b>	<b>Areas used</b>	<b>Central meridian</b>	<b>Latitude of natural origin</b>	<b>CM Scale Factor</b>	<b>Zone width</b>	<b>False Easting</b>	<b>False Northing</b>
<b>Transverse Mercator</b>	Various, world wide	Various	Various	Various	Usually less than 6°	Various	Various
<b>Transverse Mercator south oriented</b>	Southern Africa	2° intervals E of 11°E	0°	1.000000	2°	0m	0m
<b>UTM North hemisphere</b>	World wide equator to 84°N	6° intervals E & W of 3° E & W	Always 0°	Always 0.9996	Always 6°	500000 m	0m
<b>UTM South hemisphere</b>	World wide north of 80°S to equator	6° intervals E & W of 3° E & W	Always 0°	Always 0.9996	Always 6°	500000 m	10000000 m
<b>Gauss-Kruger</b>	Former USSR, Yugoslavia, Germany, S. America, China	Various, according to area of cover	Usually 0°	Usually 1.000000	Usually less than 6°, often less than 4°	Various but often 500000 prefixed by zone number	Various
<b>Gauss Boaga</b>	Italy	Various	Various	0.9996	6°	Various	0m

The most familiar and commonly used Transverse Mercator in the oil industry is the Universal Transverse Mercator (UTM) whose natural origin lies on the equator. However, some territories use a Transverse Mercator with a natural origin at a latitude of natural origin closer to that territory.

In EPSG the coordinate conversion method is considered to be the same for all forms of the Transverse Mercator projection. The formulas to derive the projected Easting and Northing coordinates for the normal case (EPSG coordinate operation method code 9807) are in the form of a series as follows:

$$\text{Easting, } E = FE + k_0 v [A + (1 - T + C)A^3/6 + (5 - 18T + T^2 + 72C - 58e'^2)A^5/120]$$

$$\text{Northing, } N = FN + k_0 \{M - M_0 + v \tan \varphi [A^2/2 + (5 - T + 9C + 4C^2)A^4/24 + (61 - 58T + T^2 + 600C - 330e'^2)A^6/720]\}$$

where  $T = \tan^2 \varphi$

$$C = e^2 \cos^2 \varphi / (1 - e^2)$$

$$A = (\lambda - \lambda_0) \cos \varphi, \text{ with } \lambda \text{ and } \lambda_0 \text{ in radians}$$

$$v = a / (1 - e^2 \sin^2 \varphi)^{0.5}$$

$$M = a [(1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots) \varphi - (3e^2/8 + 3e^4/32 + 45e^6/1024 + \dots) \sin 2\varphi + (15e^4/256 + 45e^6/1024 + \dots) \sin 4\varphi - (35e^6/3072 + \dots) \sin 6\varphi + \dots]$$

with  $\varphi$  in radians and  $M_0$  for  $\varphi_0$ , the latitude of the origin, derived in the same way.

The reverse formulas to convert Easting and Northing projected coordinates to latitude and longitude are:

$$\varphi = \varphi_1 - (v_1 \tan \varphi_1 / \rho_1) [D^2/2 - (5 + 3T_1 + 10C_1 - 4C_1^2 - 9e'^2)D^4/24 + (61 + 90T_1 + 298C_1 + 45T_1^2 - 252e'^2 - 3C_1^2)D^6/720]$$

$$\lambda = \lambda_0 + [D - (1 + 2T_1 + C_1)D^3/6 + (5 - 2C_1 + 28T_1 - 3C_1^2 + 8e'^2 + 24T_1^2)D^5/120] / \cos \varphi_1$$

where

$$v_1 = a / (1 - e^2 \sin^2 \varphi_1)^{0.5}$$

$$\rho_1 = a(1 - e^2) / (1 - e^2 \sin^2 \varphi_1)^{1.5}$$

$\varphi_1$  may be found as for the Cassini projection from:

$$\varphi_1 = \mu_1 + (3e_1/2 - 27e_1^3/32 + \dots) \sin 2\mu_1 + (21e_1^2/16 - 55e_1^4/32 + \dots) \sin 4\mu_1 + (151e_1^3/96 + \dots) \sin 6\mu_1 + (1097e_1^4/512 - \dots) \sin 8\mu_1 + \dots$$

and where

$$e_1 = [1 - (1 - e^2)^{0.5}] / [1 + (1 - e^2)^{0.5}]$$

$$\mu_1 = M_1 / [a(1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots)]$$

$$M_1 = M_0 + (N - FN) / k_0$$

$$T_1 = \tan^2 \varphi_1$$

$$C_1 = e^2 \cos^2 \varphi_1$$

$$e'^2 = e^2 / (1 - e^2)$$

$$D = (E - FE) / (v_1 k_0)$$

For areas south of the equator the value of latitude  $\varphi$  will be negative and the formulas above, to compute the E and N, will automatically result in the correct values. Note that the false northings of the origin, if the equator, will need to be large to avoid negative northings and for the UTM projection is in fact 10,000,000m. Alternatively, as in the case of Argentina's Transverse Mercator (Gauss-Kruger) zones, the origin is at the south pole with a northings of zero. However each zone central meridian takes a false easting of 500000m prefixed by an identifying zone number. This ensures that instead of points in different zones having the same eastings, every point in the country, irrespective of its projection zone, will have a unique set of projected system coordinates. Strict application of the above formulas, with south latitudes negative, will result in the derivation of the correct Eastings and Northings.

Similarly, in applying the reverse formulas to determine a latitude south of the equator, a negative sign for  $\varphi$  results from a negative  $\varphi_1$  which in turn results from a negative  $M_1$ .

**Example**

For Projected Coordinate Reference System OSGB 1936 / British National Grid

Parameters:

Ellipsoid:	Airy 1830	a = 6377563.396 metres	1/f = 299.32496
	then	e <sup>2</sup> = 0.00667054	e' <sup>2</sup> = 0.00671534

Latitude of natural origin	φ <sub>0</sub>	49°00'00"N	=	0.85521133 rad
Longitude of natural origin	λ <sub>0</sub>	2°00'00"W	=	-0.03490659 rad
Scale factor at natural origin	k <sub>0</sub>	0.9996012717		
False easting	FE	400000.00	metres	
False northing	FN	-100000.00	metres	

Forward calculation for:

Latitude φ = 50°30'00.00"N = 0.88139127 rad  
 Longitude λ = 00°30'00.00"E = 0.00872665 rad

first gives :

A = 0.02775415                      C = 0.00271699  
 T = 1.47160434                      M = 5596050.46  
 v = 6390266.03                      M<sub>0</sub> = 5429228.60

Then Easting E = 577274.99 metres  
 Northing N = 69740.50 metres

Reverse calculation for same easting and northing first gives:

e<sub>1</sub> = 0.00167322                      μ<sub>1</sub> = 0.87939562  
 M<sub>1</sub> = 5599036.80                      v<sub>1</sub> = 6390275.88  
 φ<sub>1</sub> = 0.88185987                      D = 0.02775243  
 ρ<sub>1</sub> = 6372980.21                      C<sub>1</sub> = 0.00271391  
 T<sub>1</sub> = 1.47441726

Then Latitude φ = 50°30'00.000"N  
 Longitude λ = 00°30'00.000"E

**1.4.5.2 Transverse Mercator Zoned Grid System**

(EPSG coordinate operation method code 9824)

When the growth in distortion away from the projection origin is of concern, a projected coordinate reference system cannot be used far from its origin. A means of creating a grid system over a large area but also limiting distortion is to have several grid zones with most defining parameters being made common. Coordinates throughout the system are repeated in each zone. To make coordinates unambiguous the easting is prefixed by the relevant zone number. This procedure was adopted by German mapping in the 1930's through the Gauss-Kruger systems and later by American military mapping through the Universal Transverse Mercator (or UTM) grid system. (Note: subsequent civilian adoption of the systems usually ignores the zone prefix to easting. Where this is the case the formulas below do not apply: use the standard TM formula separately for each zone).

The parameter Longitude of natural origin (λ<sub>0</sub>) is changed from being a defining parameter to a derived parameter, replaced by two other defining parameters, the Initial Longitude (the western limit of zone 1) (λ<sub>i</sub>) and the Zone Width (W). Each of the remaining four Transverse Mercator defining parameters –

Latitude of natural origin, Scale factor at natural origin, False easting and False northing – have the same parameter values in every zone.

The standard Transverse Mercator formulas above are modified as follows:

Zone number,  $Z$ , =  $\text{INT}((\lambda + \lambda_1 + W) / W)$  with  $\lambda$ ,  $\lambda_1$  and  $W$  in degrees.

where  $\lambda_1$  is the Initial Longitude of the zoned grid system

and  $W$  is the width of each zone of the zoned grid system.

If  $\lambda < 0$ ,  $\lambda = (\lambda + 360)$  degrees.

Then,

$$\lambda_0 = [Z * W] - [\lambda_1 + (W/2)]$$

For the forward calculation,

$$\text{Easting, } E = Z * 10^6 + FE + k_0.v [A + (1 - T + C)A^3/6 + (5 - 18T + T^2 + 72C - 58e'^2)A^5/120]$$

and in the reverse calculation for longitude,

$$D = (E - [FE + Z * 10^6]) / (v_1.k_0)$$

#### 1.4.5.3 **Transverse Mercator (South Orientated)**

(EPSG coordinate operation method code 9808)

For the mapping of southern Africa a south oriented Transverse Mercator map projection method is used. Here the coordinate axes are called Westings and Southings and increment to the West and South from the origin respectively. See Figure 3 for a diagrammatic illustration. The standard Transverse Mercator above formulas need to be modified to cope with this arrangement with

$$\text{Westing, } W = FE - k_0.v [A + (1 - T + C)A^3/6 + (5 - 18T + T^2 + 72C - 58e'^2)A^5/120]$$

$$\text{Southing, } S = FN - k_0\{M - M_0 + v \tan \phi [A^2/2 + (5 - T + 9C + 4C^2)A^4/24 + (61 - 58T + T^2 + 600C - 330e'^2)A^6/720]\}$$

In these formulas the terms  $FE$  and  $FN$  retain their definition, i.e. in the Transverse Mercator (South Orientated) method they increase the Westing and Southing value at the natural origin. In this method they are effectively false westing ( $FW$ ) and false southing ( $FS$ ) respectively.

For the reverse formulas, those for the standard Transverse Mercator above apply, with the exception that:

$$M_1 = M_0 - (S - FN) / k_0$$

and  $D = -(W - FE) / (v_1.k_0)$ , with  $v_1 = v$  for  $\phi_1$

#### 1.4.6 **Oblique Mercator and Hotine Oblique Mercator**

(EPSG coordinate operation method codes 9815 and 9812).

It has been noted that the Transverse Mercator map projection method is employed for the topographical mapping of longitudinal bands of territories, limiting the amount of scale distortion by limiting the extent of the projection either side of the central meridian. Sometimes the shape, general trend and extent of some countries makes it preferable to apply a single zone of the same kind of projection but with its central line aligned with the trend of the territory concerned rather than with a meridian. So, instead of a meridian forming this true scale central line for one of the various forms of Transverse Mercator, or the equator forming the line for the Mercator, a line with a particular azimuth traversing the territory is chosen and the same principles of construction are applied to derive what is now an Oblique Mercator.

Such a single zone projection suits areas which have a large extent in one direction but limited extent in the perpendicular direction and whose trend is oblique to the bisecting meridian - such as East and West Malaysia, Madagascar and the Alaskan panhandle. It was originally applied at the beginning of the 20<sup>th</sup> century by Rosenmund to the mapping of Switzerland, and in the 1970's adopted in Hungary. The projection's initial line may be selected as a line with a particular azimuth through a single point, normally at the centre of the mapped area, or as the geodesic line (the shortest line between two points on the ellipsoid) between two selected points.

EPSG identifies two forms of the oblique Mercator projection, differentiated only by the point at which false grid coordinates are defined. If the false grid coordinates are defined at the intersection of the initial line and the aposphere, that is at the natural origin of the coordinate system, the map projection method is known as the Hotine Oblique Mercator (EPSG coordinate operation method code 9812). If the false grid coordinates are defined at the projection centre the projection method is known as the Oblique Mercator (EPSG coordinate operation method code 9815).

Hotine projected the ellipsoid conformally onto a sphere of constant total curvature, called the 'aposphere', before projection onto the plane. This projection is sometimes referred to as the Rectified Skew Orthomorphic. Formulas, involving hyperbolic functions, were derived by Hotine. Snyder adapted these formulas to use exponential functions, thus avoiding use of Hotine's hyperbolic expressions. Alternative formulas derived by projecting the ellipsoid onto the 'conformal' sphere give identical results within the practical limits of the use of the formulas.

Snyder describes a variation of the Hotine Oblique Mercator where the initial line is defined by two points through which it passes. The latter approach is not currently followed by EPSG/POSC; it has been applied to mapping space imagery or, more frequently, for applying a geographical graticule to the imagery. However, the repeated path of the imaging satellite does not actually follow the centre lines of successive oblique cylindrical projections so a projection was derived whose centre line does follow the satellite path. This is known as the Space Oblique Mercator Projection and although it closely resembles an oblique cylindrical it is not quite conformal and has no application other than for space imagery.

The oblique Mercator co-ordinate system is defined by:

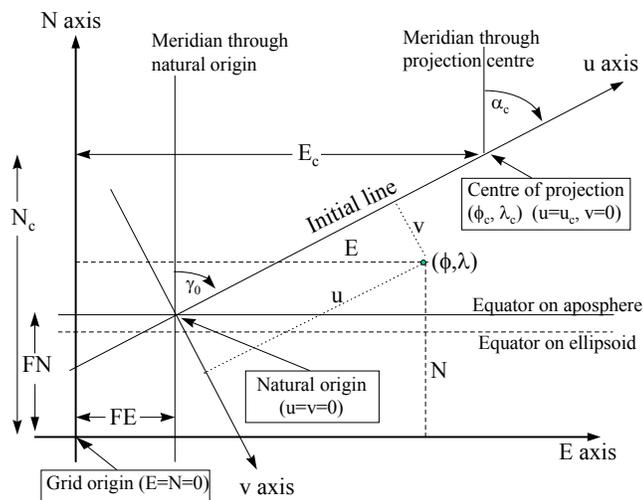


Figure 7. Key Diagram for Oblique Mercator Projection

The initial line central to the map area of given azimuth  $\alpha_c$  passes through a defined centre of the projection  $(\phi_c, \lambda_c)$ . The point where the projection of this line cuts the equator on the aposphere is the

origin of the (u , v) co-ordinate system. The u axis is parallel to the centre line and the v axis is perpendicular to (90° clockwise from) this line.

In applying the formulas for the (Hotine) Oblique Mercator the first set of co-ordinates computed are referred to the (u, v) co-ordinate axes defined with respect to the azimuth of the centre line. These co-ordinates are then ‘rectified’ to the usual Easting and Northing by applying an orthogonal conversion. Hence the alternative name as the Rectified Skew Orthomorphic. In the special case of the projection covering the Alaskan panhandle the azimuth of the line at the natural origin is taken to be identical to the azimuth of the initial line at the projection centre. This results in grid and true north coinciding at the projection centre rather than at the natural origin as is more usual.

To ensure that all co-ordinates in the map area have positive grid values, false co-ordinates are applied. These may be given values ( $E_C$  ,  $N_C$ ) if applied at the projection centre [EPSG Oblique Mercator method] or be applied as false easting (FE) and false northing (FN) at the natural origin [EPSG Hotine Oblique Mercator method].

The formulas can be used for the following cases:

- Alaska State Plane Zone 1
- Hungary EOV
- Madagascar Laborde Grid
- East and West Malaysia Rectified Skew Orthomorphic grids
- Swiss Cylindrical projection

The Swiss and Hungarian systems are a special case where the azimuth of the line through the projection centre is 90 degrees. These therefore give similar but not exactly the same results as a conventional Transverse Mercator projection.

Specific references for the formulas originally used in the individual cases of these projections are:

- Switzerland: "Die Änderung des Projektionssystems der schweizerischen Landesvermessung." M. Rosenmund 1903. Also "Die projektionen der Schweizerischen Plan und Kartenwerke." J. Bollinger 1967.
- Madagascar: "La nouvelle projection du Service Geographique de Madagascar". J. Laborde 1928.
- Malaysia: Series of Articles in numbers 62-66 of the Empire Survey Review of 1946 and 1947 by M. Hotine.

The defining parameters for the [Hotine] Oblique Mercator projection are:

- $\varphi_C$  = latitude of centre of the projection
- $\lambda_C$  = longitude of centre of the projection
- $\alpha_C$  = azimuth (true) of the centre line passing through the centre of the projection
- $\gamma_C$  = rectified bearing of the centre line
- $k_C$  = scale factor at the centre of the projection

and either

for the Oblique Mercator:

- $E_C$  = False Easting at the centre of projection
- $N_C$  = False Northing at the centre of projection

or for the Hotine Oblique Mercator:

- FE = False Easting at the natural origin
- FN = False Northing at the natural origin

From these defining parameters the following constants for the map projection may be calculated for both the Hotine Oblique Mercator and Oblique Mercator methods:

$$B = \{1 + [e^2 \cos^4 \varphi_C / (1 - e^2)]\}^{0.5}$$

$$\begin{aligned}
 A &= a B k_C (1 - e^2)^{0.5} / (1 - e^2 \sin^2 \varphi_C) \\
 t_o &= \tan(\pi / 4 - \varphi_C / 2) / [(1 - e \sin \varphi_C) / (1 + e \sin \varphi_C)]^{e/2} \\
 D &= B (1 - e^2)^{0.5} / [\cos \varphi_C (1 - e^2 \sin^2 \varphi_C)^{0.5}] \\
 \text{To avoid problems with computation of F, if } D < 1 \text{ make } D^2 &= 1 \\
 F &= D + (D^2 - 1)^{0.5} \cdot \text{SIGN}(\varphi_C) \\
 H &= F t_o^B \\
 G &= (F - 1/F) / 2 \\
 \gamma_o &= \text{asin}[\sin(\alpha_C) / D] \\
 \lambda_o &= \lambda_C - [\text{asin}(G \tan \gamma_o)] / B
 \end{aligned}$$

Then for the Oblique Mercator method only, two further constants for the map projection, the  $(u_C, v_C)$  co-ordinates for the centre point  $(\varphi_C, \lambda_C)$ , are calculated from:

$$v_C = 0$$

In general

$$u_C = (A / B) \text{atan}[(D^2 - 1)^{0.5} / \cos(\alpha_C)] \cdot \text{SIGN}(\varphi_C)$$

but for the special cases where  $\alpha_C = 90$  degrees (e.g. Hungary, Switzerland) then

$$u_C = A (\lambda_C - \lambda_o)$$

**Forward case:** To compute  $(E, N)$  from a given  $(\varphi, \lambda)$ , for both the Hotine Oblique Mercator method and the Oblique Mercator method:

$$\begin{aligned}
 t &= \tan(\pi / 4 - \varphi / 2) / [(1 - e \sin \varphi) / (1 + e \sin \varphi)]^{e/2} \\
 Q &= H / t^B \\
 S &= (Q - 1/Q) / 2 \\
 T &= (Q + 1/Q) / 2 \\
 V &= \sin(B (\lambda - \lambda_o)) \\
 U &= (-V \cos(\gamma_o) + S \sin(\gamma_o)) / T \\
 v &= A \ln[(1 - U) / (1 + U)] / 2 B
 \end{aligned}$$

Then either

(a) for the Hotine Oblique Mercator (where the FE and FN values have been specified with respect to the natural origin of the  $(u, v)$  axes):

$$u = A \text{atan}\{(S \cos \gamma_o + V \sin \gamma_o) / \cos[B (\lambda - \lambda_o)]\} / B$$

The rectified skew co-ordinates are then derived from:

$$E = v \cos(\gamma_C) + u \sin(\gamma_C) + FE$$

$$N = u \cos(\gamma_C) - v \sin(\gamma_C) + FN$$

or

(b) for the Oblique Mercator (where the false easting and northing values  $(E_C, N_C)$  have been specified with respect to the centre of the projection  $(\varphi_C, \lambda_C)$  then :

$$u = (A \text{atan}\{(S \cos \gamma_o + V \sin \gamma_o) / \cos[B (\lambda - \lambda_o)]\} / B) - (\text{ABS}(u_C) \cdot \text{SIGN}(\varphi_C))$$

The rectified skew co-ordinates are then derived from:

$$E = v \cos(\gamma_C) + u \sin(\gamma_C) + E_C$$

$$N = u \cos(\gamma_C) - v \sin(\gamma_C) + N_C$$

**Reverse case:** To compute  $(\varphi, \lambda)$  from a given  $(E, N)$  :

For the Hotine Oblique Mercator:

$$v' = (E - FE) \cos(\gamma_C) - (N - FN) \sin(\gamma_C)$$

$$u' = (N - FN) \cos(\gamma_C) + (E - FE) \sin(\gamma_C)$$

or for the Oblique Mercator:

$$v' = (E - E_C) \cos(\gamma_C) - (N - N_C) \sin(\gamma_C)$$

$$u' = (N - N_C) \cos(\gamma_C) + (E - E_C) \sin(\gamma_C) + (\text{ABS}(u_C) * \text{SIGN}(\varphi_C))$$

then for both cases:

$$Q' = e^{-(B v' / A)} \text{ where } e \text{ is the base of natural logarithms.}$$

$$S' = (Q' - 1 / Q') / 2$$

$$T' = (Q' + 1 / Q') / 2$$

$$V' = \sin(B u' / A)$$

$$U' = (V' \cos(\gamma_O) + S' \sin(\gamma_O)) / T'$$

$$t' = \{H / [(1 + U') / (1 - U')]^{0.5}\}^{1/B}$$

$$\chi = \pi / 2 - 2 \operatorname{atan}(t')$$

$$\varphi = \chi + \sin(2\chi) \cdot (e^2 / 2 + 5 e^4 / 24 + e^6 / 12 + 13 e^8 / 360)$$

$$+ \sin(4\chi) \cdot (7 e^4 / 48 + 29 e^6 / 240 + 811 e^8 / 11520)$$

$$+ \sin(6\chi) \cdot (7 e^6 / 120 + 81 e^8 / 1120) + \sin(8\chi) \cdot (4279 e^8 / 161280)$$

$$\lambda = \lambda_O - \operatorname{atan} [(S' \cos \gamma_C - V' \sin \gamma_C) / \cos(B u' / A)] / B$$

**Examples:**

For Projected Coordinate Reference System Timbalai 1948 / R.S.O. Borneo (m) using the Oblique Mercator method: (EPSG coordinate operation method code 9815).

