Chapter 6 Survey Datums

6-01 General

Today's multiorganizational Project Development efforts require the use of common, accurate horizontal and vertical survey datums and consistent, precise control-survey procedures to ensure the accurate location of fixed works and rights of way. The expanding use of Geographic Information Systems (GIS) by WSDOT and other agencies compounds these requirements. Universally accepted and used, common survey datums are essential for the efficient sharing of both engineering and GIS data with WSDOT partners in developing and operating a multimodal transportation system.

6-02 Horizontal Datum

6-02.1 Policy

All engineering work (mapping, planning, design, right of way engineering, and construction) for each specific WSDOT-involved transportation improvement project is based on a common horizontal datum.

By state law, (WAC 332-130 and RCW 58.20.180) the horizontal datum for all mapping, planning, design, right of way engineering, and construction on WSDOT-involved transportation improvement projects, including special funded State highway projects, is the North American Datum of 1983 (1991), [NAD83 (1991)], as defined by the National Geodetic Survey (NGS). The physical (on-the-ground survey station) reference network for the NAD83 (1991) datum for all WSDOT-involved transportation improvement projects is the Washington High Accuracy Reference Network (WA-HARN).

As resources are available, WSDOT will, in cooperation with NGS and others, monitor and maintain the integrity of the WA-HARN:

- The GeoServices Branch will coordinate WSDOT involvement in replacement of destroyed and disturbed HARN monuments, NGS Benchmarks (first and second order) and resurveys of the network in areas of significant seismic events.
- The regions are to report disturbed or destroyed HARN monuments to the GeoServices Branch. In addition, the regions attempt to visit each HARN station once a year and transmit to the GeoServices Branch a report that describes the station, its status, and any changes in the "to reach" description. Changes in the "to reach" description are to be submitted in a format acceptable to NGS (currently, Windows version of DDPROC). The GeoServices Branch will consolidate the data and forward it to NGS. Alternatively, NGS notification of changes to marks may be done interactively on the web at: http://www.ngs.noaa.gov/datasheet.html.

As resources permit, the WA-HARN and the WSDOT Primary Reference Network (PRN) are to be densified within the corridor areas of planned WSDOT involved transportation projects prior to, or during, the project studies (planning) phase to provide consistent, convenient geodetic reference monuments for all subsequent project-related surveys. The densification surveys are performed in accordance with the policies, standards, and procedures described in Chapter 13, "Control Survey Procedures."

6-02.2 Description of NAD83 (1991)

The reference surface used for the North American Datum of 1983 (NAD83) is an ellipsoid named the Geodetic Reference System of 1980 (GRS80). GRS80, is a world-wide model that has replaced the previously-used Clarke's spheroid of 1866. Clarke's Spheroid, the reference figure for NAD27, was a best-fitting model for North America, but did not meet the needs of world-wide geodetic systems or the Global Positioning System (GPS).

NAD83 was established by first performing a least squares adjustment of Doppler observations used to establish the NAD27 network and then redefining the mathematical reference surface from Clarke's Spheroid to the GRS80. NAD83 has geodetic coordinates that measure 230 to 330 feet (70 to 100 meters) different from those of NAD27.

The geodetic coordinate system for NAD 83 is based on longitude defined as angular distance East or West of the prime meridian, which runs through the observatory at Greenwich, England, and latitude defined as the angular distance north of the Equator.

The initial NGS station coordinates based on NAD83 were the result of a simultaneous nationwide adjustment of the original observation that incrementally built up the NAD27 network. The adjustment results were published in 1986 as the NAD83/86 datum. Subsequently, in 1991, the WA-HARN was established using GPS technology. The GPS survey was more precise than the methods used to establish the NAD83 reference system in 1986. Consequently, coordinates for stations determined with reference to the WA-HARN are more accurate and might differ from those referenced to the original NAD83 positions as much as one meter. The adjusted network is NAD83 (1991).

6-02.3 Datum Conversions

There is no direct mathematical method to accurately transform coordinates from one system to the other. Data conversion programs such as NADCON, developed by NGS, and Corpscon for Windows, developed by the Army Corps of Engineers, are only approximations that are not accurate enough for boundary or engineering surveys. With a general accuracy of 0.5 foot (0.15 m) these programs are satisfactory for some map conversions.

6-03 Vertical Datum

6-03.1 Policy

The vertical datum for all mapping, planning, design, right of way engineering, and construction on WSDOT-involved transportation improvement projects, including special-funded state highway projects, is the North American Vertical Datum of 1988 (NAVD88), as defined by the National Geodetic Survey (NGS). Exceptions to this policy, as determined by the Regional Cadastral Engineer or equivalent in consultation with the Project Manager, are permitted for:

- Projects that are small, remote, and isolated.
- Maintenance, traffic safety, and rehabilitation projects that are controlled by existing fixed works.
- Projects for which it is not cost effective to establish NAVD88 vertical control.
- Expedited projects for which it is not feasible to establish NAVD88 vertical control.
- Projects contiguous to the National Geodetic Vertical Datum of 1929 (NGVD29) projects and uniformity is desirable.

Generally, the only acceptable alternate datum is NGVD29. For project locations where published NAVD88 data is not locally available, GPS survey methods using GEOID99 or future geoid models of improved resolution may be considered. The standard deviation for results obtained from GEOID99 over a distance of 62 miles (100 km) of 0.33 feet (0.1 m) can be achieved with the right procedures, equipment, and guidelines.

Assumed datums are only considered as a last resort.

All engineering work (mapping, planning, design, right of way engineering, and construction) for each WSDOT-involved transportation improvement project must be based on common vertical datum.

6-03.2 Description of NAVD88

In 1978, NGS began a program to combine leveling surveys into a single least squares adjustment to provide improved heights for over 700,000 vertical control points throughout the United States. This adjustment was completed in June 1991 and has been designated the North American Vertical Datum of 1988 (NAVD88).

6-03.3 GPS Determined Heights

GPS survey methods, besides enabling the horizontal positioning of survey points to a high degree of accuracy, also provide accurate ellipsoidal height information. Whereas, all geodetic leveling is relative to a height or elevation (orthometric height) above the geoid, GPS heights are determined in relation to the GRS80 ellipsoid.

The sea-level surface of the Earth is called the geoid and is defined as the surface that is perpendicular to the direction of gravity at all points. The geoid is not a mathematically definable geometric shape. It is irregular because the direction of gravity varies from point to point as the result of the irregular distribution of mass within the Earth. Because of its irregular undulating nonmathematical shape, the geoid cannot be used for calculations of the relative horizontal positions of points on the Earth's surface.

The difference between the geoid (an undulating irregular surface defined by variations in the Earth's gravity field) and the ellipsoid (a mathematical surface) is referred to as geoid height. The geoid height is the separation between the ellipsoid and the geoid with the surface represented as mean sea level. This number is negative in Washington State ranging in values from -17 m to –23 m. Negative geoid heights indicate the geoid is below the ellipsoid as shown in Figure 6-1.

An exception to the visual diagram in figure 6-1, would be in an area where the ellipsoid is negative indicating that the ellipsoidal model is actually above the ground instead of below it. This occurs in a few locations within Washington State.

Geoid99, a model of geoid heights, is now available from NGS and is being used extensively in GPS data reduction to obtain elevations.

The relationship between the geoid, GRS80, and the Earth's surface is shown in Figure 6-1 and is given by Equation 6-1.