Parameters:

Ellipsoid:	Everest 1830 (1967 Definition)	a = 6377298.556 metres	1/f = 300.8017
		then e = 0.081472981	e <sup>2</sup> = 0.006637847

Latitude of projection centre	$\varphi_C$	4°00'00"N	=	0.069813170 rad
Longitude of projection centre	$\lambda_C$	115°00'00"E	=	2.007128640 rad
Azimuth of initial line	$\alpha_C$	53°18'56.9537"	=	0.930536611 rad
Angle from Rectified to Skew Grid	$\gamma_C$	53°07'48.3685"	=	0.927295218 rad
Scale factor on initial line	$k_C$	0.99984		
Easting at projection centre	$E_C$	590476.87		metres
Northings at projection centre	$N_C$	442857.65		metres

Forward calculation for:

$$\text{Latitude } \varphi = 5^\circ 23' 14.1129'' \text{N} = 0.094025313 \text{ rad}$$

$$\text{Longitude } \lambda = 115^\circ 48' 19.8196'' \text{E} = 2.021187362 \text{ rad}$$

first gives :

B	=	1.003303209	F	=	1.072121256
A	=	6376278.686	H	=	1.000002991
T <sub>O</sub>	=	0.932946976	$\gamma_O$	=	0.927295218
D	=	1.002425787	$\lambda_O$	=	1.914373469
D <sup>2</sup>	=	1.004857458			
u <sub>c</sub>	=	738096.09	v <sub>c</sub>	=	0.00
t	=	0.910700729	Q	=	1.098398182
S	=	0.093990763	T	=	1.004407419

$$\begin{array}{lcl} V & = & 0.106961709 \\ v & = & -69702.787 \end{array} \qquad \begin{array}{lcl} U & = & 0.010967247 \\ u & = & 163238.163 \end{array}$$

$$\begin{array}{lcl} \text{Then Easting} & E & = 679245.73 \text{ metres} \\ \text{Northing} & N & = 596562.78 \text{ metres} \end{array}$$

Reverse calculation for same easting and northing first gives:

$$\begin{array}{lcl} v' & = & -69702.787 \\ Q' & = & 1.011028053 \\ S' & = & 0.010967907 \\ V' & = & 0.141349378 \\ t' & = & 0.910700729 \end{array} \qquad \begin{array}{lcl} u' & = & 901334.257 \\ T' & = & 1.000060146 \\ U' & = & 0.093578324 \\ \chi & = & 0.093404829 \end{array}$$

$$\begin{array}{lcl} \text{Then Latitude} & \varphi & = 5^{\circ}23'14.113''\text{N} \\ \text{Longitude} & \lambda & = 115^{\circ}48'19.820''\text{E} \end{array}$$

If the same projection is defined using the Hotine Oblique Mercator method then:

$$\begin{array}{lcl} \text{False easting} & FE & = 0.0 \text{ metres} \\ \text{False northing} & FN & = 0.0 \text{ metres} \\ \text{Then} & u & = 901334.257 \end{array}$$

and all other values are as for the Oblique Mercator method.

### 1.4.7 Stereographic

The Stereographic projection may be imagined to be a projection of the earth's surface onto a plane in contact with the earth at a single tangent point from a projection point at the opposite end of the diameter through that tangent point.

This projection is best known in its polar form and is frequently used for mapping polar areas where it complements the Universal Transverse Mercator used for lower latitudes. Its spherical form has also been widely used by the US Geological Survey for planetary mapping and the mapping at small scale of continental hydrocarbon provinces. In its transverse or oblique ellipsoidal forms it is useful for mapping limited areas centred on the point where the plane of the projection is regarded as tangential to the ellipsoid, e.g. the Netherlands. The tangent point is the origin of the projected coordinate system and the meridian through it is regarded as the central meridian. In order to reduce the scale error at the extremities of the projection area it is usual to introduce a scale factor of less than unity at the origin such that a unitary scale factor applies on a near circle centred at the origin and some distance from it.

The coordinate conversion from geographical to projected coordinates is executed via the distance and azimuth of the point from the centre point or origin. For a sphere the formulas are relatively simple. For the ellipsoid the parameters defining the conformal sphere at the tangent point as origin are first derived. The conformal latitudes and longitudes are substituted for the geodetic latitudes and longitudes of the spherical formulas for the origin and the point.

An alternative approach is given by Snyder, where, instead of defining a single conformal sphere at the origin point, the conformal latitude at each point on the ellipsoid is computed. The conformal longitude is then always equivalent to the geodetic longitude. This approach is a valid alternative to that given here, but gives slightly different results away from the origin point. The USGS formula is therefore considered by EPSG to be a different coordinate operation method to that described here.

**1.4.7.1 Oblique and Equatorial Stereographic cases**

(EPSG coordinate operation method code 9809)

Given the geodetic origin of the projection at the tangent point ( $\phi_0, \lambda_0$ ), the parameters defining the conformal sphere are:

$$R = (\rho_0 \cdot \nu_0)^{0.5}$$

$$n = \{1 + [(e^2 \cos^4 \phi_0) / (1 - e^2)]\}^{0.5}$$

$$C = (n + \sin \phi_0) (1 - \sin \chi_0) / [(n - \sin \phi_0) (1 + \sin \chi_0)]$$

where:  $\sin \chi_0 = (w_1 - 1) / (w_1 + 1)$   
 $w_1 = [S_1 \cdot (S_2)^e]^n$   
 $S_1 = (1 + \sin \phi_0) / (1 - \sin \phi_0)$   
 $S_2 = (1 - e \sin \phi_0) / (1 + e \sin \phi_0)$

The conformal latitude and longitude of the origin ( $\chi_0, \Lambda_0$ ) are then computed from :

$$\chi_0 = \sin^{-1} [(w_2 - 1) / (w_2 + 1)]$$

where  $S_1$  and  $S_2$  are as above and  $w_2 = c [S_1 \cdot (S_2)^e]^n = c \cdot w_1$

$$\Lambda_0 = \lambda_0$$

For any point with geodetic coordinates ( $\phi, \lambda$ ) the equivalent conformal latitude and longitude ( $\chi, \Lambda$ ) are then computed from

$$\Lambda = n(\lambda - \Lambda_0) + \Lambda_0$$

and

$$\chi = \sin^{-1} [(w - 1) / (w + 1)]$$

where  $w = c [S_a \cdot (S_b)^e]^n$   
 $S_a = (1 + \sin \phi) / (1 - \sin \phi)$   
 $S_b = (1 - e \cdot \sin \phi) / (1 + e \cdot \sin \phi)$

Then

$$E = FE + 2 R k_0 \cos \chi \sin(\Lambda - \Lambda_0) / B$$

and

$$N = FN + 2 R k_0 [\sin \chi \cos \chi_0 - \cos \chi \sin \chi_0 \cos(\Lambda - \Lambda_0)] / B$$

where  $B = [1 + \sin \chi \sin \chi_0 + \cos \chi \cos \chi_0 \cos(\Lambda - \Lambda_0)]$

The reverse formulas to compute the geodetic coordinates from the grid coordinates involves computing the conformal values, then the isometric latitude and finally the geodetic values.

The parameters of the conformal sphere and conformal latitude and longitude at the origin are computed as above. Then for any point with Stereographic grid coordinates (E,N) :

$$\chi = \chi_0 + 2 \tan^{-1} \{[(N - FN) - (E - FE) \tan(j/2)] / (2 R k_0)\}$$

$$\Lambda = j + 2 i + \Lambda_0$$

where  $g = 2 R k_0 \tan(\pi/4 - \chi_0/2)$   
 $h = 4 R k_0 \tan \chi_0 + g$

$$i = \tan^{-1} \{ (E - FE) / [h + (N - FN)] \}$$

$$j = \tan^{-1} \{ (E - FE) / [g - (N - FN)] \} - i$$

Geodetic longitude  $\lambda = (\Lambda - \Lambda_0) / n + \Lambda_0$

Isometric latitude  $\psi = 0.5 \ln \{ (1 + \sin\chi) / [c (1 - \sin\chi)] \} / n$

First approximation  $\varphi_1 = 2 \tan^{-1} e^\Psi - \pi / 2$  where  $e$ =base of natural logarithms.

$\psi_1 =$  isometric latitude at  $\varphi_1$

where  $\psi_1 = \ln \{ [\tan(\varphi_1/2 + \pi/4) [(1 - e \sin\varphi_1)/(1 + e \sin\varphi_1)]^{(e/2)} \}$

Then iterate  $\varphi_{i+1} = \varphi_i - (\psi_i - \psi) \cos \varphi_i (1 - e^2 \sin^2 \varphi_i) / (1 - e^2)$

until the change in  $\varphi$  is sufficiently small.

If the projection is the equatorial case,  $\varphi_0$  and  $\chi_0$  will be zero degrees and the formulas are simplified as a result, but the above formulas remain valid.

For the polar version,  $\varphi_0$  and  $\chi_0$  will be 90 degrees and the formulas become indeterminate. See below for formulas for the polar case.

For stereographic projections centred on points in the southern hemisphere, the signs of E, N,  $\lambda_0$  and  $\lambda$  must be reversed to be used in the equations and  $\varphi$  will be negative anyway as a southerly latitude.

**Example:**

For Projected Coordinate Reference System: RD / Netherlands New

Parameters:

Ellipsoid:	Bessel 1841	a = 6377397.155 metres		1/f = 299.15281
	then	e = 0.08169683		

Latitude of natural origin	$\varphi_0$	52°09'22.178"N	=	0.910296727 rad
Longitude of natural origin	$\lambda_0$	5°23'15.500"E	=	0.094032038 rad
Scale factor at natural origin	$k_0$	0.9999079		
False easting	FE	155000.00	metres	
False northing	FN	463000.00	metres	

Forward calculation for:

Latitude  $\varphi = 53^\circ\text{N} = 0.925024504$  rad  
 Longitude  $\lambda = 6^\circ\text{E} = 0.104719755$  rad

first gives the conformal sphere constants:

$\rho_0 = 6374588.71$                        $v_0 = 6390710.613$   
 $R = 6382644.571$                        $n = 1.000475857$                        $c = 1.007576465$

where  $S_1 = 8.509582274$                        $S_2 = 0.878790173$                        $w_1 = 8.428769183$   
 $\sin \chi_0 = 0.787883237$

$w_2 = 8.492629457$                        $\chi_0 = 0.909684757$                        $\Lambda_0 = \lambda_0 = 0.094032038$  rad

For the point ( $\varphi, \lambda$ )  $\chi = 0.924394997$   $\Lambda = 0.104724841$  rad

hence  $B = 1.999870665$

and  $E = 196105.283$  m  $N = 557057.739$  m

Reverse calculation for the same Easting and Northing (196105.28E, 557057.74N) first gives:

$g = 4379954.188$   $h = 37197327.960$   $i = 0.001102255$   $j = 0.008488122$

then  $\Lambda = 0.10472467$  whence  $\lambda = 0.104719584$  rad = 6°E

Also  $\chi = 0.924394767$  and  $\psi = 1.089495123$

Then  $\varphi_1 = 0.921804948$   $\psi_1 = 1.084170164$

$\varphi_2 = 0.925031162$   $\psi_2 = 1.089506925$

$\varphi_3 = 0.925024504$   $\psi_3 = 1.089495505$

$\varphi_4 = 0.925024504$

Then Latitude  $\varphi = 53^{\circ}00'00.000''$ N

Longitude  $\lambda = 6^{\circ}00'00.000''$ E

### 1.4.7.2 Polar Stereographic

For the polar stereographic projection, three variants are recognised, differentiated by their defining parameters. In the basic variant (**variant A**) the latitude of origin is either the north or the south pole, at which is defined a scale factor at the natural origin, the meridian along which the northing axis increments and along which intersecting parallels increment *towards the north pole* (the longitude of origin), and false grid coordinates. In **variant B** instead of the scale factor at the pole being defined, the (non-polar) latitude at which the scale is unity – the standard parallel – is defined. In **variant C** the latitude of a standard parallel along which the scale is unity is defined; the intersection of this parallel with the longitude of origin is the false origin, at which grid coordinate values are defined.

Parameter	Method		
	Variant A	Variant B	Variant C
Latitude of natural origin ( $\varphi_0$ )	(note 1)	(note 2)	(note 2)
Latitude of standard parallel ( $\varphi_F$ )		x	x
Longitude of origin ( $\lambda_0$ )	x	x	x
Scale at natural origin ( $k_0$ )	x		
False easting (easting at natural origin = pole) (FE)	x	x	
False northing (northing at natural origin = pole) (FN)	x	x	
Easting at false origin ( $E_F$ )			x
Northing at false origin ( $N_F$ )			x

In all three variants the formulae for the **south pole case** are straightforward but some require modification for the **north pole case** to allow the longitude of origin going towards (as opposed to away from) the natural origin and for the anticlockwise increase in longitude value when viewed from the north pole (see figure 8). Several equations are common between the variants and cases.

Notes:

1. In variant A the parameter *Latitude of natural origin* is used only to identify which hemisphere case is required. The only valid entries are  $\pm 90^{\circ}$  or equivalent in alternative angle units.
2. For variants B and C, whilst it is mathematically possible for the standard parallel to be in the opposite hemisphere to the pole at which is the projection natural origin, such an arrangement would be

unsatisfactory from a cartographic perspective as the rate of change of scale would be excessive in the area of interest. EPSG therefore excludes the hemisphere of pole as a defining parameter for these variants. In the formulas that follow for these variants B and C, the hemisphere of pole is taken to be that of the hemisphere of the standard parallel.

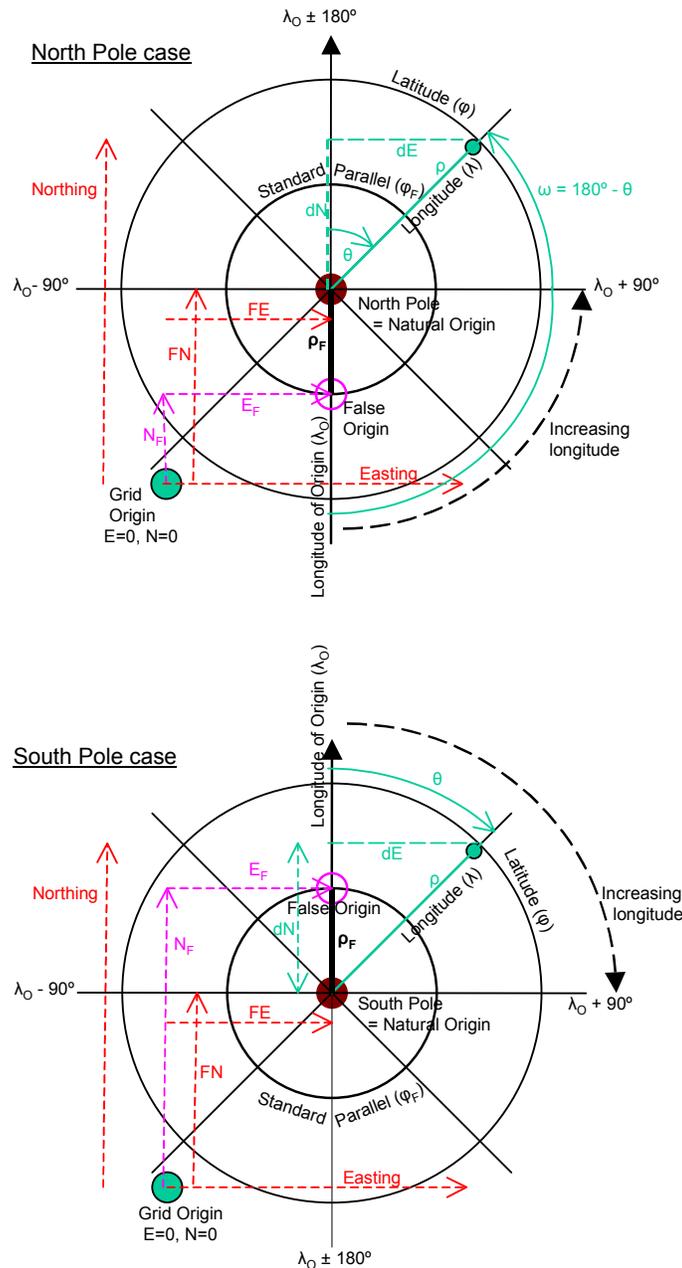


Figure 8. Key Diagram for Stereographic Projection

Polar Stereographic (Variant A) (EPSG coordinate operation method code 9810).

For the forward conversion from latitude and longitude, for the south pole case

$$dE = \rho \sin(\theta) \text{ and } dN = \rho \cos(\theta)$$

Then

$$E = dE + FE = FE + \rho \sin(\lambda - \lambda_0)$$

$$N = dN + FN = FN + \rho \cos(\lambda - \lambda_0)$$

where

$$t = \tan(\pi/4 + \varphi/2) / \{[(1 + e \sin\varphi) / (1 - e \sin\varphi)]^{(e/2)}\}$$

$$\rho = 2 a k_0 t / \{[(1+e)^{(1+e)}(1-e)^{(1-e)}]^{0.5}\}$$

For the north pole case,

$$dE = \rho \sin(\theta) = \rho \sin(\omega).$$

$$dN = \rho \cos(\theta) = -\rho \cos(\omega).$$

$\rho$  and  $E$  are found as for the south pole case but

$$t = \tan(\pi/4 - \varphi/2) \{[(1 + e \sin\varphi) / (1 - e \sin\varphi)]^{(e/2)}\}$$

$$N = FN - \rho \cos(\lambda - \lambda_0)$$

For the reverse conversion from easting and northing to latitude and longitude,

$$\varphi = \chi + (e^2/2 + 5e^4/24 + e^6/12 + 13e^8/360) \sin(2\chi)$$

$$+ (7e^4/48 + 29e^6/240 + 811e^8/11520) \sin(4\chi)$$

$$+ (7e^6/120 + 81e^8/1120) \sin(6\chi) + (4279e^8/161280) \sin(8\chi)$$

where  $\rho' = [(E-FE)^2 + (N-FN)^2]^{0.5}$

$$t' = \rho' \{[(1+e)^{(1+e)}(1-e)^{(1-e)}]^{0.5}\} / 2 a k_0$$

and for the south pole case

$$\chi = 2 \operatorname{atan}(t') - \pi/2$$

but for the north pole case

$$\chi = \pi/2 - 2 \operatorname{atan} t'$$

Then for for both north and south cases if  $E = FE$ ,  $\lambda = \lambda_0$

else for the south pole case

$$\lambda = \lambda_0 + \operatorname{atan} [(E - FE) / (N - FN)]$$

and for the north pole case

$$\lambda = \lambda_0 + \operatorname{atan} [(E - FE) / -(N - FN)] = \lambda_0 + \operatorname{atan} [(E - FE) / (FN - N)]$$

**Example:**

For Projected Coordinate Reference System: WGS 84 / UPS North

Parameters:

Ellipsoid:	WGS 84	a = 6378137.0 metres	1/f = 298.2572236
	then	e = 0.081819191	

Latitude of natural origin	$\varphi_0$	90°00'00.000"N	=	1.570796327 rad
Longitude of natural origin	$\lambda_0$	0°00'00.000"E	=	0.0 rad
Scale factor at natural origin	$k_0$	0.994		
False easting	FE	2000000.00	metres	
False northing	FN	2000000.00	metres	

Forward calculation for:

$$\begin{aligned} \text{Latitude } \varphi &= 73^\circ\text{N} &= 1.274090354 \text{ rad} \\ \text{Longitude } \lambda &= 44^\circ\text{E} &= 0.767944871 \text{ rad} \end{aligned}$$

$$t = 0.150412808$$

$$\rho = 1900814.564$$

whence

$$E = 3320416.75 \text{ m}$$

$$N = 632668.43 \text{ m}$$

Reverse calculation for the same Easting and Northing (3320416.75 E, 632668.43 N) first gives:

$$\rho' = 1900814.566$$

$$t' = 0.150412808$$

$$\chi = 1.2722090$$

$$\begin{array}{ll} \text{Then Latitude } \varphi & = 73^{\circ}00'00.000''\text{N} \\ \text{Longitude } \lambda & = 44^{\circ}00'00.000''\text{E} \end{array}$$

Polar Stereographic (Variant B) (EPSG coordinate operation method code 9829).

For the forward conversion from latitude and longitude:

for the south pole case

$$t_F = \tan(\pi/4 + \varphi_F/2) / \{[(1 + e \sin\varphi_F) / (1 - e \sin\varphi_F)]^{(e/2)}\}$$

$$m_F = \cos \varphi_F / (1 - e^2 \sin^2 \varphi_F)^{0.5}$$

$$k_O = m_F \{[(1+e)^{(1+e)}(1-e)^{(1-e)}]^{0.5}\} / (2*t_F)$$

then t, ρ, E and N are found as in the south pole case of variant A.

For the north pole case, m<sub>F</sub> and k<sub>O</sub> are found as for the south pole case above, but

$$t_F = \tan(\pi/4 - \varphi_F/2) \{[(1 + e \sin\varphi_F) / (1 - e \sin\varphi_F)]^{(e/2)}\}$$

Then t, ρ, E and N are found as in variant A.

For the reverse conversion from easting and northing to latitude and longitude, first k<sub>O</sub> is found from m<sub>F</sub> and t<sub>F</sub> as in the forward conversion above, then φ and λ are found as for variant A.

**Example:**

For Projected Coordinate Reference System: WGS 84 / Australian Antarctic Polar Stereographic

Parameters:

Ellipsoid:	WGS 84	a = 6378137.0 metres		1/f = 298.2572236
	then	e = 0.081819191		

Latitude of standard parallel	φ <sub>F</sub>	71°00'00.000"S	=	-1.239183769 rad
Longitude of origin	λ <sub>O</sub>	70°00'00.000"E	=	1.221730476 rad
False easting	FE	6000000.00	metres	
False northing	FN	6000000.00	metres	

Forward calculation for:

$$\text{Latitude } \varphi = 75^{\circ}00'00.000''\text{S} = -1.308996939 \text{ rad}$$

$$\text{Longitude } \lambda = 120^{\circ}00'00.000''\text{E} = 2.094395102 \text{ rad}$$

$$t_F = 0.168407325$$

$$m_F = 0.326546781$$

$$k_O = 0.97276901$$

$$t = 0.132508348$$

$$\rho = 1638783.238$$

whence

$$E = 7255380.79 \text{ m}$$

$$N = 7053389.56 \text{ m}$$

Reverse calculation for the same Easting and Northing (7255380.79 E, 7053389.56 N) first gives:

$$t_F = 0.168407325 \quad m_F = 0.326546781 \quad \text{and} \quad k_O = 0.97276901$$

$$\text{then } \rho' = 1638783.236 \quad t' = 0.132508347 \quad \chi = -1.3073146$$

$$\text{Then Latitude } \varphi = 75^{\circ}00'00.000''\text{S}$$

$$\text{Longitude } \lambda = 120^{\circ}00'00.000''\text{E}$$

Polar Stereographic (Variant C) (EPSG coordinate operation method code 9830).

For the forward conversion from latitude and longitude, for the south pole case

$$E = E_F + \rho \sin(\lambda - \lambda_0)$$

$$N = N_F - \rho_F + \rho \cos(\lambda - \lambda_0)$$

where

$$m_F \text{ is found as in variant B} = \cos \varphi_F / (1 - e^2 \sin^2 \varphi_F)^{0.5}$$

$$t_F \text{ is found as in variant B} = \tan(\pi/4 + \varphi_F/2) / \{[(1 + e \sin \varphi_F) / (1 - e \sin \varphi_F)]^{(e/2)}\}$$

$$t \text{ is found as in variants A and B} = \tan(\pi/4 + \varphi/2) / \{[(1 + e \sin \varphi) / (1 - e \sin \varphi)]^{(e/2)}\}$$

$$\rho_F = a m_F$$

$$\rho = \rho_F t / t_F$$

For the north pole case,  $m_F$ ,  $\rho_F$ ,  $\rho$  and  $E$  are found as for the south pole case but

$$t_F \text{ is found as in variant B} = \tan(\pi/4 - \varphi_F/2) \{[(1 + e \sin \varphi_F) / (1 - e \sin \varphi_F)]^{(e/2)}\}$$

$$t \text{ is found as in variants A and B} = \tan(\pi/4 - \varphi/2) \{[(1 + e \sin \varphi) / (1 - e \sin \varphi)]^{(e/2)}\}$$

$$N = N_F + \rho_F - \rho \cos(\lambda - \lambda_0)$$

For the reverse conversion from easting and northing to latitude and longitude,

$$\varphi = \chi + (e^2/2 + 5e^4/24 + e^6/12 + 13e^8/360) \sin(2\chi)$$

$$+ (7e^4/48 + 29e^6/240 + 811e^8/11520) \sin(4\chi)$$

$$+ (7e^6/120 + 81e^8/1120) \sin(6\chi) + (4279e^8/161280) \sin(8\chi)$$

(as for variants A and B)

where for the south pole case

$$\rho' = [(E - E_F)^2 + (N - N_F + \rho_F)^2]^{0.5}$$

$$t' = \rho' t_F / \rho_F$$

$$\chi = 2 \operatorname{atan}(t') - \pi/2$$

and where  $m_F$  and  $t_F$  are as for the forward conversion

For the reverse conversion north pole case,  $m_F$ ,  $t_F$  and  $\rho_F$  are found as for the north pole case of the forward conversion, and

$$\rho' = [(E - E_F)^2 + (N - N_F - \rho_F)^2]^{0.5}$$

$$t' \text{ is found as for the south pole case of the reverse conversion} = \rho' t_F / \rho_F$$

$$\chi = \pi/2 - 2 \operatorname{atan} t'$$

Then for both north and south pole cases

if  $E = E_F$ ,  $\lambda = \lambda_0$

else for the south pole case

$$\lambda = \lambda_0 + \operatorname{atan} [(E - E_F) / (N - N_F + \rho_F)]$$

and for the north pole case

$$\lambda = \lambda_0 + \operatorname{atan} [(E - E_F) / -(N - N_F - \rho_F)] = \lambda_0 + \operatorname{atan} [(E - E_F) / (N_F + \rho_F - N)]$$

**Example:**

For Projected Coordinate Reference System: Petrels 1972 / Terre Adelie Polar Stereographic

Parameters:

Ellipsoid:	International 1924	a = 6378388.0 metres		1/f = 297.0
	then	e = 0.081991890		

Latitude of false origin	$\phi_F$	67°00'00.000"S	=	-1.169370599 rad
Longitude of origin	$\lambda_O$	140°00'00.000"E	=	2.443460953 rad
Easting at false origin	$E_F$	300000.00	metres	
Northing at false origin	$N_F$	200000.00	metres	

Forward calculation for:

$$\begin{aligned} \text{Latitude } \phi &= 66^\circ 36' 18.820''\text{S} &= -1.162480524 \text{ rad} \\ \text{Longitude } \lambda &= 140^\circ 04' 17.040''\text{E} &= 2.444707118 \text{ rad} \end{aligned}$$

$$\begin{aligned} m_F &= 0.391848769 \\ \rho_F &= 2499363.488 \\ t_F &= 0.204717630 \\ t &= 0.208326304 \\ \rho &= 2543421.183 \end{aligned}$$

whence

$$\begin{aligned} E &= 303169.52 \text{ m} \\ N &= 244055.72 \text{ m} \end{aligned}$$

Reverse calculation for the same Easting and Northing (303169.522 E, 244055.721 N) first gives:

$$\begin{aligned} \rho' &= 2543421.183 \\ t' &= 0.208326304 \\ \chi &= -1.1600190 \end{aligned}$$

$$\begin{aligned} \text{Then Latitude } \phi &= 66^\circ 36' 18.820''\text{S} \\ \text{Longitude } \lambda &= 140^\circ 04' 17.040''\text{E} \end{aligned}$$

**1.4.8 New Zealand Map Grid**

(EPSG coordinate operation method code 9811)

This projection system typifies the recent development in the design and formulation of map projections where, by more complex mathematics yielding formulas readily handled by modern computers, it is possible to maintain the conformal property and minimise scale distortion over the total extent of a country area regardless of shape. Thus both North and South Islands of New Zealand, previously treated not very satisfactorily in two zones of a Transverse Mercator projection, can now be projected as one zone of what resembles most closely a curved version Oblique Mercator but which, instead of being based on a minimum scale factor straight central line, has a central line which is a complex curve roughly following the trend of both North and South Islands. The projected coordinate reference system achieves this by a form of double projection where a conformal projection of the ellipsoid is first made to say an oblique Stereographic projection and then the Cauchy-Riemann equations are invoked in order to further project the rectangular coordinates on this to a modification in which lines of constant scale can be made to follow other than the normal great or small circles of Central meridians or standard parallels. The mathematical treatment of the New Zealand Map Grid is covered by a publication by New Zealand Department of Lands and Survey Technical Circular 1973/32 by I.F.Stirling.

### 1.4.9 Tunisia Mining Grid

(EPSG coordinate operation method code 9816)

This grid is used as the basis for mineral leasing in Tunisia. Lease areas are approximately 2 x 2 km or 400 hectares. The corners of these blocks are defined through a six figure grid reference where the first three digits are an easting in kilometres and the last three digits are a northing. The latitudes and longitudes for block corners at 2 km intervals are tabulated in a mining decree dated 1<sup>st</sup> January 1953. From this tabulation in which geographical coordinates are given to 5 decimal places it can be seen that:

- a) the minimum easting is 94 km, on which the longitude is 5.68989 grads east of Paris.
- b) the maximum easting is 490 km, on which the longitude is 10.51515 grads east of Paris.
- c) each 2 km grid easting interval equals 0.02437 grads.
- d) the minimum northing is 40 km, on which the latitude is 33.39 grads.
- e) the maximum northing is 860 km, on which the latitude is 41.6039 grads.
- f) between 40 km N and 360 km N, each 2 km grid northing interval equals 0.02004 grads.
- g) between 360 km N and 860 km N, each 2 km grid northing interval equals 0.02003 grads.

This grid could be considered to be two equidistant cylindrical projection zones, north and south of the 360 km northing line. However this would require the introduction of two spheres of unique dimensions. EPSG has therefore implemented the Tunisia mining grid as a coordinate conversion method in its own right. Formulas are:

#### Grads from Paris

$$\varphi \text{ (grads)} = 36.5964 + [(N - 360) * A]$$

where N is in kilometres and A = 0.010015 if N > 360, else A = 0.01002.

$$\lambda_{\text{Paris}} \text{ (grads)} = 7.83445 + [(E - 270) * 0.012185], \text{ where E is in kilometres.}$$

The reverse formulas are:

$$E \text{ (km)} = 270 + [(\lambda_{\text{Paris}} - 7.83445) / 0.012185] \text{ where } \lambda_{\text{Paris}} \text{ is in grads.}$$

$$N \text{ (km)} = 360 + [(\varphi - 36.5964) / B]$$

where  $\varphi$  is in grads and B = 0.010015 if  $\varphi > 36.5964$ , else B = 0.01002.

#### Degrees from Greenwich

Modern practice in Tunisia is to quote latitude and longitude in degrees with longitudes referenced to the Greenwich meridian. The formulas required in addition to the above are:

$$\varphi_d \text{ (degrees)} = (\varphi_g * 0.9) \text{ where } \varphi_g \text{ is in grads.}$$

$$\lambda_{\text{Greenwich}} \text{ (degrees)} = [(\lambda_{\text{Paris}} + 2.5969213) * 0.9] \text{ where } \lambda_{\text{Paris}} \text{ is in grads.}$$

$$\varphi_g \text{ (grads)} = (\varphi_d / 0.9) \text{ where } \varphi_d \text{ is in decimal degrees.}$$

$$\lambda_{\text{Paris}} \text{ (grads)} = [(\lambda_{\text{Greenwich}} / 0.9) - 2.5969213] \text{ where } \lambda_{\text{Greenwich}} \text{ is in decimal degrees.}$$

#### **Example:**

For grid location 302598,

Latitude  $\varphi = 36.5964 + [(598 - 360) * A]$ . As N > 360, A = 0.010015.

$$\varphi = 38.97997 \text{ grads} = 35.08197 \text{ degrees.}$$

Longitude  $\lambda = 7.83445 + [(E - 270) * 0.012185]$ , where E = 302.

$$\lambda = 8.22437 \text{ grads east of Paris} = 9.73916 \text{ degrees east of Greenwich.}$$

### 1.4.10 American Polyconic

(EPSG coordinate operation method code 9818)

This projection was popular before the advent of modern computers due to its ease of mechanical construction, particularly in the United States. It is neither conformal nor equal area, and is distortion-free only along the longitude of origin. A modified form of the polyconic projection was adopted in 1909 for the International Map of the World series of 1/1,000,000 scale topographic maps. A general study of the polyconic family of projections by Oscar Adams of the US Geological Survey was published in 1919 (and reprinted in 1934). The mathematical treatment of the American Polyconic is covered on pages 124-131 of USGS professional paper 1395 by J.P.Snyder.

### 1.4.11 Lambert Azimuthal Equal Area

(EPSG coordinate operation method code 9820)

To derive the projected coordinates of a point, geodetic latitude ( $\varphi$ ) is converted to authalic latitude ( $\beta$ ). The formulae to convert geodetic latitude and longitude ( $\varphi, \lambda$ ) to Easting and Northing are:

$$\text{Easting, } E = FE + \{(B \cdot D) \cdot [\cos \beta \cdot \sin(\lambda - \lambda_0)]\}$$

$$\text{Northing, } N = FN + (B / D) \cdot \{(\cos \beta_0 \cdot \sin \beta) - [\sin \beta_0 \cdot \cos \beta \cdot \cos(\lambda - \lambda_0)]\}$$

where

$$B = R_q \cdot (2 / \{1 + \sin \beta_0 \cdot \sin \beta + [\cos \beta_0 \cdot \cos \beta \cdot \cos(\lambda - \lambda_0)]\})^{0.5}$$

$$D = a \cdot [\cos \lambda_0 / (1 - e^2 \sin^2 \lambda_0)^{0.5}] / (R_q \cdot \cos \beta_0)$$

$$R_q = a \cdot (q_p / 2)^{0.5}$$

$$\beta = \sin(q / q_p)$$

$$\beta_0 = \sin(q_0 / q_p)$$

$$q = (1 - e^2) \cdot ([\sin \varphi / (1 - e^2 \sin^2 \varphi)] - \{[1/(2e)] \cdot \ln [(1 - e \sin \varphi) / (1 + e \sin \varphi)]\})$$

$$q_0 = (1 - e^2) \cdot ([\sin \varphi_0 / (1 - e^2 \sin^2 \varphi_0)] - \{[1/(2e)] \cdot \ln [(1 - e \sin \varphi_0) / (1 + e \sin \varphi_0)]\})$$

$$q_p = (1 - e^2) \cdot ([\sin \varphi_p / (1 - e^2 \sin^2 \varphi_p)] - \{[1/(2e)] \cdot \ln [(1 - e \sin \varphi_p) / (1 + e \sin \varphi_p)]\})$$

The reverse formulas to derive the geodetic latitude and longitude of a point from its Easting and Northing values are:

$$\varphi = \beta' + [(e^2/3 + 31e^4/180 + 517e^6/5040) \cdot \sin 2\beta'] + [(23e^4/360 + 251e^6/3780) \cdot \sin 4\beta'] + [(761e^6/45360) \cdot \sin 6\beta']$$

$$\lambda = \lambda_0 + \text{atan} \{ (X-FE) \cdot \sin C / [D \cdot \rho \cdot \cos \beta_0 \cdot \cos C - D^2 \cdot (Y-FN) \cdot \sin \beta_0 \cdot \sin C] \}$$

where

$$\beta' = \sin \{ (\cos C \cdot \sin \beta_0) + [(D \cdot (Y-FN) \cdot \sin C \cdot \cos \beta_0) / \rho] \}$$

$$C = 2 \cdot \sin(\rho / 2 \cdot R_q)$$

$$\rho = \{ [(X-FE)/D]^2 + [D \cdot (Y-FN)]^2 \}^{0.5}$$

and D,  $R_q$ , and  $\beta_0$  are as in the forward equations.

#### Example

For Projected Coordinate Reference System: ETRS89 / ETRS-LAEA

Parameters:

Ellipsoid:	GRS 1980	a = 6378137.0 metres	1/f = 298.2572221
	then	e = 0.081819191	

Latitude of natural origin	$\varphi_0$	53°00'00.000"N	=	0.925024504 rad
Longitude of natural origin	$\lambda_0$	9°00'00.000"E	=	0.157079633 rad
False easting	FE	4321000.00	metres	
False northing	FN	3210000.00	metres	

Forward calculation for:

$$\begin{aligned} \text{Latitude } \varphi &= 50^{\circ}00'00.000''\text{N} = 0.872664626 \text{ rad} \\ \text{Longitude } \lambda &= 5^{\circ}00'00.000''\text{E} = 0.087266463 \text{ rad} \end{aligned}$$

First gives

$$\begin{aligned} qP &= 1.995531087 & qO &= 1.591111956 \\ q &= 1.525832247 & Rq &= 6371007.181 \\ \text{betaO} &= 0.922870909 & \text{beta} &= 0.870458708 \\ D &= 1.000406507 & B &= 6374706.698 \end{aligned}$$

whence

$$\begin{aligned} E &= 4034299.86 \text{ m} \\ N &= 2884152.53 \text{ m} \end{aligned}$$

Reverse calculation for the same Easting and Northing (4034299.86 E, 2884152.53 N) first gives:

$$\begin{aligned} \rho &= 434042.7347 \\ C &= 0.068140987 \\ \text{beta}' &= 0.870458708 \end{aligned}$$

$$\begin{aligned} \text{Then Latitude } \varphi &= 50^{\circ}00'00.000''\text{N} \\ \text{Longitude } \lambda &= 5^{\circ}00'00.000''\text{E} \end{aligned}$$

#### 1.4.11.1 Lambert Azimuthal Equal Area (Spherical)

(EPSG coordinate operation method code 9821)

The US National Atlas uses the spherical form of the map projection method, so exceptionally EPSG documents this. See USGS Professional Paper 1395, "Map Projections - A Working Manual" by John P. Snyder for formulas and example.

#### 1.4.12 Albers Equal Area

(EPSG coordinate operation method code 9822)

To derive the projected coordinates of a point, geodetic latitude ( $\varphi$ ) is converted to authalic latitude ( $\beta$ ). The formulas to convert geodetic latitude and longitude ( $\varphi, \lambda$ ) to Easting (E) and Northing (N) are:

$$\begin{aligned} \text{Easting (E)} &= E_F + (\rho \cdot \sin \theta) \\ \text{Northing (N)} &= N_F + \rho_O - (\rho \cdot \cos \theta) \end{aligned}$$

where

$$\begin{aligned} \theta &= n \cdot (\lambda - \lambda_O) \\ \rho &= [a \cdot (C - n \alpha)^{0.5}] / n \\ \rho_O &= [a \cdot (C - n \alpha_O)^{0.5}] / n \end{aligned}$$

and

$$\begin{aligned} C &= m_1^2 + (n \cdot \alpha_1) \\ n &= (m_1^2 - m_2^2) / (\alpha_2 - \alpha_1) \\ m_1 &= \cos \varphi_1 / (1 - e^2 \sin^2 \varphi_1)^{0.5} \\ m_2 &= \cos \varphi_2 / (1 - e^2 \sin^2 \varphi_2)^{0.5} \\ \alpha &= (1 - e^2) \cdot [(\sin \varphi / (1 - e^2 \sin^2 \varphi)) - \{[1/(2e)] \cdot \ln [(1 - e \sin \varphi) / (1 + e \sin \varphi)]\}] \\ \alpha_O &= (1 - e^2) \cdot [(\sin \varphi_O / (1 - e^2 \sin^2 \varphi_O)) - \{[1/(2e)] \cdot \ln [(1 - e \sin \varphi_O) / (1 + e \sin \varphi_O)]\}] \\ \alpha_1 &= (1 - e^2) \cdot [(\sin \varphi_1 / (1 - e^2 \sin^2 \varphi_1)) - \{[1/(2e)] \cdot \ln [(1 - e \sin \varphi_1) / (1 + e \sin \varphi_1)]\}] \\ \alpha_2 &= (1 - e^2) \cdot [(\sin \varphi_2 / (1 - e^2 \sin^2 \varphi_2)) - \{[1/(2e)] \cdot \ln [(1 - e \sin \varphi_2) / (1 + e \sin \varphi_2)]\}] \end{aligned}$$

The reverse formulas to derive the geodetic latitude and longitude of a point from its Easting and Northing values are:

$$\varphi = \beta' + (e^2/3 + 31e^4/180 + 517e^6/5040) \cdot \sin 2\beta' + [(23e^4/360 + 251e^6/3780) \cdot \sin 4\beta'] + [(761e^6/45360) \cdot \sin 6\beta']$$

$$\lambda = \lambda_0 + (\theta / n)$$

where

$$\beta' = \sin(\alpha' / \{1 - [(1 - e^2) / (2 \cdot e)] \cdot \ln [(1 - e / (1 + e))]$$

$$\alpha' = [C - (\rho^2 \cdot n^2 / a^2)] / n$$

$$\rho = \{(E - E_F)^2 + [\rho_0 - (N - N_F)]^2\}^{0.5}$$

$$\theta = \text{atan} [(E - E_F) / [\rho_0 - (N - N_F)]]$$

and C, n and  $\rho_0$  are as in the forward equations.

### Example

See USGS Professional Paper 1395, "Map Projections - A Working Manual" by John P. Snyder.