Equation 6-1:

$$h = N + H$$

where:

h = ellipsoidal height

N = geoid height

H = orthometric height (elevation)

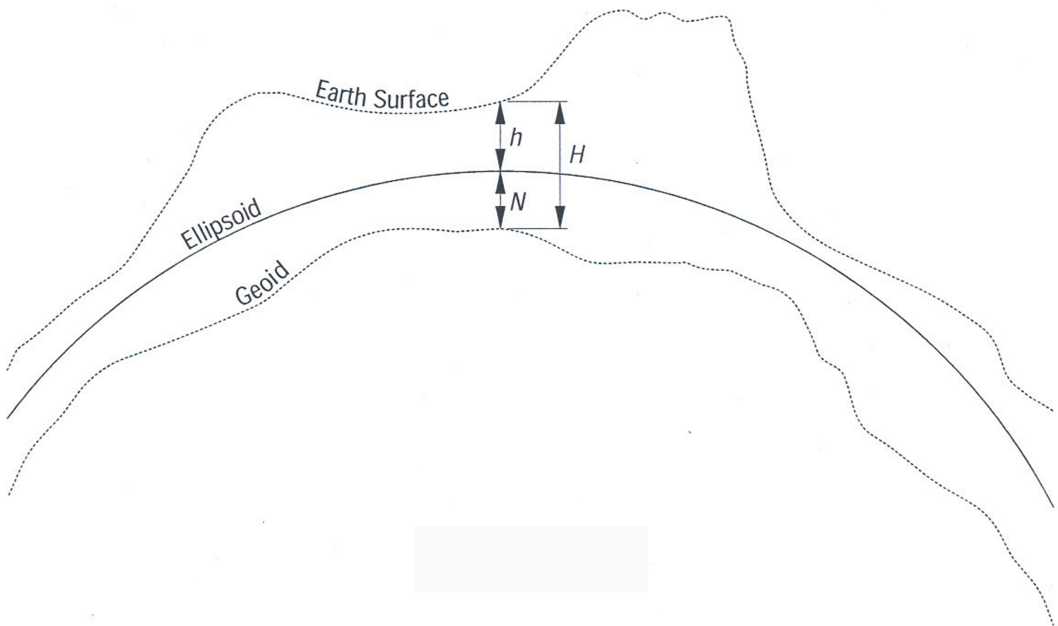


Figure 6-1

6-03.4 Datum Conversions

NGS, and other public agencies that maintain bench marks, periodically readjust level networks as new field data is obtained. Always use elevations from the most recent adjustment. When using the published elevations and benchmarks of other agencies, it is important to convert them to the datum selected for the WSDOT project. Example: Published monument data will show Geoid99 adjusted coordinates. It is incorrect to use one monument to set up a total station on, using Geoid99 data and another monument, such as in a back-sight point using Geoid96 data. The datum must be the same on both points.

Because NAVD88 is an independent readjustment and redefinition of NGVD29 there is not a precise mathematical method to convert exactly between the two datums. If using a conversion program like NGS's VERTCON or the US Army Corps of Engineers' Corpscon for Windows to convert NGVD29 elevations to NAVD88, be sure to verify that the results will meet the accuracy requirements of the work to be performed. Generally, accuracies when using VERTCON and Corpscon are within 0.25 m. Both programs require the input of the benchmark location expressed as Latitude and Longitude in NAD83 (1991).

6-04 The Washington Coordinate System of 1983 (WCS83)

6-04.1 Policy

WAC 332-130 and RCW 58.20.180 requires that all new surveys and new mapping projects, which record State Plane Coordinates, must use the Washington Coordinate System of 1983 (WCS83).

WCS83 is the coordinate system used for all mapping, planning, design, right of way engineering, and construction on WSDOT involved transportation improvement projects, including special-funded State highway projects. The physical (on-the-ground) reference network for WCS83 is the WA-HARN.

Coordinates shown on maps, plans, and other related documents are WCS83 coordinates. The reference network for WCS83 coordinates are the WA-HARN.

When a map, set of plans, or other document uses State Plane Coordinates, place a note on the document to show the basis of the coordinates used including the WCS zone and the physical reference network.

6-04.2 Description of WCS83

Because of the complexity of performing the calculations for geodetic surveying and the limited extent of most surveying projects, most surveyors generally use plane surveying methods. For local projects, plane surveying yields accurate results, but for large systems (like the WSDOT transportation system) local plane surveying systems are not adequate. Not only are local plane coordinate systems inaccurate over large areas, but they cannot be easily related to other local systems.

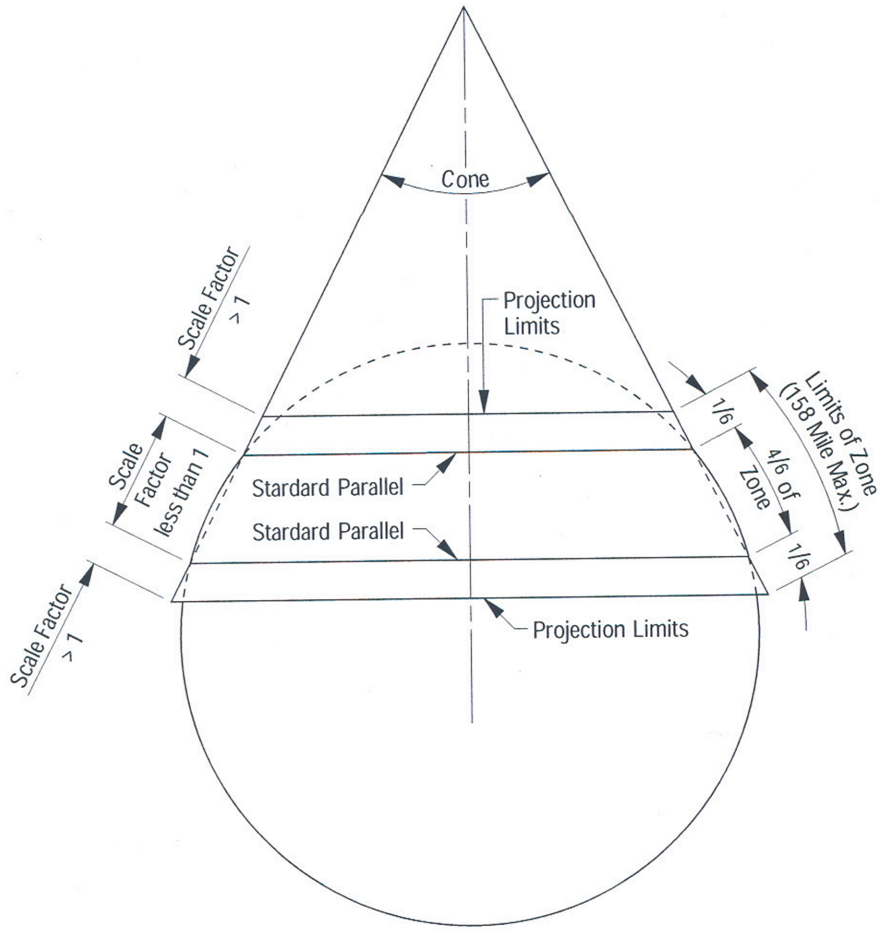
In response to the needs of local surveyors for an accurate plane surveying datum that is useful over relatively large areas, the U. S. Coast and Geodetic Survey (the predecessor of NGS) developed the State Plane Coordinate Systems. The first system for Washington State, WCS of 1927, was based on the NAD27 datum. Coordinates, in feet, were given as X (easting) followed by Y (northing) and bearings were reckoned from the south. WCS83 was established July 1, 1990, with coordinates, in meters, given as N (northing) followed by E (easting), and with bearings reckoned from north.

RCW 58.20.190 “Conversion of coordinates – Metric” *Any conversion of coordinates between the meter and the United States survey foot shall be based upon the length of one meter being equal to exactly 39.37 inches.*

The State Plane Coordinate System was established to provide a means for transferring the geodetic positions of monumented points to plane coordinates that would permit the use of these monuments in plane surveying over relatively large areas without introducing significant error.