#### 1.4.13 Equidistant Cylindrical

(EPSG coordinate operation method code 9823)

This method has one of the simplest formulas available. If the latitude of natural origin ( $\varphi_0$ ) is at the equator the method is also known as Plate Carrée. It is not used for rigorous topographic mapping because its distortion characteristics are unsuitable. Formulas are included to distinguish this map projection method from an approach sometimes mistakenly called by the same name and used for simple computer display of geographic coordinates – see Pseudo Plate Carrée below.

For the forward calculation of the Equidistant Cylindrical method:

$$X = R \cdot (\lambda - \lambda_0) \cdot \cos(\varphi_0)$$

$$Y = R \cdot \varphi$$

$$\text{where } R = (\rho_0^2 + \nu_0^2)^{0.5} = \{[a^2 \cdot (1 - e^2)] / (1 - e^2 \sin^2 \varphi_0)\}^{0.5}$$

and  $\varphi_0$ ,  $\varphi$  and  $\lambda$  are expressed in radians.

For the Equidistant Cylindrical method on a sphere (not ellipsoid),  $e = 0$  and  $R = a$ .

For the reverse calculation:

$$\varphi = Y / R$$

$$\lambda = \lambda_0 + (X / R \cos(\varphi_0))$$

where R is as for the forward method.

##### 1.4.13.1 Pseudo Plate Carrée

(EPSG coordinate operation method code 9825)

This is not a map projection in the true sense as the coordinate system units are decimal degrees and therefore of variable linear scale. It is used only for depiction of graticule (latitude/longitude) coordinates on a computer display. The origin is at latitude ( $\varphi$ ) = 0, longitude ( $\lambda$ ) = 0. See above for the formulas for the proper Plate Carrée map projection method.

For the forward calculation:

$$X = \lambda$$

$$Y = \varphi$$

where  $\varphi$  and  $\lambda$  are expressed in radians.

For the reverse calculation:

$$\varphi = Y$$

$$\lambda = X$$

#### 1.4.14 **Bonne**

(EPSG coordinate operation method code 9827)

The Bonne projection was frequently adopted for 18<sup>th</sup> and 19<sup>th</sup> century mapping, but being equal area rather than conformal its use for topographic mapping was replaced during the 20<sup>th</sup> century by conformal map projection methods.

The formulas to convert geodetic latitude and longitude ( $\varphi, \lambda$ ) to Easting and Northing are:

$$E = (\rho \cdot \sin T) + FE$$

$$N = (a \cdot m_0 / \sin \varphi_0 - \rho \cdot \cos T) + FN$$

where

$$m = \cos \varphi / (1 - e^2 \sin^2 \varphi)^{0.5}$$

with  $\varphi$  in radians and  $m_0$  for  $\varphi_0$ , the latitude of the origin, derived in the same way.

$$M = a[(1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots)\varphi - (3e^2/8 + 3e^4/32 + 45e^6/1024 + \dots)\sin 2\varphi + (15e^4/256 + 45e^6/1024 + \dots)\sin 4\varphi - (35e^6/3072 + \dots)\sin 6\varphi + \dots]$$

with  $\varphi$  in radians and  $M_0$  for  $\varphi_0$ , the latitude of the origin, derived in the same way.

$$\rho = a \cdot m_0 / \sin \varphi_0 + M_0 - M$$

$$T = a \cdot m (\lambda - \lambda_0) / \rho \quad \text{with } \lambda \text{ and } \lambda_0 \text{ in radians}$$

For the reverse calculation:

$$X = E - FE$$

$$Y = N - FN$$

$$\rho = \pm [X^2 + (a \cdot m_0 / \sin \varphi_0 - Y)^2]^{0.5} \quad \text{taking the sign of } \varphi_0$$

$$M = a \cdot m_0 / \sin \varphi_0 + M_0 - \rho$$

$$\mu = M / [a (1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots)]$$

$$e_1 = [1 - (1 - e^2)^{0.5}] / [1 + (1 - e^2)^{0.5}]$$

$$\varphi = \mu + (3e_1/2 - 27e_1^3/32 + \dots)\sin 2\mu + (21e_1^2/16 - 55e_1^4/32 + \dots)\sin 4\mu + (151e_1^3/96 + \dots)\sin 6\mu + (1097e_1^4/512 - \dots)\sin 8\mu + \dots$$

$$m = \cos \varphi / (1 - e^2 \sin^2 \varphi)^{0.5}$$

If  $\varphi_0$  is not negative

$$\lambda = \lambda_0 + \rho \{ \text{atan}[X / (a \cdot m_0 / \sin \varphi_0 - Y)] \} / a \cdot m$$

but if  $\varphi_0$  is negative

$$\lambda = \lambda_0 + \rho \{ \text{atan}[-X / (Y - a \cdot m_0 / \sin \varphi_0)] \} / a \cdot m$$

In either case, if  $\varphi = \pm 90^\circ$ ,  $m = 0$  and the equation for  $\lambda$  is indeterminate, so use  $\lambda = \lambda_0$ .

**1.4.14.1 Bonne (South Orientated)**

(EPSG coordinate operation method code 9828)

In Portugal a special case of the method with coordinate system axes positive south and west has been used for older mapping. The formulas are as for the general case above except:

$$W = FE - (\rho \cdot \sin T)$$

$$S = FN - (a \cdot m_0 / \sin \phi_0 - \rho \cdot \cos T)$$

In these formulas the terms FE and FN retain their definition, i.e. in the Bonne (South Orientated) method they increase the Westing and Southing value at the natural origin. In this method they are effectively false westing (FW) and false southing (FS) respectively.

For the reverse formulas, those for the standard Bonne method above apply, with the exception that:

$$X = FE - W$$

$$Y = FN - S$$

**1.4.15 Azimuthal Equidistant**

**1.4.15.1 Guam Projection**

(EPSG coordinate operation method code 9831)

The Guam projection is a simplified form of the oblique case of the azimuthal equidistant projection. The regular form of the azimuthal equidistant projection is not covered in this Guidance Note. For the Guam projection the forward conversion from latitude and longitude is given by:

$$x = a (\lambda - \lambda_0) \cos \phi / [(1 - e^2 \sin^2 \phi)^{(1/2)}]$$

$$E = FE + x$$

$$N = FN + M - M_0 + \{x^2 \tan \phi [(1 - e^2 \sin^2 \phi)^{(1/2)}] / (2a)\}$$

where

$$M = a[(1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots)\phi - (3e^2/8 + 3e^4/32 + 45e^6/1024 + \dots)\sin 2\phi + (15e^4/256 + 45e^6/1024 + \dots)\sin 4\phi - (35e^6/3072 + \dots)\sin 6\phi + \dots]$$

with  $\phi$  in radians and  $M_0$  for  $\phi_0$ , the latitude of the natural origin, derived in the same way.

The reverse conversion from easting and northing to latitude and longitude requires iteration of three equations. The Guam projection uses three iterations, which is satisfactory over the small area of application. First  $M_0$  for the latitude of the origin  $\phi_0$  is derived as for the forward conversion. Then:

$$e_1 = [1 - (1 - e^2)^{0.5}] / [1 + (1 - e^2)^{0.5}]$$

and

$$M' = M_0 + (N - FN) - \{(E - FE)^2 \tan \phi_0 [(1 - e^2 \sin^2 \phi_0)^{(1/2)}] / (2a)\}$$

$$\mu' = M' / a(1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots)$$

$$\phi' = \mu' + (3e_1/2 - 27e_1^3/32)\sin(2\mu') + (21e_1^2/16 - 55e_1^4/32)\sin(4\mu') + (151e_1^3/96)\sin(6\mu') + (1097e_1^4/512)\sin(8\mu')$$

$$M'' = M_0 + (N - FN) - \{(E - FE)^2 \tan \phi' [(1 - e^2 \sin^2 \phi')^{(1/2)}] / (2a)\}$$

$$\mu'' = M'' / a(1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots)$$

$$\phi'' = \mu'' + (3e_1/2 - 27e_1^3/32)\sin(2\mu'') + (21e_1^2/16 - 55e_1^4/32)\sin(4\mu'') + (151e_1^3/96)\sin(6\mu'') + (1097e_1^4/512)\sin(8\mu'')$$

$$M''' = M_0 + (N - FN) - \{(E - FE)^2 \tan \phi'' [(1 - e^2 \sin^2 \phi'')^{(1/2)}] / (2a)\}$$

$$\mu''' = M''' / a(1 - e^2/4 - 3e^4/64 - 5e^6/256 - \dots)$$

$$\phi''' = \mu''' + (3e_1/2 - 27e_1^3/32)\sin(2\mu''') + (21e_1^2/16 - 55e_1^4/32)\sin(4\mu''') + (151e_1^3/96)\sin(6\mu''') + (1097e_1^4/512)\sin(8\mu''')$$

Then

$$\lambda = \lambda_0 + \{(E - FE) \cdot [(1 - e^2 \sin^2 \varphi'')^{(1/2)}] / (a \cos \varphi'')\}$$

**Example:**

For Projected Coordinate Reference System: Guam 1963 / Guam SPCS

Parameters:

Ellipsoid:	Clarke 1866	a = 6378206.400 metres	1/f = 294.97870
	then	e = 0.08227185	e <sup>2</sup> = 0.00676866

Latitude of natural origin	$\varphi_0$	13°28'20.87887"N	=	0.235138896 rad
Longitude of natural origin	$\lambda_0$	144°44'55.50254"E	=	2.526342288 rad
False easting	FE	50000.00 metres		
False northing	FN	50000.00 metres		

Forward calculation for:

$$\begin{aligned} \text{Latitude } \varphi &= 13^\circ 20' 20.53846'' \text{N} = 0.232810140 \text{ rad} \\ \text{Longitude } \lambda &= 144^\circ 38' 07.19265'' \text{E} = 2.524362746 \text{ rad} \end{aligned}$$

$$\begin{aligned} x &= -12287.52 \text{ m} \\ M_0 &= 1489888.76 \text{ m} \\ M &= 1475127.96 \text{ m} \end{aligned}$$

whence

$$\begin{aligned} E &= 37,712.48 \text{ m} \\ N &= 35,242.00 \text{ m} \end{aligned}$$

Reverse calculation for the same Easting and Northing (37,712.48 m E, 35,242.00 m N) first gives:

$$\begin{aligned} M_0 &= 1489888.76 \text{ m} \\ e_1 &= 0.001697916 \end{aligned}$$

and

	<u>M (metres)</u>	<u><math>\mu</math> (radians)</u>	<u><math>\varphi</math> (radians)</u>	
First iteration:	1475127.93	0.231668814	0.232810136	
Second iteration:	1475127.96	0.231668819	0.232810140	
Third iteration:	1475127.96	0.231668819	0.232810140	= 13°20'20.538"N

Then

$$\lambda = 2.524362746 \text{ rad} = 144^\circ 38' 07.193'' \text{E}$$

## **2 Formulas for Coordinate Operations other than Map Projections**

### **2.1 Introduction**

Several types of coordinate reference system are recognised. The previous section discussed conversions of coordinates between geographic 2-dimensional and projected coordinate reference systems. The projected system is derived from its base geographic system.

Geographical coordinates (latitude and longitude) are calculated on a model of the earth. They are only unique and unambiguous when the model and its relationship to the real earth is identified. This is accomplished through a geodetic datum. A change of geodetic datum changes the geographic coordinates of a point. A geodetic datum combined with description of coordinate system gives a coordinate reference system. Coordinates are only unambiguous when their coordinate reference system is identified and defined.

It is frequently required to change coordinates derived in one geographic coordinate reference system to values expressed in another. For example, land and marine seismic surveys are nowadays most conveniently positioned by GPS satellite in the WGS 84 geographic coordinate reference system, whereas coordinates may be required referenced to the national geodetic reference system in use for the country concerned. It may therefore be necessary to transform the observed WGS 84 data to the national geodetic reference system in order to avoid discrepancies caused by the change of geodetic datum.

Some transformation methods operate directly between geographic coordinates. Others are between geocentric coordinates (3-dimensional Cartesian coordinates where the coordinate system origin is fixed at the centre of the earth). The second part of this Guidance Note covers conversions and transformations between geographic coordinate reference systems, both directly and indirectly through geocentric systems. Some of these methods (polynomial family) may also be encountered for use between other types of coordinate reference systems, for example directly between projected coordinate reference systems. This second part also describes transformations of vertical coordinates.

Coordinate handling software may execute more complicated operations, concatenating a number of steps linking together geographic, projected and/or engineering coordinates referenced to different datums. Other than as mentioned above, these concatenated operations are beyond the scope of this document.

Note that it is very important to ensure that the signs of the parameter values used in the transformations are correct in respect of the transformation being executed. Preferably one should always express transformations in terms of "From"....."To"..... thus avoiding the confusion which may result from interpreting a dash as a minus sign or vice versa.

## 2.2 Coordinate Conversions other than Map Projections

### 2.2.1 Geographic/Geocentric conversions

(EPSG coordinate operation method code 9602)

Latitude,  $\phi$ , and Longitude,  $\lambda$ , and ellipsoidal height,  $h$ , in terms of a 3-dimensional geographic coordinate reference system may be expressed in terms of a geocentric (earth centred) Cartesian coordinate reference system X, Y, Z with the Z axis corresponding with the earth's rotation axis positive northwards, the X axis through the intersection of the prime meridian and equator, and the Y axis through the intersection of the equator with longitude 90°E. The geographic and geocentric systems are based on the same geodetic datum.

Geocentric coordinate reference systems are conventionally taken to be defined with the X axis through the intersection of the Greenwich meridian and equator. This requires that the equivalent geographic coordinate reference system be based on the Greenwich meridian. In application of the formulas below, geographic coordinate reference systems based on a non-Greenwich prime meridian should first be transformed to their Greenwich equivalent. Geocentric coordinates X, Y and Z take their units from the units for the ellipsoid axes (a and b). As it is conventional for X, Y and Z to be in metres, if the ellipsoid axis dimensions are given in another linear unit they should first be converted to metres.

If the ellipsoidal semi major axis is **a**, semi minor axis **b**, and inverse flattening **1/f**, then

$$\begin{aligned} X &= (v + h) \cos \phi \cos \lambda \\ Y &= (v + h) \cos \phi \sin \lambda \\ Z &= ((1 - e^2) v + h) \sin \phi \end{aligned}$$

where  $v$  is the prime vertical radius of curvature at latitude  $\phi$  and is equal to

$$v = a / (1 - e^2 \sin^2 \phi)^{0.5},$$

$\phi$  and  $\lambda$  are respectively the latitude and longitude (related to the prime meridian) of the point,

$h$  is height above the ellipsoid, (see note below), and

$e$  is the eccentricity of the ellipsoid where  $e^2 = (a^2 - b^2)/a^2 = 2f - f^2$

*(Note that  $h$  is the height above the ellipsoid.. This is the height value that is delivered by GPS satellite observations but is not the gravity-related height value which is normally used for national mapping and levelling operations. The gravity-related height ( $H$ ) is usually the height above mean sea level or an alternative level reference for the country. If one starts with a gravity-related height  $H$ , it will be necessary to convert it to an ellipsoid height ( $h$ ) before using the above transformation formulas. See section 2.4.5 below. For the WGS 84 ellipsoid the difference between ellipsoid and mean sea level can vary between values of -100m in the Sri Lanka area to +60m in the North Atlantic.)*

For the reverse conversion, Cartesian coordinates in the geocentric coordinate reference system may be converted to geographic coordinates in terms of the geographic 3D coordinate reference system by:

$$\phi = \text{atan} (Z + e^2 v \sin \phi) / (X^2 + Y^2)^{0.5} \text{ by iteration}$$

$$\lambda = \text{atan} Y/X$$

$$h = X \sec \lambda \sec \phi - v$$

where  $\lambda$  is relative to the Greenwich prime meridian.

#### **Example:**

Consider a North Sea point with position derived by GPS satellite in the WGS84 geocentric coordinate reference system, with coordinates of:

$$\begin{aligned} X_s &= 3771\ 793.97 \text{ m} \\ Y_s &= 140\ 253.34 \text{ m} \\ Z_s &= 5124\ 304.35 \text{ m} \end{aligned}$$

Using the reverse formulas above, coordinates in the the WGS84 geographic 3D coordinate reference system are:

$$\begin{aligned} \text{latitude } \varphi_s &= 53^\circ 48' 33.82'' \text{N} \\ \text{longitude } \lambda_s &= 2^\circ 07' 46.38'' \text{E} \\ \text{and ellipsoidal height } h_s &= 73.0\text{m} \end{aligned}$$

### **2.2.2 Geographic 3D to 2D conversions**

(EPSG coordinate operation method code 9659)

The forward case is trivial. A 3-dimensional geographic coordinate reference system comprising of geodetic latitude, geodetic longitude and ellipsoidal height is converted to its 2-dimensional subset by the simple expedient of dropping the height.

The reverse conversion, from 2D to 3D, is indeterminate. It is however a requirement when a geographic 2D coordinate reference system is to be transformed using a geocentric method which is 3-dimensional (see section 2.4.4.1 below). In practice an artificial ellipsoidal height is created and appended to the geographic 2D coordinate reference system to create a geographic 3D coordinate reference system referenced to the same geodetic datum. The assumed ellipsoidal height is usually either set to the gravity-related height of a position in a compound coordinate reference system, or set to zero. As long as the height chosen is within a few kilometres of sea level, no error will be induced into the horizontal position resulting from the later geocentric transformation; the vertical coordinate will however be meaningless.

#### **Example:**

A location in the ETRS89 Geographic 3D coordinate reference system

$$\begin{aligned} \text{latitude } \varphi_s &= 53^\circ 48' 33.82'' \text{N} \\ \text{longitude } \lambda_s &= 2^\circ 07' 46.38'' \text{E} \\ \text{and ellipsoidal height } h_s &= 73.0\text{m} \end{aligned}$$

is converted to the ETRS89 Geographic 2D coordinate reference system as

$$\begin{aligned} \text{latitude } \varphi_s &= 53^\circ 48' 33.82'' \text{N} \\ \text{longitude } \lambda_s &= 2^\circ 07' 46.38'' \text{E} \end{aligned}$$

For the reverse conversion of the same point in the ETRS89 Geographic 2D coordinate reference system with horizontal coordinates of

$$\begin{aligned} \text{latitude } \varphi_s &= 53^\circ 48' 33.82'' \text{N} \\ \text{longitude } \lambda_s &= 2^\circ 07' 46.38'' \text{E} \end{aligned}$$

an arbitrary value is given to the ellipsoidal height resulting in coordinates in the ETRS89 Geographic 3D coordinate reference system of

$$\begin{aligned} \text{latitude } \varphi_s &= 53^\circ 48' 33.82'' \text{N} \\ \text{longitude } \lambda_s &= 2^\circ 07' 46.38'' \text{E} \\ \text{and ellipsoidal height } h_s &= 0.0\text{m} \end{aligned}$$

## 2.3 Coordinate Operation Methods that can be conversions or transformations

In theory, certain coordinate operation methods do not readily fit the ISO 19111 classification of being either a coordinate conversion (no change of datum involved) or a coordinate transformation. These methods change coordinates directly from one coordinate reference system to another and may be applied with or without change of datum, depending upon whether the source and target coordinate reference systems are based on the same or different datums. In practice, most usage of these methods does in fact include a change of datum. EPSG follows the general mathematical usage of these methods and classifies them as transformations.

### 2.3.1 Polynomial transformations

*Note: In the sections that follow, the general mathematical symbols  $X$  and  $Y$  representing the axes of a coordinate reference system must not be confused with the specific axis abbreviations or axis order in particular coordinate reference systems.*

#### 2.3.1.1 General case

Polynomial transformations between two coordinate reference systems are typically applied in cases where one or both of the coordinate reference systems exhibits lack of homogeneity in orientation and scale. The small distortions are then approximated by polynomial functions in latitude and longitude or in easting and northing. Depending on the degree of variability in the distortions, approximation may be carried out using polynomials of degree 2, 3, or higher. In the case of transformations between two projected coordinate reference systems, the additional distortions resulting from the application of two map projections and a datum transformation can be included in a single polynomial approximation function.

Polynomial approximation functions themselves are subject to variations, as different approximation characteristics may be achieved by different polynomial functions. The simplest of all polynomials is the general polynomial function. In order to avoid problems of numerical instability this type of polynomial should be used after reducing the coordinate values in both the source and the target coordinate reference system to ‘manageable’ numbers, between  $-10$  and  $+10$  at most. This is achieved by working with offsets relative to a central evaluation point, scaled to the desired number range by applying a scaling factor to the coordinate offsets.

Hence an evaluation point is chosen in the source coordinate reference system ( $X_{S0}$ ,  $Y_{S0}$ ) and in the target coordinate reference system ( $X_{T0}$ ,  $Y_{T0}$ ). Often these two sets of coordinates do not refer to the same physical point but two points are chosen that have the same coordinate values in both the source and the target coordinate reference system. (When the two points have identical coordinates, these parameters are conveniently eliminated from the formulas, but the general case where the coordinates differ is given here).

The selection of an evaluation point in each of the two coordinate reference systems allows the point coordinates in both to be reduced as follows:

$$\begin{aligned} X_S - X_{S0} \\ Y_S - Y_{S0} \end{aligned}$$

and

$$\begin{aligned} X_T - X_{T0} \\ Y_T - Y_{T0} \end{aligned}$$

These coordinate differences are expressed in their own unit of measure, which may not be the same as that of the corresponding coordinate reference system.<sup>3)</sup>

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<sup>3)</sup> If the source and/or the target coordinate reference system are geographical, the coordinates themselves may be expressed in sexagesimal degrees (degrees, minutes, seconds), which cannot be directly processed by a mathematical formula.

A further reduction step is usually necessary to bring these coordinate differences into the desired numerical range by applying a scaling factor to the coordinate differences in order to reduce them to a value range that may be applied to the polynomial formulae below without introducing numerical precision errors:

$$U = m_S.(X_S - X_{S0})$$

$$V = m_S.(Y_S - Y_{S0})$$

where

$X_S, Y_S$  are coordinates in the source coordinate reference system,  
 $X_{S0}, Y_{S0}$  are coordinates of the evaluation point in the source coordinate reference system,  
 $m_S$  is the scaling factor applied the coordinate differences in the source coordinate reference system.

The normalised coordinates  $U$  and  $V$  of the point whose coordinates are to be transformed are used as input to the polynomial transformation formula. In order to control the numerical range of the polynomial coefficients  $A_n$  and  $B_n$  the output coordinate differences  $dX$  and  $dY$  are multiplied by a scaling factor,  $m_T$ .

$$m_T.dX = A_0 + A_1.U + A_2.V + A_3.U^2 + A_4.U.V + A_5.V^2 \quad (\text{to degree 2})$$

$$+ A_6.U^3 + A_7.U^2.V + A_8.U.V^2 + A_9.V^3 \quad (\text{degree 3 terms})$$

$$+ A_{10}.U^4 + A_{11}.U^3.V + A_{12}.U^2.V^2 + A_{13}.U.V^3 + A_{14}.V^4 \quad (\text{degree 4 terms})$$

$$+ A_{15}.U^5 + A_{16}.U^4.V + A_{17}.U^3.V^2 + A_{18}.U^2.V^3 + A_{19}.U.V^4 + A_{20}.V^5 \quad (\text{degree 5 terms})$$

$$+ A_{21}.U^6 + A_{22}.U^5.V + A_{23}.U^4.V^2 + A_{24}.U^3.V^3 + A_{25}.U^2.V^4 + A_{26}.U.V^5 + A_{27}.V^6 \quad (\text{degree 6 terms})$$

$$+ \dots + A_{104}.V^{13} \quad (\text{degree 13 terms})$$

$$m_T.dY = B_0 + B_1.U + B_2.V + B_3.U^2 + B_4.U.V + B_5.V^2 \quad (\text{to degree 2})$$

$$+ B_6.U^3 + B_7.U^2.V + B_8.U.V^2 + B_9.V^3 \quad (\text{degree 3 terms})$$

$$+ B_{10}.U^4 + B_{11}.U^3.V + B_{12}.U^2.V^2 + B_{13}.U.V^3 + B_{14}.V^4 \quad (\text{degree 4 terms})$$

$$+ B_{15}.U^5 + B_{16}.U^4.V + B_{17}.U^3.V^2 + B_{18}.U^2.V^3 + B_{19}.U.V^4 + B_{20}.V^5 \quad (\text{degree 5 terms})$$

$$+ B_{21}.U^6 + B_{22}.U^5.V + B_{23}.U^4.V^2 + B_{24}.U^3.V^3 + B_{25}.U^2.V^4 + B_{26}.U.V^5 + B_{27}.V^6 \quad (\text{degree 6 terms})$$

$$+ \dots + B_{104}.V^{13} \quad (\text{degree 13 terms})$$

from which  $dX$  and  $dY$  are evaluated. These will be in the units of the target coordinate reference system.

In the EPSG dataset, the polynomial coefficients are given as parameters of the form  $A_{umvn}$  and  $B_{umvn}$ , where  $m$  is the power to which  $U$  is raised and  $n$  is the power to which  $V$  is raised. For example,  $A_{17}$  is represented as coordinate operation parameter  $Au3v2$ .

The relationship between the two coordinate reference systems can now be written as follows:

$$(X_T - X_{T0}) = (X_S - X_{S0}) + dX$$

$$(Y_T - Y_{T0}) = (Y_S - Y_{S0}) + dY$$

or

$$X_T = X_S - X_{S0} + X_{T0} + dX$$

$$Y_T = Y_S - Y_{S0} + Y_{T0} + dY$$

where:

$X_T, Y_T$  are coordinates in the target coordinate reference system,

$X_S, Y_S$  are coordinates in the source coordinate reference system,  
 $X_{S0}, Y_{S0}$  are coordinates of the evaluation point in the source coordinate reference system,  
 $X_{T0}, Y_{T0}$  are coordinates of the evaluation point in the target coordinate reference system,  
 $dX, dY$  are derived through the scaled polynomial formulas.

Other (arguably better) approximating polynomials are described in mathematical textbooks such as “*Theory and applications of numerical analysis*”, by G.M. Phillips and P.J. Taylor (Academic Press, 1973).

**Example: General polynomial of degree 6** (EPSG coordinate operation method code 9648)

For coordinate transformation TM75 to ETRS89 (1)

Ordinate 1 of evaluation point  $X_0$  in source CRS:  $X_{S0} = \varphi_{S0} = 53^\circ30'00.000''N = +53.5$  degrees  
 Ordinate 2 of evaluation point  $Y_0$  in source CRS:  $Y_{S0} = \lambda_{S0} = 7^\circ42'00.000''W = - 7.7$  degrees  
 Ordinate 1 of evaluation point  $X_0$  in target CRS :  $X_{T0} = \varphi_{T0} = 53^\circ30'00.000''N = +53.5$  degrees  
 Ordinate 2 of evaluation point  $Y_0$  in target CRS :  $Y_{T0} = \lambda_{T0} = 7^\circ42'00.000''W = - 7.7$  degrees  
 Scaling factor for source CRS coordinate differences:  $m_S = 0.1$   
 Scaling factor for target CRS coordinate differences:  $m_T = 3600$

Parameters:

$A_0 = 0.763$                        $A_1 = -4.487$     ...                       $A_{24} = -265.898$     ...                       $A_{27} = 0$   
 $B_0 = -2.810$                        $B_1 = -0.341$     ...                       $B_{24} = -853.950$     ...                       $B_{27} = 0$

Forward calculation for:

Latitude  $\varphi_{TM75} = X_S = 55^\circ00'00''N = + 55.000$  degrees  
 Longitude  $\lambda_{TM75} = Y_S = 6^\circ30'00''W = - 6.500$  degrees

$X_S - X_{S0} = \varphi_{TM75} - \varphi_{S0} = 55.0 - 53.5 = 1.5$  degrees  
 $Y_S - Y_{S0} = \lambda_{TM75} - \lambda_{S0} = -6.5 - (-7.7) = 1.2$  degrees

$U = m_S.(X_S - X_{S0}) = m_S.(\varphi_{TM75} - \varphi_{S0}) = 0.1*(1.5) = 0.15$   
 $V = m_S.(Y_S - Y_{S0}) = m_S.(\lambda_{TM75} - \lambda_{S0}) = 0.1*(1.2) = 0.12$

$dX = (A_0 + A_1.U + \dots + A_{24}.U^3.V^3) / k_{TCD}$   
 $dX = \{0.763 + (-4.487 * 0.15) + \dots + (-265.898 * 0.15^3 * 0.12^3)\} / 3600$   
 $= 0.00003046$  degrees

$dY = (B_0 + B_1.U + \dots + B_{24}.U^3.V^3) / k_{TCD}$   
 $dY = \{-2.81 + (-0.341 * 0.12) + \dots + (-853.95 * 0.12^3 * 0.12^3)\} / 3600$   
 $= -0.00094799$  degrees

Then Latitude  $\varphi_{ETRS89} = X_T = X_S + dX = 55.0 + 0.00003046$  degrees =  $55^\circ00'10.9656''N$   
 Longitude  $\lambda_{ETRS89} = Y_T = Y_S + dY = -6.5 - 0.00094799$  degrees =  $6^\circ30'03.4128''W$

**Polynomial reversibility**

Approximation polynomials are in a strict mathematical sense *not reversible*, i.e. the same polynomial coefficients cannot be used to execute the reverse transformation.

In principle two options are available to execute the reverse transformation:

1. By applying a similar polynomial transformation with a different set of polynomial coefficients for the reverse polynomial transformation. This would result in a separate forward and reverse

transformation being stored in the EPSG database (or any other geodetic data repository).

2. By applying the polynomial transformation with the same coefficients but with their signs reversed and then iterate to an acceptable solution, the number of iteration steps being dependent on the desired accuracy. (Note that only the signs of the polynomial coefficients should be reversed and not the coordinates of the evaluation points or the scaling factors!) The iteration procedure is usually described by the information source of the polynomial transformation.

However, under certain conditions, described below, a satisfactory solution for the reverse transformation may be obtained using the forward coefficient values in a single step, rather than multiple step iteration. If such a solution is possible, the polynomial coordinate transformation method is classified by EPSG as a **reversible polynomial of degree  $n$** .

A (general) polynomial transformation is reversible only when the following conditions are met.

1. The co-ordinates of source and target evaluation point are (numerically) the same.
2. The unit of measure of the coordinate differences in source and target coordinate reference system are the same.
3. The scaling factors applied to source and target coordinate differences are the same.
4. The spatial variation of the differences between the coordinate reference systems around any given location is sufficiently small.

Clarification on conditions for polynomial reversibility:

Re 1 and 2 - In the reverse transformation the roles of the source and target coordinate reference systems are reversed. Consequently, the co-ordinates of the evaluation point in the *source* coordinate reference system become those in the *target* coordinate reference system in the reverse transformation. Usage of the same transformation parameters for the reverse transformation will therefore only be valid if the evaluation point coordinates are numerically the same in source and target coordinate reference system and in the same units. That is,  $X_{S0} = X_{T0} = X_0$  and  $Y_{S0} = Y_{T0} = Y_0$ .

Re 3 - The same holds for the scaling factors of the source and target coordinate differences and for the units of measure of the coordinate differences. That is,  $m_S = m_T = m$ .

Re 4 - If conditions 1, 2 and 3 are all satisfied it then may be possible to use the forward polynomial algorithm with the forward parameters for the reverse transformation. This is the case if the spatial variations in dX and dY around any given location are sufficiently constant. The signs of the polynomial coefficients are then reversed but the scaling factor and the evaluation point coordinates retain their signs. If these spatial variations in dX and dY are too large, for the reverse transformation iteration would be necessary. It is therefore not the algorithm that determines whether a single step solution is sufficient or whether iteration is required, but the desired accuracy combined with the degree of spatial variability of dX and dY.

An example of a reversible polynomial is transformation is ED50 to ED87 (1) for the North Sea. The suitability of this transformation to be described by a reversible polynomial can easily be explained. In the first place both source and target coordinate reference systems are of type geographic 2D. The typical difference in coordinate values between ED50 and ED87 is in the order of 2 metres ( $\approx 10^{-6}$  degrees) in the area of application. The polynomial functions are evaluated about central points with coordinates of  $55^\circ$  N,  $0^\circ$  E in both coordinate reference systems. The reduced coordinate differences (*in degrees*) are used as input parameters to the polynomial functions. The output coordinate differences are corrections to the input coordinate offsets of about  $10^{-6}$  degrees. This difference of several orders of magnitude between input and output values is the property that makes a polynomial function reversible in practice (although not in a formal mathematical sense).

The error made by the polynomial approximation formulas in calculating the reverse correction is of the same order of magnitude as the ratio of output versus input:

$$\frac{\text{output error}}{\text{output value}} \approx \frac{\text{output value}}{\text{output value}} (\approx 10^{-6})$$

*input error*      *input value*

As long as the input values (the coordinate offsets from the evaluation point) are orders of magnitude larger than the output (the corrections), and provided the coefficients are used with changed signs, the polynomial transformation may be considered to be reversible.

Hence EPSG acknowledges two classes of general polynomial functions, reversible and non-reversible, as distinguished by whether or not the coefficients may be used in both forward and reverse transformations, i.e. are reversible. EPSG does not describe the iterative solution as a separate algorithm. The iterative solution for the reverse transformation, when applicable, is deemed to be implied by the (forward) algorithm.

**Example: Reversible polynomial of degree 4** (EPSG coordinate operation method code 9651)

For coordinate transformation ED50 to ED87 (1)

Ordinate 1 of evaluation point:                       $X_0 = \varphi_0 = 55^{\circ}00'00.000''N = +55$  degrees  
 Ordinate 2 of evaluation point:                       $Y_0 = \lambda_0 = 0^{\circ}00'00.000''E = +0$  degrees

Scaling factor for coordinate differences:               $m = 1.0$

Parameters:

$A_0 = -5.56098E-06$                        $A_1 = -1.55391E-06$     ...     $A_{14} = -4.01383E-09$   
 $B_0 = +1.48944E-05$                        $B_2 = +2.68191E-05$     ...     $B_{14} = +7.62236E-09$

Forward calculation for:

Latitude     $\varphi_{ED50} = X_s = 52^{\circ}30'30''N = +52.508333333$  degrees  
 Longitude  $\lambda_{ED50} = Y_s = 2^{\circ}E = +2.0$  degrees

$U = m * (X_s - X_0) = m * (\varphi_{ED50} - \varphi_0) = 1.0 * (52.508333333 - 55.0) = -2.491666667$  degrees  
 $V = m * (Y_s - Y_0) = m * (\lambda_{ED50} - \lambda_0) = 1.0 * (2.0 - 0.0) = 2.0$  degrees

$dX = (A_0 + A_1.U + \dots + A_{14}.V^4) / k_{CD}$   
 $= [-5.56098E-06 + (-1.55391E-06 * -2.491666667) + \dots + (-4.01383E-09 * 2.0^4)] / 1.0$   
 $= -3.12958E-06$  degrees

$dY = (B_0 + B_1.U + \dots + B_{14}.V^4) / k_{CD}$   
 $= [+1.48944E-05 + (2.68191E-05 * -2.491666667) + \dots + (7.62236E-09 * 2.0^4)] / 1.0$   
 $= +9.80126E-06$  degrees

Then: Latitude     $\varphi_{ED87} = X_T = X_s + dX = 52.508333333 - 3.12958E-06$  degrees =  $52^{\circ}30'29.9887''N$   
 Longitude     $\lambda_{ED87} = Y_T = Y_s + dY = 2.000000000 + 9.80126E-06$  degrees =  $2^{\circ}00'00.0353''E$

Reverse calculation for coordinate transformation ED50 to ED87 (1).

The transformation method for the ED50 to ED87 (1) coordinate transformation, 4th-order reversible polynomial, is reversible. The same formulas may be applied for the reverse calculation, but coefficients  $A_0$  through  $A_{14}$  and  $B_0$  through  $B_{14}$  are applied with reversal of their signs. Sign reversal is not applied to the coordinates of the evaluation point or scaling factor for coordinate differences. Thus:

Ordinate 1 of evaluation point:                       $X_0 = \varphi_0 = 55^{\circ}00'00.000''N = +55$  degrees  
 Ordinate 2 of evaluation point:                       $Y_0 = \lambda_0 = 0^{\circ}00'00.000''E = +0$  degrees  
 Scaling factor for coordinate differences:               $m = 1.0$

$A_0 = +5.56098E-06$                        $A_1 = +1.55391E-06$     ...     $A_{14} = +4.01383E-09$   
 $B_0 = -1.48944E-05$                        $B_1 = -2.68191E-05$     ...     $B_{14} = -7.62236E-09$

Reverse calculation for:

$$\begin{aligned} \text{Latitude } \varphi_{ED87} &= X_S = 52^\circ 30' 29.9887'' \text{N} = +52.5083301944 \text{ degrees} \\ \text{Longitude } \lambda_{ED87} &= Y_S = 2^\circ 00' 00.0353'' \text{E} = +2.0000098055 \text{ degrees} \end{aligned}$$

$$U = 1.0 * (52.5083301944 - 55.0) = -2.4916698056 \text{ degrees}$$

$$V = 1.0 * (2.0000098055 - 0.0) = 2.0000098055 \text{ degrees}$$

$$\begin{aligned} dX &= (A_0 + A_1.U + \dots + A_{14}.V^4)/k \\ &= [+5.56098E-06 + (1.55391E-06 * -2.491666667) + \dots \\ &\quad \dots + (4.01383E-09 * 2.0000098055^4)]/1.0 \\ &= +3.12957E-06 \text{ degrees} \end{aligned}$$

$$\begin{aligned} dY &= (B_0 + B_1.U + \dots + B_{14}.V^4)/k \\ &= [-1.48944E-05 + (-2.68191E-05 * -2.491666667) + \dots \\ &\quad \dots + (-7.62236E-09 * 2.0000098055^4)]/1.0 \\ &= -9.80124E-06 \text{ degrees} \end{aligned}$$

$$\begin{aligned} \text{Then: Latitude } \varphi_{ED50} = X_T = X_S + dX &= 52.5083301944 + 3.12957E-06 \text{ degrees} = 52^\circ 30' 30.000'' \text{N} \\ \text{Longitude } \lambda_{ED50} = Y_T = Y_S + dY &= 2^\circ 00' 00.000'' \text{E} \end{aligned}$$

### 2.3.1.2 Polynomial transformation with complex numbers

The relationship between two projected coordinate reference systems may be approximated more elegantly by a single polynomial regression formula written in terms of complex numbers. The advantage is that the dependence between the ‘A’ and ‘B’ coefficients (for U and V) is taken into account in the formula, resulting in fewer coefficients for the same order polynomial. A polynomial to degree 3 in complex numbers is used in Belgium. A polynomial to degree 4 in complex numbers is used in The Netherlands for transforming coordinates referenced to the Amersfoort / RD system to and from ED50 / UTM.

$$\begin{aligned} m_T.(dX + i.dY) &= (A_1 + i.A_2).(U + i.V) + (A_3 + i.A_4).(U + i.V)^2 \quad (\text{to degree 2}) \\ &\quad + (A_5 + i.A_6).(U + i.V)^3 \quad (\text{additional degree 3 terms}) \\ &\quad + (A_7 + i.A_8).(U + i.V)^4 \quad (\text{additional degree 4 terms}) \end{aligned}$$

$$\begin{aligned} \text{where } U &= m_S.(X_S - X_{S0}) \\ V &= m_S.(Y_S - Y_{S0}) \end{aligned}$$

and  $m_S, m_T$  are the scaling factors for the coordinate differences in the source and target coordinate reference systems.

The polynomial to degree 4 can alternatively be expressed in matrix form as

$$\begin{pmatrix} m_T.dX \\ m_T.dY \end{pmatrix} = \begin{pmatrix} +A_1 & -A_2 & +A_3 & -A_4 & +A_5 & -A_6 & +A_7 & -A_8 \\ +A_2 & +A_1 & +A_4 & +A_3 & +A_6 & +A_5 & +A_8 & +A_7 \end{pmatrix} * \begin{pmatrix} U \\ V \\ U^2 - V^2 \\ 2UV \\ U^3 - 3UV^2 \\ 3U^2V - V^3 \\ U^4 - 6U^2V^2 + V^4 \\ 4U^3V - 4UV^3 \end{pmatrix}$$

Then as for the general polynomial case above

$$X_T = X_S - X_{S0} + X_{T0} + dX$$

$$Y_T = Y_S - Y_{S0} + Y_{T0} + dY$$

where, as above,

- $X_T, Y_T$  are coordinates in the target coordinate system,
- $X_S, Y_S$  are coordinates in the source coordinate system,
- $X_{S0}, Y_{S0}$  are coordinates of the evaluation point in the source coordinate reference system,
- $X_{T0}, Y_{T0}$  are coordinates of the evaluation point in the target coordinate reference system.

Note that the zero order coefficients of the general polynomial,  $A_0$  and  $B_0$ , have apparently disappeared. In reality they are absorbed by the different coordinates of the source and of the target evaluation point, which in this case, are numerically very different because of the use of two different projected coordinate systems for source and target.

The transformation parameter values (the coefficients) are not reversible. For the reverse transformation a different set of parameter values are required, used within the same formulas as the forward direction.