A plane-rectangular coordinate system is by definition a flat surface. Geodetic positions on the curved surface of the Earth must be “projected” to their corresponding plane coordinate positions. Projecting the curved surface onto a plane requires some form of deformation. Imagine the stretching and tearing necessary to flatten a piece of orange peel. The orange peel cannot be flattened without deformation of the surface. Similarly, the surface of the earth cannot be represented on a flat plane surface without distortion. A long narrow strip of an orange peel can be flattened with a minimum of distortion. If coordinate systems are limited to long narrow strips a minimum of mapping error results. In Washington the Lambert Conformal map projection is used to transform the geodetic positions of latitude and longitude into the “N” (Northing) and “E” (Easting) coordinates of the WCS83.

The Lambert Conformal projection can be illustrated by a cone that intersects the GRS80 ellipsoid along two parallels of latitude as shown in Figure 6-2. These latitudes are known as the standard parallels for the projection. Distances lying along the standard parallels are the same on both the GRS80 ellipsoid and the cone. Between the standard parallels, distances projected from the ellipsoid to the conic surface become smaller. Outside the standard parallels, distances projected from the ellipsoid to the conic surface become larger. Scale factors are used to reduce and increase distances when converting between the WCS surface and the ellipsoid surface. The scale factor is exactly one on the standard parallels, greater than one outside them and less than one between them.



Cone
Projection Limits
Scale Factor > 1
Scale Factor less than 1
Stardard Parallel
Stardard Parallel
Scale Factor > 1
Projection Limits
1/6
4/6 of Zone
1/6
Limits of Zone (158 Mile Max.)

Figure 6-2

The limits of each Lambert projection are generally chosen so that scale factors will be less than 1.00010 and greater than 0.99990 so that, even if scale factors are disregarded, discrepancies between ground measurements at sea level and distances on the WCS grid will be within 1:10,000. Maintaining the 1:10,000 constraint requires two zones in Washington. The zones have been created so that zone boundaries run along County lines, with the exception of Grant County where the line between the "north zone" and the "south zone" lies along the parallel 47°30' north latitude. See Figure 6-3.