**Example: Complex polynomial of degree 4** (EPSG coordinate operation method code 9653)

Projected coordinate transformation: Amersfoort / RD New to ED50 / UTM zone 31N (1):

**Formula Parameter**

EPSG coordinate transformation parameter name	symbol	value	Unit
ordinate 1 of the evaluation point in the source CS	$X_{S0}$	155,000.000	metre
ordinate 2 of the evaluation point in the source CS	$Y_{S0}$	463,000.000	metre
ordinate 1 of the evaluation point in the target CS	$X_{T0}$	663,395.607	metre
ordinate 2 of the evaluation point in the target CS	$Y_{T0}$	5,781,194.380	metre
scaling factor for source CRS coordinate differences:	$m_S$	$10^{-5}$	
scaling factor for target CRS coordinate differences:	$m_T$	1.0	
A1	$A_1$	-51.681	coefficient
A2	$A_2$	+3,290.525	coefficient
A3	$A_3$	+20.172	coefficient
A4	$A_4$	+1.133	coefficient
A5	$A_5$	+2.075	coefficient
A6	$A_6$	+0.251	coefficient
A7	$A_7$	+0.075	coefficient
A8	$A_8$	-0.012	coefficient

For input point:

Easting,  $X_{AMERSFOORT/RD} = X_S = 200,000.00$  metres  
 Northing,  $Y_{AMERSFOORT/RD} = Y_S = 500,000.00$  metres

$$U = m_S \cdot (X_S - X_{S0}) = (200,000 - 155,000) \cdot 10^{-5} = 0.45$$

$$V = m_S \cdot (Y_S - Y_{S0}) = (500,000 - 463,000) \cdot 10^{-5} = 0.37$$

$$dX = (-1,240.050) / 1.0$$

$$dY = (1,468.748) / 1.0$$

$$\begin{aligned} \text{Then: Easting, } E_{\text{ED50/UTM31}} = X_T &= X_S - X_{S0} + X_{T0} + dX \\ &= 200,000 - 155,000 + 663,395.607 + (-1,240.050) \\ &= 707,155.557 \text{ metres} \end{aligned}$$

$$\begin{aligned} \text{Northing, } N_{\text{ED50/UTM31N}} = Y_T &= Y_S - Y_{S0} + Y_{T0} + dY \\ &= 500,000 - 463,000 + 5,781,194.380 + 1,468.748 \\ &= 5,819,663.128 \text{ metres} \end{aligned}$$

**2.3.1.3 Polynomial transformation for Spain**  
(EPSG coordinate operation method code 9617)

The original geographic coordinate reference system for the Spanish mainland was based on Madrid 1870 datum, Struve 1860 ellipsoid, with longitudes related to the Madrid meridian. Three second-order polynomial expressions have been empirically derived by El Servicio Geográfico del Ejército to transform geographical coordinates based on this system to equivalent values based on the European Datum of 1950 (ED50). The polynomial coefficients derived can be used to transform coordinates from the Madrid 1870 (Madrid) geographic coordinate reference system to the ED50 system. Three pairs of expressions have been derived: each pair is used to calculate the shift in latitude and longitude respectively for (i) a mean for all Spain, (ii) a better fit for the north of Spain, (iii) a better fit for the south of Spain.

The polynomial expressions are:

$$\begin{aligned} d\phi \text{ (arc sec)} &= A_0 + (A_1 * \phi_s) + (A_2 * \lambda_s) + (A_3 * H_s) \\ d\lambda \text{ (arc sec)} &= B_0 + B_1 * \phi_s + (B_2 * \lambda_s) + (B_3 * H_s) \end{aligned}$$

where latitude  $\phi_s$  and longitude  $\lambda_s$  are in decimal degrees referred to the Madrid 1870 (Madrid) geographic coordinate reference system and  $H_s$  is gravity-related height in metres.  $B_0$  is the longitude (in seconds) of the Madrid meridian measured from the Greenwich meridian; it is the value to be applied to a longitude relative to the Madrid meridian to transform it to a longitude relative to the Greenwich meridian.

The results of these expressions are applied through the formulas:

$$\begin{aligned} \phi_{\text{ED50}} &= \phi_{\text{M1870(M)}} + d\phi \\ \text{and } \lambda_{\text{ED50}} &= \lambda_{\text{M1870(M)}} + d\lambda. \end{aligned}$$

Example:

Input point coordinate reference system: Madrid 1870 (Madrid) (geographic 2D)

$$\begin{aligned} \text{Latitude } \phi_s &= 42^\circ 38' 52.77'' \text{N} \\ &= +42.647992 \text{ degrees} \end{aligned}$$

$$\begin{aligned} \text{Longitude } \lambda_s &= 3^\circ 39' 34.57'' \text{E of Madrid} \\ &= +3.659603 \text{ degrees from the Madrid meridian.} \end{aligned}$$

$$\text{Gravity-related height } H_s = 0 \text{ m}$$

For the north zone transformation:

$$\begin{aligned} A_0 &= 11.328779 & B_0 &= -13276.58 \\ A_1 &= -0.1674 & B_1 &= 2.5079425 \\ A_2 &= -0.03852 & B_2 &= 0.8352 \\ A_3 &= 0.0000379 & B_3 &= -0.0000038 \end{aligned}$$

$$\begin{aligned}
 & d\phi = +4.05 \text{ seconds} \\
 \text{Then latitude } \phi_{ED50} &= 42^\circ 38' 52.77'' \text{N} + 4.05'' \\
 &= 42^\circ 38' 56.82'' \text{N} \\
 \\ 
 & d\lambda = -13270.54 \text{ seconds} = -3^\circ 41' 10.54'' \\
 \text{Then longitude } \lambda_{ED50} &= 3^\circ 39' 34.57'' \text{E} - 3^\circ 41' 10.54'' \\
 &= 0^\circ 01' 35.97'' \text{W of Greenwich.}
 \end{aligned}$$

### 2.3.2 Miscellaneous Linear Coordinate Operations

An affine 2D transformation is used for converting or transforming a coordinate reference system possibly with non-orthogonal axes and possibly different units along the two axes to an isometric coordinate reference system (i.e. a system of which the axes are orthogonal and have equal scale units). The transformation therefore involves a change of origin, differential change of axis orientation and a differential scale change. EPSG distinguishes four methods to implement this class of coordinate operation:

- 1) the parametric representation
- 2) the geometric representation, which is described in
  - (a) a general case,
  - (b) a simplified case in which the axes are constrained to be orthogonal, and
  - (c) a further simplified case known as the Similarity Transformation.

#### 2.3.2.1 Affine Parametric Transformation

(EPSG coordinate operation method code 9624)

Mathematical and survey literature usually provides the parametric representation of the affine transformation. The parametric algorithm is commonly used for rectification of digitised maps. It is often embedded in CAD software and Geographical Information Systems where it is frequently referred to as “rubber sheeting”. Although the application of this algorithm falls outside the scope of the EPSG geodesy data set it is presented here for reasons of clarity.

The formula in matrix form is as follows:

$$\begin{pmatrix} X_T \\ Y_T \end{pmatrix} = \begin{pmatrix} A_0 \\ B_0 \end{pmatrix} + \begin{pmatrix} A_1 & A_2 \\ B_1 & B_2 \end{pmatrix} * \begin{pmatrix} X_S \\ Y_S \end{pmatrix}$$

or using algebraic coefficients:

$$\begin{aligned}
 X_T &= A_0 + A_1 \cdot X_S + A_2 \cdot Y_S \\
 Y_T &= B_0 + B_1 \cdot X_S + B_2 \cdot Y_S
 \end{aligned}$$

where

$X_T, Y_T$  are the coordinates of a point P in the target coordinate reference system;  
 $X_S, Y_S$  are the coordinates of P in the source coordinate reference system.

This form of describing an affine transformation is analogous to the general polynomial transformation formulas (section 3.1 above). Although it is somewhat artificial, an affine transformation could be considered to be a first order general polynomial transformation but without the reduction to source and target evaluation points.

#### Reversibility

The parameter values for an affine transformation cannot be used for the reverse operation. However, the reverse operation is another affine transformation using the same formulas but with different parameter values. The reverse parameter values, indicated by a prime ('), can be calculated from those of the forward operation as follows:

$$\begin{aligned}
 D &= A_1 \cdot B_2 - A_2 \cdot B_1 \\
 A_0' &= (A_2 \cdot B_0 - B_2 \cdot A_0) / D \\
 B_0' &= (B_1 \cdot A_0 - A_1 \cdot B_0) / D \\
 A_1' &= +B_2 / D \\
 A_2' &= -A_2 / D \\
 B_1' &= -B_1 / D \\
 B_2' &= +A_1 / D
 \end{aligned}$$

**2.3.2.2 Affine General Geometric Transformation**

(EPSG coordinate operation method code 9623)

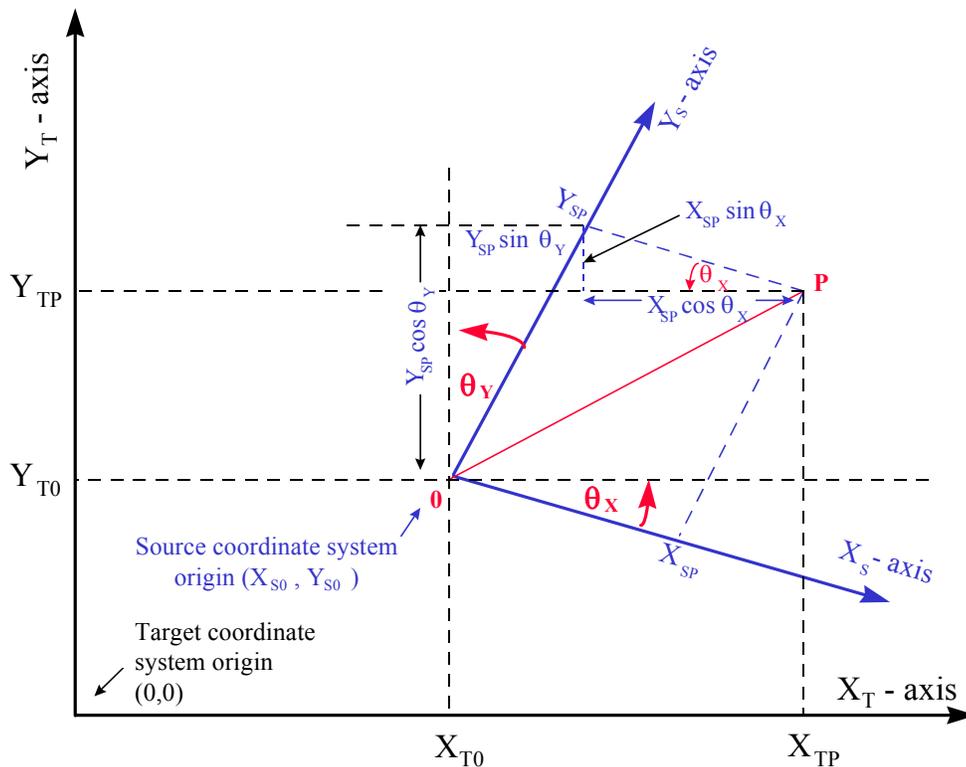


Figure 9 Geometric representation of the affine coordinate transformation  
(Please note that to prevent cluttering of the figure the scale parameters of the X<sub>s</sub> and Y<sub>s</sub> axes have been omitted).

From the diagram above it can be seen that:

$$\begin{aligned}
 X_{TP} &= X_{T0} + Y_{SP} \cdot \sin \theta_Y + X_{SP} \cdot \cos \theta_X \\
 Y_{TP} &= Y_{T0} + Y_{SP} \cdot \cos \theta_Y - X_{SP} \cdot \sin \theta_X
 \end{aligned}$$

**Scale of the two coordinate reference systems**

The scaling of both source and target coordinate reference systems adds some complexity to this formula.

The operation will often be applied to transform an engineering coordinate reference system to a projected coordinate reference system. The engineering coordinate reference system, e.g. a seismic bin grid, may have different units of measure on its two axes. These have scale ratios of dS<sub>X</sub> and dS<sub>Y</sub> respective to the axes of the projected coordinate reference system.

The projected coordinate reference system is nominally defined to be in well-known units, e.g. metres. However, the distortion characteristics of the map projection only preserve true scale along certain defined lines or curves, hence the projected coordinate reference system's unit of measure is strictly speaking only valid along those lines or curves. Everywhere else its scale is distorted by the map projection. For conformal map projections the distortion at any point can be expressed by the point scale factor 'k' for that point. Please note that this point scale factor 'k' should NOT be confused with the scale factor at the natural origin of the projection, denominated by 'k<sub>0</sub>'. For non-conformal map projections the scale distortion at a point is bearing-dependent and will not be described in this document.

It has developed as working practice to choose the origin of the source (engineering) coordinate reference system as the point in which to calculate this point scale factor 'k', although for engineering coordinate reference systems with a large coverage area a point in the middle of the coverage area may be a better choice.

Adding the scaling between each pair of axes and dropping the suffix for point P, after rearranging the terms we have the geometric representation of the general affine transformation:

$$\begin{aligned} X_T &= X_{T0} + X_S \cdot k \cdot dS_X \cdot \cos \theta_X + Y_S \cdot k \cdot dS_Y \cdot \sin \theta_Y \\ Y_T &= Y_{T0} - X_S \cdot k \cdot dS_X \cdot \sin \theta_X + Y_S \cdot k \cdot dS_Y \cdot \cos \theta_Y \end{aligned}$$

or, in matrix form:

$$\begin{pmatrix} X_T \\ Y_T \end{pmatrix} = \begin{pmatrix} X_{T0} \\ Y_{T0} \end{pmatrix} + \begin{pmatrix} \cos \theta_X & \sin \theta_Y \\ -\sin \theta_X & \cos \theta_Y \end{pmatrix} * \begin{pmatrix} k \cdot dS_X & 0 \\ 0 & k \cdot dS_Y \end{pmatrix} * \begin{pmatrix} X_S \\ Y_S \end{pmatrix}$$

where:

- $X_{T0}, Y_{T0}$  = the coordinates of the origin point of the source coordinate reference system, expressed in the target coordinate reference system;
- $dS_X, dS_Y$  = the length of one unit of the source axis, expressed in units of the target axis, for the first and second source and target axis pairs respectively;
- $k$  = point scale factor of the target coordinate reference system at a chosen reference point;
- $\theta_X, \theta_Y$  = the angles about which the source coordinate reference system axes  $X_S$  and  $Y_S$  must be rotated to coincide with the target coordinate reference system axes  $X_T$  and  $Y_T$  respectively (counter-clockwise being positive).

Comparing the algebraic representation with the parameters of the parameteric form in section 2.3.2.1 above it can be seen that the parametric and geometric forms of the affine coordinate transformation are related as follows:

$$\begin{aligned} A_0 &= X_{T0} \\ A_1 &= k \cdot dS_X * \cos \theta_X \\ A_2 &= k \cdot dS_Y * \sin \theta_Y \\ B_0 &= Y_{T0} \\ B_1 &= -k \cdot dS_X * \sin \theta_X \\ B_2 &= k \cdot dS_Y * \cos \theta_Y \end{aligned}$$

### Reversibility

The parameters for an affine transformation cannot be used for the reverse transformation. However, the reverse coordinate operation is another affine transformation using the same formulas but with different parameters. The reverse parameter values can be calculated from the formulas provided above and applying those to the same algorithm. Alternatively the reverse operation can be described by a different formula, as shown below, using the same parameters as the forward transformation.

$$\begin{pmatrix} X_S \\ Y_S \end{pmatrix} = \frac{1}{k} * \begin{pmatrix} 1/dS_X & 0 \\ 0 & 1/dS_Y \end{pmatrix} * \begin{pmatrix} \cos \theta_Y & -\sin \theta_Y \\ \sin \theta_X & \cos \theta_X \end{pmatrix} * \begin{pmatrix} X_T - X_{T0} \\ Y_T - Y_{T0} \end{pmatrix}$$

$$\begin{pmatrix} Y_S \\ \end{pmatrix} = k.D \begin{pmatrix} 0 & 1/dS_Y \\ \end{pmatrix} \begin{pmatrix} \sin \theta_X & \cos \theta_X \\ \end{pmatrix} \begin{pmatrix} Y_T - Y_{T0} \\ \end{pmatrix}$$

where  $D = \cos(\theta_X - \theta_Y)$ ;

or algebraically:

$$X_S = [(X_T - X_{T0}) \cdot \cos \theta_Y - (Y_T - Y_{T0}) \cdot \sin \theta_Y] / [k \cdot dS_X \cdot \cos(\theta_X - \theta_Y)]$$

$$Y_S = [(X_T - X_{T0}) \cdot \sin \theta_X + (Y_T - Y_{T0}) \cdot \cos \theta_X] / [k \cdot dS_Y \cdot \cos(\theta_X - \theta_Y)]$$

### 2.3.2.3 Affine Orthogonal Geometric Transformation

(EPSG coordinate operation method code 9622)

If the source coordinate reference system happens to have orthogonal axes, that is both axes are rotated through the same angle to bring them into the direction of the orthogonal target coordinate reference system axes, i.e.  $\theta_X = \theta_Y = \theta$ , then the Affine General Geometric Transformation can be simplified to the Affine Orthogonal Geometric Transformation. In matrix form this is:

$$\begin{pmatrix} X_T \\ Y_T \end{pmatrix} = \begin{pmatrix} X_{T0} \\ Y_{T0} \end{pmatrix} + \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} * \begin{pmatrix} k \cdot dS_X & 0 \\ 0 & k \cdot dS_Y \end{pmatrix} * \begin{pmatrix} X_S \\ Y_S \end{pmatrix}$$

or algebraically:

$$X_T = X_{T0} + X_S \cdot k \cdot dS_X \cdot \cos \theta + Y_S \cdot k \cdot dS_Y \cdot \sin \theta$$

$$Y_T = Y_{T0} - X_S \cdot k \cdot dS_X \cdot \sin \theta + Y_S \cdot k \cdot dS_Y \cdot \cos \theta$$

where:

$X_{T0}, Y_{T0}$  = the coordinates of the origin point of the source coordinate reference system, expressed in the target coordinate reference system;

$dS_X, dS_Y$  = the length of one unit of the source axis, expressed in units of the target axis, for the X axes and the Y axes respectively;

$k$  = point scale factor of the target coordinate reference system at a chosen reference point;

$\theta$  = the angle through which the source coordinate reference system axes must be rotated to coincide with the target coordinate reference system axes (counter-clockwise is positive). Alternatively, the bearing (clockwise positive) of the source coordinate reference system  $Y_S$ -axis measured relative to target coordinate reference system north.

For the reverse case the Affine General Geometric Transformation formulas given above can be similarly simplified by replacing  $\theta_X$  and  $\theta_Y$  with  $\theta$ .

#### **Example:**

Source coordinate reference system: imaginary 3D seismic acquisition bin grid. The two axes are orthogonal, but the unit on the I-axis is 25 metres, whilst the unit on the J-axis is 12.5 metres.

The target projected coordinate reference system is WGS 84 / UTM Zone 31N and the origin of the bin grid (centre of bin 0,0) is defined at E = 456781.0, N = 5836723.0. The projected coordinate reference system point scale factor at the bin grid origin is 0.99984.

The map grid bearing of the I and J axes are 110° and 20° respectively. Thus the angle through which both the positive I and J axes need to be rotated to coincide with the positive Easting axis and Northing axis respectively is +20 degrees.

Hence:

$$X_{T0} = 456\,781.0 \text{ m}$$

$$Y_{T0} = 5\,836\,723.0 \text{ m}$$

$$\begin{aligned} dS_X &= 25 \\ dS_Y &= 12.5 \\ k &= 0.99984 \\ \theta &= +20 \text{ degrees} \end{aligned}$$

Forward calculation for centre of bin with coordinates: I = 300, J = 247:

$$X_T = \text{Easting} = X_{T0} + X_S \cdot k \cdot dS_X \cdot \cos \theta + Y_S \cdot k \cdot dS_Y \cdot \sin \theta = 464\,855.62 \text{ m.}$$

$$Y_T = \text{Northing} = Y_{T0} - X_S \cdot k \cdot dS_X \cdot \sin \theta + Y_S \cdot k \cdot dS_Y \cdot \cos \theta = 5\,837\,055.90 \text{ m}$$

Reverse calculation for this point:

$$X_S = [(X_T - X_{T0}) \cdot \cos \theta_Y - (Y_T - Y_{T0}) \cdot \sin \theta_Y] / [k \cdot dS_X \cdot \cos (\theta_X - \theta_Y)] = 230 \text{ bins}$$

$$Y_S = [(X_T - X_{T0}) \cdot \sin \theta_X + (Y_T - Y_{T0}) \cdot \cos \theta_X] / [k \cdot dS_Y \cdot \cos (\theta_X - \theta_Y)] = 162 \text{ bins}$$

### 2.3.2.4 Similarity Transformation

(EPSG coordinate operation method code 9621)

If the source coordinate reference system happens to have axes of the same scale, that is both axes are scaled by the same factor to bring them into the scale of the target coordinate reference system axes (i.e.  $dS_X = dS_Y = dS$ ) then the Affine Orthogonal Geometric Transformation can be simplified further to a Similarity Transformation.

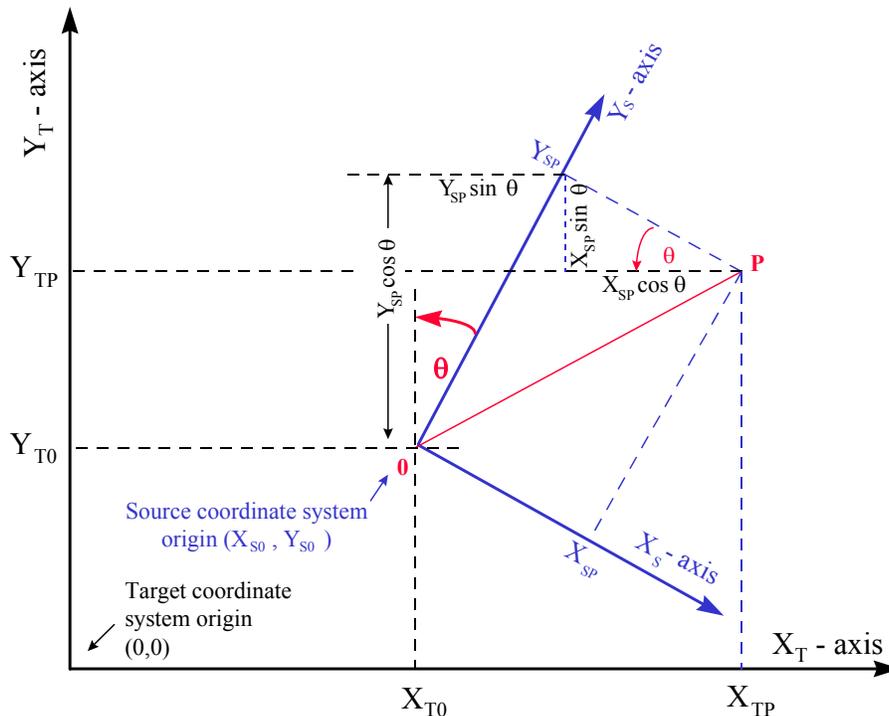


Figure 10 Similarity Transformation

From the above diagram the Similarity Transformation in algebraic form is:

$$X_{TP} = X_{T0} + Y_{SP} \cdot dS \cdot \sin \theta + X_{SP} \cdot dS \cdot \cos \theta$$

$$Y_{TP} = Y_{T0} + Y_{SP} \cdot dS \cdot \cos \theta - X_{SP} \cdot dS \cdot \sin \theta$$

Dropping the suffix for point P and rearranging the terms

$$\begin{aligned} X_T &= X_{T0} + X_S \cdot dS \cdot \cos \theta + Y_S \cdot dS \cdot \sin \theta \\ Y_T &= Y_{T0} - X_S \cdot dS \cdot \sin \theta + Y_S \cdot dS \cdot \cos \theta \end{aligned}$$

or in matrix form:

$$\begin{pmatrix} X_T \\ Y_T \end{pmatrix} = \begin{pmatrix} X_{T0} \\ Y_{T0} \end{pmatrix} + (1 + dS) * \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} * \begin{pmatrix} X_S \\ Y_S \end{pmatrix}$$

where:

- $X_{T0}, Y_{T0}$  = the coordinates of the origin point of the source coordinate reference system expressed in the target coordinate reference system;
- $1+dS$  = the length of one unit in the source coordinate reference system expressed in units of the target coordinate reference system;
- $\theta$  = the angle about which the axes of the source coordinate reference system need to be rotated to coincide with the axes of the target coordinate reference system, counter-clockwise being positive. Alternatively, the bearing of the source coordinate reference system  $Y_S$ -axis measured relative to target coordinate reference system north.

The Similarity Transformation can also be described as a special case of the Affine Parametric Transformation where coefficients  $A_1 = B_2$  and  $A_2 = -B_1$ .

### Reversibility

In contrast with an Affine Transformation, the Similarity Transformation parameters are reversible, but only on the condition that the scale difference between the two coordinate reference systems is small (order of several parts per million). Then  $dS$  is the deviation from unity of the ratio of the units of measure of the two coordinate reference systems. In these cases the reverse operation would require a scale correction of  $1/(1+dS) \approx (1-dS)$ . This enables usage of the same scale and rotation parameters, but with reversed sign, for the reverse conversions. (The rotation angle of  $+\theta$  becomes  $-\theta$ , which is valid for all  $\theta$ ). However for the reverse transformation the translation parameters,  $X_{T0}'$  and  $Y_{T0}'$ , take entirely different values. Thus for all practical purposes the similarity conversion is not reversible.

### When to use the Similarity Transformation

Similarity Transformations can be used when source and target coordinate reference systems

- each have orthogonal axes,
- each have the same scale along both axes,

and

- both have the same units of measure,

for example between engineering plant grids and projected coordinate reference systems.

A coordinate conversion between two systems that:

- each have orthogonal axes,

but:

- significantly different scales or units of measure,

should be defined as an Affine Orthogonal Transformation and not as a Similarity Transformation. This may be the case with seismic bin grids with square bins.

Coordinate Operations between two coordinate reference systems where in either system either the scale along axes differ or the axes are not orthogonal should be defined as an Affine General Transformation in either the parametric or geometric form.

**Example**

Source coordinate reference system: Astra Minas Grid (an engineering coordinate reference system)  
 Target coordinate reference system: Campo Inchauspe / Argentina 2 (a projected CRS)

Note that for the Astra Minas Grid the coordinate axes are:

X (positive axis oriented *north*)

Y (positive axis oriented *west*)

and coordinates are quoted in that order.

whereas for Campo Inchauspe / Argentina 2 the axes are:

X (positive axis oriented *north*)

Y (positive axis oriented *east*)

and coordinates are quoted in that order.

Thus the Astra Minas grid X and Y axes map to the Campo Inchauspe / Argentina 2 Y and X-axes respectively. With respect to the symbols in the formulas,

$X_S$  = Astra Minas *X*

$Y_S$  = Astra Minas *Y*

$X_T$  = Campo Inchauspe / Argentina 2 *Y*

$Y_T$  = Campo Inchauspe / Argentina 2 *X*

Parameters of the Similarity Transformation:

$X_{T0}$  = 2610200.48 metre

$Y_{T0}$  = 4905282.73 metre

$\theta$  = 271°05' 30" = 271.0916667 degrees

$k$  = 0 whence  $(1+k)=1.0$

Forward calculation for Astra Minas point : X (north) =10000 m, Y (west) =50000 m.

$X_S$  = Astra Minas *X* = 10000

$Y_S$  = Astra Minas *Y* = 50000

$$\begin{aligned} \text{Gauss-Kruger zone 2 Easting (Y)} &= X_T = X_{T0} + X_S \cdot dS \cdot \cos \theta + Y_S \cdot dS \cdot \sin \theta \\ &= 2610200.48 + (50000 * 1.0 * \cos(271.0916667\text{deg})) \\ &\quad + (10000 * 1.0 * \sin(271.0916667\text{deg})) \\ &= 2601154.90 \text{ m.} \end{aligned}$$

$$\begin{aligned} \text{Gauss-Kruger zone 2 Northing (X)} &= Y_T = Y_{T0} - X_S \cdot dS \cdot \sin \theta + Y_S \cdot dS \cdot \cos \theta \\ &= 4905282.73 - (50000 * 1.0 * \sin(271.0916667\text{deg})) \\ &\quad + (10000 * 1.0 * \cos(271.0916667\text{deg})) \\ &= 4955464.17 \text{ m.} \end{aligned}$$

## **2.4 Coordinate Transformations**

### **2.4.1 Offsets - general**

Several transformation methods which utilise offsets in coordinate values are recognised. The offset methods may be in n-dimensions. These include longitude rotations, geographical coordinate offsets and vertical offsets.

Mathematically, if the origin of a one-dimensional coordinate system is shifted along the positive axis and placed at a point with ordinate A, then the transformation formula is:

$$X_{\text{new}} = X_{\text{old}} - A$$

However it is common practice in coordinate system transformations to apply the shift as an addition, with the sign of the shift parameter value having been suitably reversed to compensate for the practice. Since 1999 this practice has been adopted by EPSG. Hence transformations allow calculation of coordinates in the target system by adding a correction parameter to the coordinate values of the point in the source system:

$$X_t = X_s + A$$

where  $X_s$  and  $X_t$  are the values of the coordinates in the source and target coordinate systems and A is the value of the transformation parameter to transform source coordinate reference system coordinate to target coordinate reference system coordinate.

Offset methods are reversible. For the reverse transformation, the offset parameter value is applied with its sign reversed.

### **2.4.2 Transformations between Vertical Coordinate Reference Systems**

#### **2.4.2.1 Vertical Offset**

(EPSG coordinate operation method code 9616)

If the coordinate reference system axes are positive in opposite directions, for instance in the transformation of heights in the source vertical CRS to depths in the target vertical CRS, or in differing units, the above formula is modified to:

$$X_t = [(X_s * U_s) + (A * U_A)] * (m / U_t)$$

where

$X_t$  = value in the target vertical coordinate reference system.

$X_s$  = value in the source vertical coordinate reference system.

A is the value of the origin of the target system in the source system.

m is unit direction multiplier (m=1 if both systems are height or both are depth; m = -1 if one system is height and the other system is depth; the value of m is implied through the vertical coordinate reference system type attribute).

$U_s$ ,  $U_t$  and  $U_A$  are unit conversion ratios to metres for the source and target systems and the offset value respectively.

#### **2.4.2.2 Vertical Offset by Interpolation of Gridded Data**

The relationship between some gravity-related coordinate reference systems is available through gridded data sets of offsets (sometimes called height differences). The vertical offset at a point is first interpolated within the grid of values. It is then applied through the formula above,  $X_t = X_s + A$ .

For the purposes of interpolation, horizontal coordinates of the point are required. However the transformation remains 1-dimensional. Although the providers of some gridded data sets suggest a particular interpolation method within the grid, generally the density of grid nodes should be such that

any reasonable grid interpolation method will give the same offset value within an appropriately small tolerance. Bi-linear interpolation is the most usual grid interpolation mechanism. EPSG differentiates methods by the format of the gridded data file. The grid file format is given in documentation available from the information source. An example is *Vertcon* (EPSG coordinate operation method code 9658) which is used by the US National Geodetic Survey for transformation between the NGVD29 and NAVD88 gravity-related height systems. Because the difference in NAD27 and NAD83 horizontal coordinate values of a point is insignificant in comparison to the rate of change of height offset, interpolation within the *Vertcon* gridded data file may be made in either NAD27 or NAD83 horizontal systems.

### 2.4.2.3 Vertical Offset and Slope

(EPSG coordinate operation method code 9657)

In Europe, national height systems are related to the pan-European height system through three transformation parameters and the formula:

$$H_t = H_s + A + [(I_\varphi * \rho_o * (\varphi - \varphi_o)] + [I_\lambda * v_o * (\lambda - \lambda_o) * \cos(\varphi)]$$

where

$H_t$  = gravity-related height value in the target vertical coordinate reference system.

$H_s$  = gravity-related height value in the source vertical coordinate reference system.

A is the value of a vertical offset to be applied.

$I_\varphi$  is the value in radians of the slope parameter in the latitude domain, i.e. in the plane of the meridian, derived at an evaluation point with coordinates of  $\varphi_o, \lambda_o$ .

$I_\lambda$  is the value in radians of the slope parameter in the longitude domain, i.e. perpendicular to the plane of the meridian.

$\rho_o$  is the radius of curvature of the meridian at latitude  $\varphi_o$ ,

$$\text{where } \rho_o = a(1 - e^2)/(1 - e^2 \sin^2 \varphi_o)^{3/2}$$

$v_o$  is the radius of curvature on the prime vertical (i.e. perpendicular to the meridian) at latitude  $\varphi_o$ ,

$$\text{where } v_o = a/(1 - e^2 \sin^2 \varphi_o)^{1/2}$$

$\varphi, \lambda$  are the horizontal coordinates of the point in the ETRS89 coordinate reference system, in radians.

$\varphi_o, \lambda_o$  are the coordinates of the evaluation point in the ETRS89 coordinate reference system, in radians.

The horizontal location of the point must always be given in ETRS89 terms. Care is required where compound coordinate reference systems are in use: if the horizontal coordinates of the point are known in the local CRS they must first be transformed to ETRS89 values. The method is reversible – the signs of the parameters are to be reversed in the reverse transformation.

#### **Example:**

For coordinate transformation LN02 to EVRF2000 (1)

Ordinate 1 of evaluation point:	$\varphi_{s0} =$	46°55'N	=	0.818850307 rad
Ordinate 2 of evaluation point:	$\lambda_{s0} =$	8°11'E (of Greenwich)	=	0.142826110 rad
Transformation Parameters:	A =	-0.245 m		
	$I_\varphi =$	-0.210"	=	-0.000001018 rad
	$I_\lambda =$	-0.032"	=	-0.000000155 rad

Consider a point having a gravity-related height in the LN02 system ( $H_s$ ) of 473.0m and with horizontal coordinates in the ETRS89 geographical coordinate reference system of:

$$\text{Latitude } \varphi_{\text{ETRS89}} = 47^\circ 20' 00.00'' \text{N} = 0.826122513 \text{ rad}$$

$$\text{Longitude } \lambda_{\text{ETRS89}} = 9^\circ 40' 00.00'' \text{E} = 0.168715161 \text{ rad}$$

ETRS89 uses the GRS1980 ellipsoid for which  $a = 6378137$  m and  $1/f = 298.25722221$

Then

$$\begin{aligned} \rho_0 &= 6369526.88 \text{ m} \\ I_\phi \text{ term} &= -0.047 \text{ m} \\ v_0 &= 6389555.64 \text{ m} \\ I_\lambda \text{ term} &= -0.017 \text{ m} \end{aligned}$$

whence EVRF2000 height  $H_t$

$$= 473.0 + (-0.245) + (-0.047) + (-0.017)$$

$$= 472.690 \text{ m.}$$

### 2.4.3 Transformations between Geocentric Coordinate Reference Systems

The methods in this section operate in the geocentric coordinate domain. However they are often used as the middle part of a transformation of coordinates from one geographic coordinate reference system into another forming a concatenated operation of three steps:

[geographical to geocentric >> geocentric to geocentric >> geocentric to geographic]

See section 2.4.4.1 for a fuller description of these concatenated operations, and Guidance Note 7 part 1 (Use of the EPSG geodetic dataset) for a more general treatment of implicit concatenated operations created by application software.

#### 2.4.3.1 Geocentric Translations

(EPSG coordinate operation method code 9603)

If we assume that the axes of the ellipsoids are parallel, that the prime meridian is Greenwich, and that there is no scale difference between the source and target coordinate reference system, then geocentric coordinate reference systems may be related to each other through three translations (colloquially known as shifts) **dX**, **dY**, **dZ** in the sense from source geocentric coordinate reference system to target geocentric coordinate reference system. They may then be applied as

$$\begin{aligned} X_t &= X_s + dX \\ Y_t &= Y_s + dY \\ Z_t &= Z_s + dZ \end{aligned}$$

#### **Example:**

Consider a North Sea point with coordinates derived by GPS satellite in the WGS84 geocentric coordinate reference system, with coordinates of:

$$\begin{aligned} X_s &= 3771\ 793.97 \text{ m} \\ Y_s &= 140\ 253.34 \text{ m} \\ Z_s &= 5124\ 304.35 \text{ m} \end{aligned}$$

whose coordinates are required in terms of the ED50 coordinate reference system which takes the International 1924 ellipsoid. The three parameter geocentric translations method's parameter values from WGS84 to ED50 for this North Sea area are given as  $dX = +84.87\text{m}$ ,  $dY = +96.49\text{m}$ ,  $dZ = +116.95\text{m}$ .

Applying the quoted geocentric translations to these, we obtain new geocentric values now related to ED50:

$$\begin{aligned} X_t &= 3771\ 793.97 + 84.87 = 3771\ 878.84 \text{ m} \\ Y_t &= 140\ 253.34 + 96.49 = 140\ 349.83 \text{ m} \\ Z_t &= 5124\ 304.35 + 116.95 = 5124\ 421.30 \text{ m} \end{aligned}$$

**2.4.3.2 Helmert 7-parameter transformations**

**2.4.3.2.1 Position Vector 7-parameter transformation**

(EPSG coordinate operation method code 9606)

It is rare for the condition assumed in the geocentric translation method above – that the axes of source and target systems are exactly parallel and the two systems have an identical scale – is true. Further parameters to account for rotation and scale differences may be introduced. This is usually described as a simplified 7-parameter Helmert transformation, expressed in matrix form in what is known as the "Bursa-Wolf" formula:

$$\begin{pmatrix} X_T \\ Y_T \\ Z_T \end{pmatrix} = M * \begin{pmatrix} 1 & -R_Z & +R_Y \\ +R_Z & 1 & -R_X \\ -R_Y & +R_X & 1 \end{pmatrix} * \begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} + \begin{pmatrix} dX \\ dY \\ dZ \end{pmatrix}$$

The parameters are commonly referred to defining the transformation "from source coordinate reference system to target coordinate reference system", whereby (X<sub>S</sub>, Y<sub>S</sub>, Z<sub>S</sub>) are the coordinates of the point in the source geocentric coordinate reference system and (X<sub>T</sub>, Y<sub>T</sub>, Z<sub>T</sub>) are the coordinates of the point in the target geocentric coordinate reference system. But that does not define the parameters uniquely; neither is the definition of the parameters implied in the formula, as is often believed. However, the following definition, which is consistent with the "Position Vector Transformation" convention (EPSG coordinate operation method code 9606), is common E&P survey practice, used by the International Association of Geodesy (IAG) and recommended by ISO 19111:

(dX, dY, dZ) :Translation vector, to be added to the point's position vector in the source coordinate reference system in order to transform from source system to target system; also: the coordinates of the origin of the source coordinate reference system in the target coordinate reference system.

(R<sub>X</sub>, R<sub>Y</sub>, R<sub>Z</sub>) :Rotations to be applied to the point's vector. The sign convention is such that a positive rotation about an axis is defined as a clockwise rotation of the position vector when viewed from the origin of the Cartesian coordinate reference system in the positive direction of that axis; e.g. a positive rotation about the Z-axis only from source system to target system will result in a larger longitude value for the point in the target system. Although rotation angles may be quoted in any angular unit of measure, the formula as given here requires the angles to be provided in radians.

M : The scale correction to be made to the position vector in the source coordinate reference system in order to obtain the correct scale in the target coordinate reference system. M = (1 + dS\*10<sup>-6</sup>), where dS is the scale correction expressed in parts per million.

Example

Transformation from WGS 72 to WGS 84 (EPSG transformation code 1238). Transformation parameter values:

- dX = 0.000 m
- dY = 0.000 m
- dZ = +4.5 m
- R<sub>X</sub> = 0.000 sec
- R<sub>Y</sub> = 0.000 sec
- R<sub>Z</sub> = +0.554 sec = 0.000002685868 radians
- dS = +0.219 ppm

Input point coordinate system: WGS 72 (Cartesian geocentric coordinates):

- X<sub>S</sub> = 3 657 660.66 m
- Y<sub>S</sub> = 255 768.55 m

$$Z_S = 5\,201\,382.11 \text{ m}$$

Application of the 7 parameter Position Vector Transformation results in:

$$X_T = 3\,657\,660.78 \text{ m}$$

$$Y_T = 255\,778.43 \text{ m}$$

$$Z_T = 5\,201\,387.75 \text{ m}$$

on the WGS 84 geocentric coordinate reference system.

### Reversibility

The Helmert 7-parameter transformations is an approximation formula that is valid only when the transformation parameters are small compared to the magnitude of the geocentric coordinates. Under this condition the transformation is considered to be reversible for practical purposes.

#### 2.4.3.2.2 Coordinate Frame Rotation

(EPSG coordinate operation method code 9607)

Although being common practice particularly in the European E&P industry, the Position Vector Transformation sign convention is not universally accepted. A variation on this formula is also used, particularly in the USA E&P industry. That formula is based on the same definition of translation and scale parameters, but a different definition of the rotation parameters. The associated convention is known as the "Coordinate Frame Rotation" convention.

The formula is:

$$\begin{pmatrix} X_T \\ Y_T \\ Z_T \end{pmatrix} = M * \begin{pmatrix} 1 & +R_Z & -R_Y \\ -R_Z & 1 & +R_X \\ +R_Y & -R_X & 1 \end{pmatrix} * \begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} + \begin{pmatrix} dX \\ dY \\ dZ \end{pmatrix}$$

and the parameters are defined as:

(dX, dY, dZ) : Translation vector, to be added to the point's position vector in the source coordinate reference system in order to transform from source coordinate reference system to target coordinate reference system; also: the coordinates of the origin of source coordinate reference system in the target frame.

(R<sub>X</sub>, R<sub>Y</sub>, R<sub>Z</sub>) : Rotations to be applied to the coordinate reference frame. The sign convention is such that a positive rotation of the frame about an axis is defined as a clockwise rotation of the coordinate reference frame when viewed from the origin of the Cartesian coordinate reference system in the positive direction of that axis, that is a positive rotation about the Z-axis only from source coordinate reference system to target coordinate reference system will result in a smaller longitude value for the point in the target coordinate reference system. Although rotation angles may be quoted in any angular unit of measure, the formula as given here requires the angles to be provided in radians.

M : The scale factor to be applied to the position vector in the source coordinate reference system in order to obtain the correct scale of the target coordinate reference system.  $M = (1+dS*10^{-6})$ , where dS is the scale correction expressed in parts per million.

In the absence of rotations the two formulas are identical; the difference is solely in the rotations. The name of the second method reflects this.

Note that the same rotation that is defined as positive in the Position Vector method is consequently negative in the Coordinate Frame method and vice versa. It is therefore crucial that the convention underlying the definition of the rotation parameters is clearly understood and is communicated when exchanging transformation parameter values, so that the parameter values may be associated with the correct coordinate transformation method (algorithm).

The same example as for the Position Vector Transformation can be calculated, however the following transformation parameters have to be applied to achieve the same input and output in terms of coordinate values:

Transformation parameters Coordinate Frame Rotation convention:

$$\begin{aligned}
 dX &= 0.000 \text{ m} \\
 dY &= 0.000 \text{ m} \\
 dZ &= +4.5 \text{ m} \\
 R_X &= -0.000 \text{ sec} \\
 R_Y &= -0.000 \text{ sec} \\
 R_Z &= -0.554 \text{ sec} = -0.000002685868 \text{ radians} \\
 dS &= +0.219 \text{ ppm}
 \end{aligned}$$

Please note that only the rotation has changed sign as compared to the Position Vector Transformation. The Position Vector convention is used by IAG and recommended by ISO 19111.

The comments on reversibility of the Position Vector method apply equally to the Coordinate Frame method.

### 2.4.3.3 Molodensky-Badekas 10-parameter transformation

(EPSG coordinate operation method code 9636)

To eliminate high correlation between the translations and rotations in the derivation of parameter values for the Helmert transformation methods discussed in the previous section, instead of the rotations being derived about the geocentric coordinate reference system origin they may be derived at a location within the points used in the determination. Three additional parameters, the coordinates of the rotation point, are then required. The formula is:

$$\begin{pmatrix} X_T \\ Y_T \\ Z_T \end{pmatrix} = M * \begin{pmatrix} 1 & +R_Z & -R_Y \\ -R_Z & 1 & +R_X \\ +R_Y & -R_X & 1 \end{pmatrix} * \begin{pmatrix} X_S - X_P \\ Y_S - Y_P \\ Z_S - Z_P \end{pmatrix} + \begin{pmatrix} X_P \\ Y_P \\ Z_P \end{pmatrix} + \begin{pmatrix} dX \\ dY \\ dZ \end{pmatrix}$$

and the parameters are defined as:

(dX, dY, dZ) : Translation vector, to be added to the point's position vector in the source coordinate system in order to transform from source coordinate reference system to target coordinate reference system; also: the coordinates of the origin of source coordinate reference system in the target frame.

(R<sub>X</sub>, R<sub>Y</sub>, R<sub>Z</sub>) : Rotations to be applied to the coordinate reference frame. The sign convention is such that a positive rotation of the frame about an axis is defined as a clockwise rotation of the coordinate reference frame when viewed from the origin of the Cartesian coordinate system in the positive direction of that axis, that is a positive rotation about the Z-axis only from source coordinate reference system to target coordinate reference system will result in a smaller longitude value for the point in the target coordinate reference system. Although rotation angles may be quoted in any angular unit of measure, the formula as given here requires the angles to be provided in radians.

(X<sub>P</sub>, Y<sub>P</sub>, Z<sub>P</sub>) : Coordinates of the point about which the coordinate reference frame is rotated, given in the source Cartesian coordinate reference system.

M : The scale factor to be applied to the position vector in the source coordinate reference system in order to obtain the correct scale of the target coordinate reference system.  $M = (1+dS*10^{-6})$ , where dS is the scale correction expressed in parts per million.

The [Helmert 7-parameter] Coordinate Frame Rotation method discussed in the previous section is a specific case of the Molodensky-Badekas 10-parameter transformation in which the evaluation point is the origin of the geocentric coordinate system, at which geocentric coordinate values are zero.

See section 2.4.4.1 below for an example.

**Reversibility**

The Molodensky-Badekas 10-parameter transformation strictly speaking is not reversible, i.e. in principle the same parameter values cannot be used to execute the reverse transformation. This is because the evaluation point coordinates are in the forward direction source coordinate reference system and the rotations have been derived about this point. They should not be applied about the point having the same coordinate values in the target coordinate reference system, as is required for the reverse transformation. However, in practical application there are exceptions when applied to the approximation of small differences between the geometry of a set of points in two different coordinate reference systems. The typical vector difference in coordinate values is in the order of  $6 \cdot 10^1$  to  $6 \cdot 10^2$  metres, whereas the evaluation point on or near the surface of the earth is  $6.3 \cdot 10^6$  metres from the origin of the coordinate systems at the Earth’s centre. This difference of four or five orders of magnitude allows the transformation in practice to be considered reversible. Note that in the reverse transformation, only the signs of the translations and rotation parameter values are reversed; the coordinates of the evaluation point remain unchanged.

**2.4.4 Transformations between Geographic Coordinate Reference Systems**

**2.4.4.1 Transformations using geocentric methods**

Transformation of coordinates from one geographic coordinate reference system into another is often carried out as a concatenation of three operations:

geographical (3D) to geocentric + geocentric to geocentric + geocentric to geographic (3D)

The middle step of the concatenated transformation, from geocentric to geocentric, may be through any of the methods described in section 2.4.3 above: geocentric translations, 7-parameter Helmert transformation or 10-parameter Molodensky-Badekas transformation. The first and last steps of the concatenated transformation (geographic 3D to/from geocentric) are described in section 2.2.1 above.

If involving geographic 2D coordinates, the techniques described in section 2.2.2 above (geographic 3D to/from 2D) may also be used as additional steps at each end of the concatenation.

**Example**

Transformation from La Canoa to REGVEN (EPSG transformation code 1771). The 10 Molodensky-Badekas transformation parameter values are:

dX	=	-270.933 m	
dY	=	+115.599 m	
dZ	=	-360.226 m	
R <sub>X</sub>	=	-5.266 sec	= -0.000025530288 radians
R <sub>Y</sub>	=	-1.238 sec	= -0.000006001993 radians
R <sub>Z</sub>	=	+2.381 sec	= +0.000011543414 radians
dS	=	-5.109 ppm	
Ordinate 1 of evaluation point	=	2464351.59 m	
Ordinate 2 of evaluation point	=	-5783466.61 m	
Ordinate 3 of evaluation point	=	974809.81 m	

Input point coordinate system: La Canoa (geographic 2D)

Latitude  $\phi_s$  = 9°35'00.386"N

$$\text{Longitude } \lambda_S = 66^{\circ}04'54.705''\text{W}$$

Using the technique described in section 2.2.2 above, this is taken to be geographic 3D with an assumed ellipsoidal height  $h_S = 201.46$  m

Using the geographic (3D) to geocentric conversion method given in section 2.2.1, these three coordinates convert to Cartesian geocentric coordinates:

$$\begin{aligned} X_S &= 2\,550\,408.965 \text{ m} \\ Y_S &= -5\,749\,912.266 \text{ m} \\ Z_S &= 1\,054\,891.114 \text{ m} \end{aligned}$$

Application of the 10 parameter Molodensky-Badekas Transformation (section 2.4.3.3) results in:

$$\begin{aligned} X_T &= 2\,550\,138.467 \text{ m} \\ Y_T &= -5\,749\,799.862 \text{ m} \\ Z_T &= 1\,054\,530.826 \text{ m} \end{aligned}$$

on the REGVEN geocentric coordinate reference system (CRS code 4962)

Using the reverse formulas for the geographic/geocentric conversion method given in section 2.2.1 on the REGVEN geographic 3D coordinate reference system (CRS code 4963) this converts into:

$$\begin{aligned} \text{Latitude } \varphi_T &= 9^{\circ}34'49.001''\text{N} \\ \text{Longitude } \lambda_T &= 66^{\circ}04'54.705''\text{W} \\ \text{Ellipsoidal height } h_T &= 180.51 \text{ m} \end{aligned}$$

Because the source coordinates were 2D, the target system ellipsoidal height is ignored (see section 2.2.2 above) and the results treated as a geographic 2D coordinate reference system (CRS code 4189):

$$\begin{aligned} \text{Latitude } \varphi_T &= 9^{\circ}34'49.001''\text{N} \\ \text{Longitude } \lambda_T &= 66^{\circ}04'54.705''\text{W} \end{aligned}$$

#### 2.4.4.1.1 France geocentric interpolation (EPSG coordinate operation method code 9655)

In France the national mapping agency (IGN) have promulgated a transformation between the classical geographic 2D coordinate reference system NTF and the modern 3-dimensional system RGF93 which uses geocentric translations interpolated from a grid file. The method is described in IGN document NTG-88. In summary:

- The grid file nodes are given in RGF93 geographic 2D coordinates.
- Within the grid file the sense of the parameter values is *from* NTF *to* RGF93.

For NTF to RGF93 transformations an iteration to obtain coordinates in the appropriate system for interpolation within the grid is required. The steps are:

- Convert NTF geographic 2D coordinates to geographic 3D by assuming a height and then to NTF geocentric coordinates.
- Transform NTF geocentric coordinates to approximate RGF93 coordinates using an average value for all France (EPSG coordinate operation code 1651):

$$\begin{aligned} X_{NTF} &= X_{RGF93} - 168 \text{ m} \\ Y_{NTF} &= Y_{RGF93} - 60 \text{ m} \\ Z_{NTF} &= Z_{RGF93} + 320 \text{ m} \end{aligned}$$

- Convert the approximate RGF93 geocentric coordinates to approximate RGF93 geographic coordinates.
- Using the approximate RGF93 geographic coordinates, interpolate within the grid file to obtain the three geocentric translations (dX, dY, dZ) applicable at the point.
- Apply these geocentric translations to the NTF geocentric coordinates to obtain RGF93 geocentric coordinates:

- Transform RGF93 geocentric coordinates to NTF geocentric coordinates, taking account of the sense of the parameter values.

$$\begin{aligned} X_{\text{RGF93}} &= X_{\text{NTF}} + dX \\ Y_{\text{RGF93}} &= Y_{\text{NTF}} + dY \\ Z_{\text{RGF93}} &= Z_{\text{NTF}} + dZ \end{aligned}$$

- Convert RGF93 geocentric coordinates to RGF93 geographic 3D coordinates. Because the original input NTF coordinates were geographic 2D, the RGF93 ellipsoidal height is meaningless so it is dropped to give RGF93 geographic 3D coordinates.

For RGF93 to NTF transformations the steps are:

- Using the RGF93 geographic coordinates, interpolate within the grid file to obtain the three geocentric translations (dX, dY, dZ) applicable at the point.
- Convert RGF93 geographic coordinates to RGF93 geocentric coordinates.
- Transform RGF93 geocentric coordinates to NTF geocentric coordinates, taking into account the sense of the parameter values:

$$\begin{aligned} X_{\text{NTF}} &= X_{\text{RGF93}} + (-dX) \\ Y_{\text{NTF}} &= Y_{\text{RGF93}} + (-dY) \\ Z_{\text{NTF}} &= Z_{\text{RGF93}} + (-dZ) \end{aligned}$$

- Convert NTF geocentric coordinates to geographic 3D coordinates.
- Drop the ellipsoid height to give NTF geographic 2D coordinates.

#### 2.4.4.2 Abridged Molodensky transformation

(EPSG coordinate operation method code 9605)

As an alternative to the computation of the new latitude, longitude and ellipsoid height by concatenation of three operations (geographical to geocentric + geocentric to geocentric + geocentric to geographic), the changes in these coordinates may be derived directly as geographical coordinate offsets through formulas derived by Molodensky (EPSG coordinate operation method code 9604, not detailed in this Guidance Note). Abridged versions of these formulas, which are equivalent to three-parameter geocentric transformations, are as follows:

$$\begin{aligned} \varphi_t &= \varphi_s + d\varphi \\ \lambda_t &= \lambda_s + d\lambda \\ h_t &= h_s + dh \end{aligned}$$

where

$$\begin{aligned} d\varphi &= (-dX \cdot \sin\varphi \cdot \cos\lambda - dY \cdot \sin\varphi \cdot \sin\lambda + dZ \cdot \cos\varphi + [a \cdot df + f \cdot da] \cdot \sin 2\varphi) / (\rho \cdot \sin 1'') \\ d\lambda &= (-dX \cdot \sin\lambda + dY \cdot \cos\lambda) / (v \cdot \cos\varphi \cdot \sin 1'') \\ dh &= dX \cdot \cos\varphi \cdot \cos\lambda + dY \cdot \cos\varphi \cdot \sin\lambda + dZ \cdot \sin\varphi + (a \cdot df + f \cdot da) \cdot \sin^2\varphi - da \end{aligned}$$

and where the dX, dY and dZ terms are as before, ρ and v are the meridian and prime vertical radii of curvature at the given latitude φ on the first ellipsoid (see table 2 in section 1.3 above), da is the difference in the semi-major axes of the target and source ellipsoids [da = a<sub>t</sub> - a<sub>s</sub>] and df is the difference in the flattening of the two ellipsoids [df = f<sub>t</sub> - f<sub>s</sub> = 1/(1/f<sub>t</sub>) - 1/(1/f<sub>s</sub>)].

The formulas for dφ and dλ indicate changes in φ and λ in arc-seconds.

#### **Example:**

For a North Sea point with coordinates derived by GPS satellite in the WGS84 geographical coordinate reference system, with coordinates of:

$$\begin{aligned} \text{latitude } \varphi_s &= 53^\circ 48' 33.82'' \text{N}, \\ \text{longitude } \lambda_s &= 2^\circ 07' 46.38'' \text{E}, \\ \text{and ellipsoidal height } h_s &= 73.0 \text{m}, \end{aligned}$$

whose coordinates are required in terms of the ED50 geographical coordinate reference system which takes the International 1924 ellipsoid.

The three geocentric translations parameter values *from* WGS84 *to* ED50 for this North Sea area are given as  $dX = +84.87\text{m}$ ,  $dY = +96.49\text{m}$ ,  $dZ = +116.95\text{m}$ .

Ellipsoid Parameters are:

WGS 1984	$a = 6378137.0$ metres	$1/f = 298.2572236$
International 1924	$a = 6378388.0$ metres	$1/f = 297.0$

Then

$$da = 6378137 - 6378388 = -251$$

$$df = 0.003352811 - 0.003367003 = -1.41927\text{E-}05$$

whence

$$d\phi = 2.545''$$

$$d\lambda = 5.097''$$

$$dh = -44.98 \text{ m}$$

ED50 values on the International 1924 ellipsoid are then:

latitude $\phi_t$	=	$53^\circ 48' 36.565''\text{N}$
longitude $\lambda_t$	=	$2^\circ 07' 51.477''\text{E}$
and ellipsoidal height $h_t$	=	$28.02 \text{ m}$

Because ED50 is a geographical 2D coordinate reference system the height is dropped to give:

latitude $\phi_t$	=	$53^\circ 48' 36.565''\text{N}$
longitude $\lambda_t$	=	$2^\circ 07' 51.477''\text{E}$

#### 2.4.4.3 Geographic Offsets

This is the simplest of transformations between two geographic coordinate reference systems, but is normally used only for purposes where low accuracy can be tolerated. It is generally used for transformations in two dimensions, latitude and longitude, where:

$$\phi_t = \phi_s + d\phi$$

$$\lambda_t = \lambda_s + d\lambda$$

(EPSG coordinate operation method code 9619).

In very rare circumstances, a transformation in three dimensions additionally including ellipsoidal height may be encountered:

$$\phi_t = \phi_s + d\phi$$

$$\lambda_t = \lambda_s + d\lambda$$

$$h_t = h_s + dh$$

(EPSG coordinate operation method code 9660)

This should not be confused with the Geographic2D with Height Offsets method used in Japan, where the height difference is between the ellipsoidal height component of a 3D geographic coordinate reference system and a gravity-related height system. This is discussed in section 2.4.5 below.

#### **Example:**

A position with coordinates of  $38^\circ 08' 36.565''\text{N}$ ,  $23^\circ 48' 16.235''\text{E}$  referenced to the old Greek geographic 2D coordinate reference system (EPSG CRS code 4120) is to be transformed to the newer GGRS87 system (EPSG CRS code 4121). Transformation parameters from Greek to GGRS87 are:

$$d\phi = -5.86''$$

$$d\lambda = +0.28''$$

Then	$\phi_{\text{GGRS87}}$	=	$38^\circ 08' 36.565''\text{N}$	+	$(-5.86'')$	=	$38^\circ 08' 30.705''\text{N}$
and	$\lambda_{\text{GGRS87}}$	=	$23^\circ 48' 16.235''\text{E}$	+	$0.28''$	=	$23^\circ 48' 16.515''\text{E}$

For the reverse transformation for the same point,

$$\begin{aligned} \varphi_{\text{GREEK}} &= 38^{\circ}08'30.705''\text{N} + 5.86'' = 38^{\circ}08'36.565''\text{N} \\ \lambda_{\text{GREEK}} &= 23^{\circ}48'16.515''\text{E} + (-0.28'') = 23^{\circ}48'16.235''\text{E} \end{aligned}$$

#### 2.4.4.4 Geographic Offset by Interpolation of Gridded Data

The relationship between some geographical 2D coordinate reference systems is available through gridded data sets of latitude and longitude offsets. This family of methods includes:

*NADCON* (EPSG coordinate operation method code 9613) which is used by the US National Geodetic Survey for transformation between US systems,

*NTv2* (code 9615) which originated in the national mapping agency of Canada and was subsequently adopted in Australia and New Zealand, and

*OSTN* (code 9633) used in Great Britain.

The offsets at a point are interpolated within the gridded data. In some methods, separate grid files are given for latitude and longitude offsets whilst in other methods the offsets for both latitude and longitude are given within a single grid file. EPSG differentiates methods by the format of the gridded data file(s). The grid file format is given in documentation available from the information source. Although the authors of some data sets suggest a particular interpolation method within the grid(s), generally the density of grid nodes should be such that any reasonable grid interpolation method will give the same offset value. Bi-linear interpolation is the most usual grid interpolation mechanism.

The coordinate reference system for the coordinates of the grid nodes will be given either in the file itself or in accompanying documentation. This will normally be the source coordinate reference system for the forward transformation. Then in forward transformations the interpolation is straightforward. But for the reverse transformation the first grid interpolation entry will be the value of the point in the second coordinate reference system, the offsets are interpolated and applied, and the result used in a further iteration of interpolation and application of offset.

### 2.4.5 Geoid Models

#### 2.4.5.1 Geographic3D to GravityRelatedHeight

Although superficially involving a change of dimension from three to one, this transformation method is actually one-dimensional. The transformation applies an offset to the ellipsoidal height component of a geographic 3D coordinate reference system with the result being a gravity-related height in a vertical coordinate reference system. However the ellipsoidal height component of a geographic 3D coordinate reference system cannot exist without the horizontal components, i.e. it cannot exist as a one-dimensional coordinate reference system.

If  $h$  is the ellipsoidal height (height of point above the ellipsoid, positive if up) in the geographic 3D CRS,  $H$  is the gravity-related height in a vertical CRS and  $\zeta$  is the correction from ellipsoidal height to gravity-related height<sup>4</sup>, then

$$H = h + \zeta$$

The offset value is interpolated from a grid of height differences and the interpolation requires the latitude and longitude components of the geographic 3D coordinate reference system as arguments.

EPSG differentiates between the formats of the gridded height files and distinguishes separate coordinate

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<sup>4</sup> Geodetic science recognises several types of gravity-related height. A discussion of these types is beyond the scope of this document. In this document the symbol  $\zeta$  is used to indicate the correction to be applied. In some contexts the correction may be called “quasi-geoid height”. In other contexts the symbol  $N$  may be encountered and the term “geoid height” used.

operation methods for each file format. The coordinate operation method may also define the interpolation technique to be used. However the density of grid nodes is usually sufficient for any reasonable interpolation technique to be used, with bi-linear interpolation usually being applied.

**Reversibility**

The reverse transformation, from gravity-related height in the vertical coordinate reference system to the ellipsoidal height component of the geographic3D coordinate reference system, requires that a horizontal position be associated with the gravity-related height. This is indeterminate unless a compound coordinate reference system is involved (see the Geographic3D to Geographic2D+GravityRelatedHeight method described below). Geographic3D to GravityRelatedHeight methods therefore are not reversible.

**2.4.5.2 Geographic3D to Geographic2D+GravityRelatedHeight**

This method transforms coordinates between a geographic 3D coordinate reference system and a compound coordinate reference system consisting of separate geographic 2D and vertical coordinate reference systems. Separate operations are made between the horizontal and vertical components. In its simplest form it combines a Geographic 3D to 2D conversion and a Geographic3D to GravityRelatedHeight transformation (see sections 2.2.2 and 2.4.5.1 above). However, complexities arise (a) for the forward transformation if the source 3D and target 2D geographic coordinate reference systems are based on different geodetic datums, or (b) in the reverse transformation of height from compound to geographic 3D.

**Horizontal component**

If the horizontal component of the compound coordinate reference system and the geographic 3D coordinate reference system are based on the same geodetic datum, this operation is simply the Geographic 3D to 2D conversion described in section 2.2.2 above except that for the reverse case (2D to 3D) no assumption is required for the ellipsoidal height as it will come from the operation for the vertical part.

If the horizontal component of the compound coordinate reference system and the geographic 3D coordinate reference system are based on different geodetic datums then any of the geographic to geographic transformations discussed in section 2.4.4 above, including those using geocentric methods (sections 2.4.3 and 2.4.4.1), may be used.

**Vertical component**

The forward transformation from geographic 3D to vertical component of the compound system uses the Geographic3D to GravityRelatedHeight method described in section 2.4.5.1 above. Then:

$$H = h + \zeta$$

where, as before, **h** is the ellipsoidal height (height of point above the ellipsoid, positive if up) in the geographic 3D CRS, **H** is the gravity-related height in the vertical CRS part of the compound CRS and **ζ** is the correction from ellipsoidal height to gravity-related height from the gridded data.

The reverse transformation, from to vertical component of the compound system to geographic 3D system, requires interpolation within the grid of height differences (“geoid model”). However the latitude and longitude arguments for this interpolation must be in the geographic 3D coordinate reference system, as the nodes for the gridded data will be in this system. Therefore the reverse operation on the horizontal component of the compound system must be executed before the reverse vertical transformation can be made. Then:

$$h = H - \zeta$$

**2.4.5.3 Geographic2D with Height Offsets**

(EPSG coordinate operation method code 9618)

This method used in Japan is a simplified form of the general Geographic3D to Geographic2D+GravityRelatedHeight method described above. It combines the geographical 2D offset method described in section 2.4.4.3 above with an ellipsoidal height to gravity-related height value  $\zeta$  applied as an offset.

$$\begin{aligned}\varphi_{\text{WGS84}} &= \varphi_{\text{Tokyo}} + d\varphi \\ \lambda_{\text{WGS84}} &= \lambda_{\text{Tokyo}} + d\lambda \\ h_{\text{WGS84}} &= H_{\text{JSLD}} + \zeta\end{aligned}$$

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