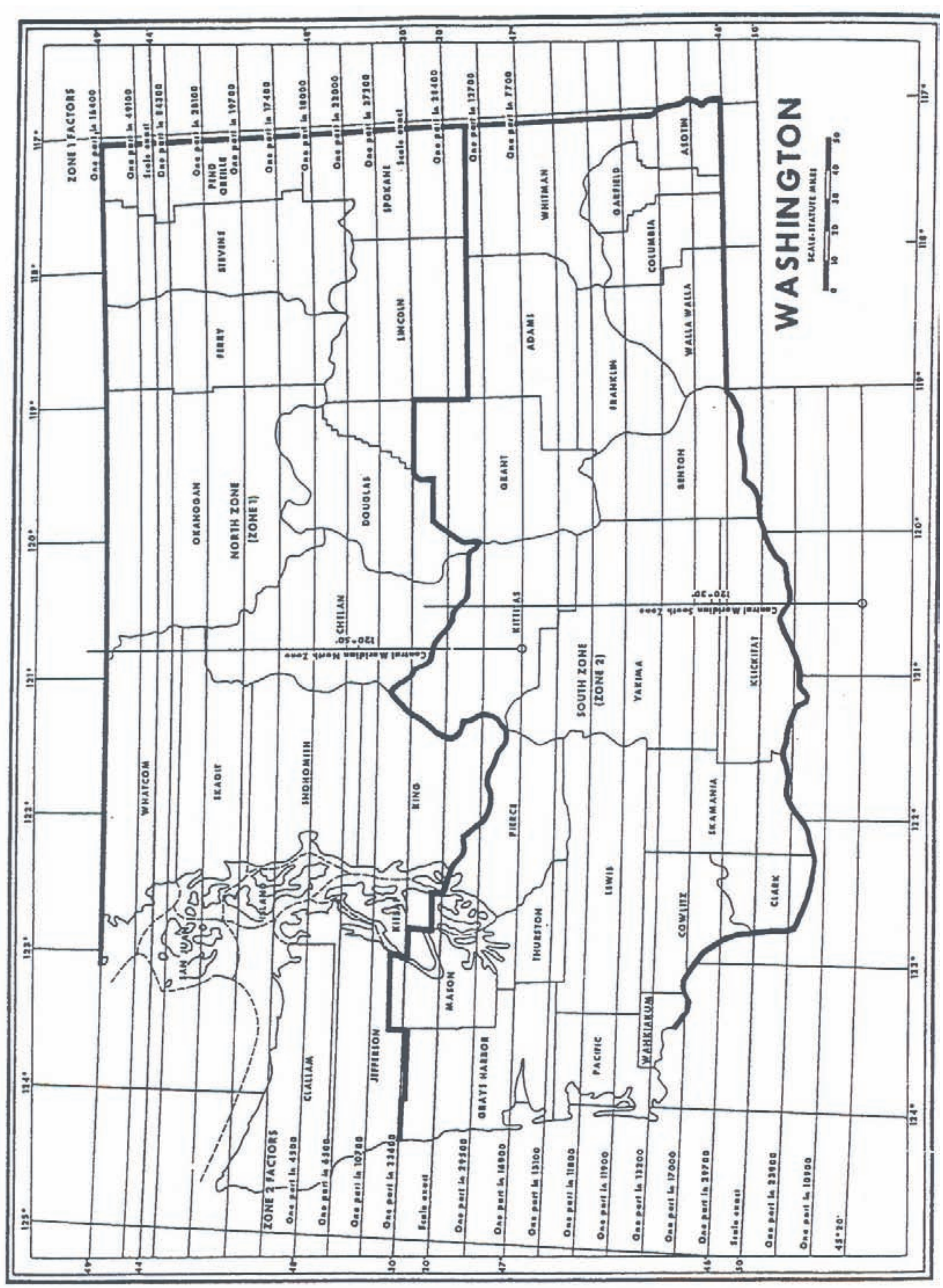
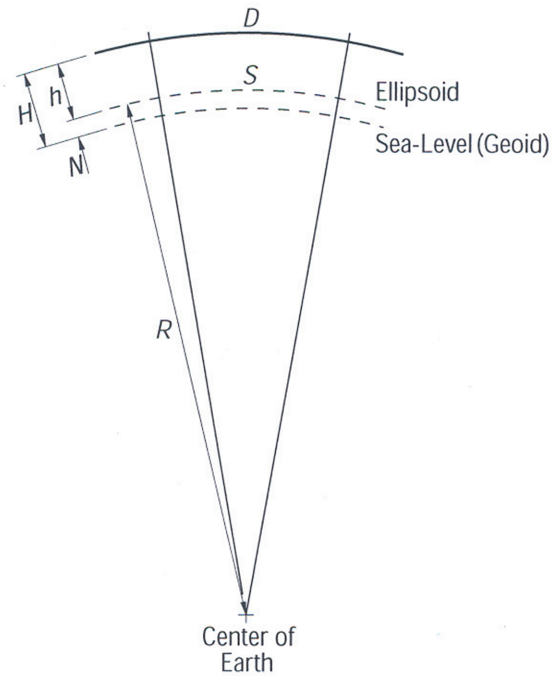


Figure 6-3

Distances measured on the surface of the Earth are to corresponding lengths on the ellipsoid. This ellipsoidal or elevation factor varies with the elevation of the surface where the distance is measured. As the elevation of the measured line increases, the distance (radius) from the surface of the Earth to its center increases, whichcorrespondingly increases the length of the measured line. Thus, distances are reduced in proportion to the change in radius between the ellipsoid and the radius of the Earth's surface where the measurement is made. See Figure 6-4.



$$\frac{S}{D} = \frac{R}{R+h}$$

$$S = D\left(\frac{R}{R+h}\right)$$

or:

$$S = D\left(\frac{R}{R+N+H}\right)$$

Where:

- S = Distance on ellipsoid
- D = Distance on ground
- R = Radius of ellipsoid for zone
- N = Geoidal height
- H = Elevation
- h = Ellipsoid height

Figure 6-4

Normally the elevation factor (sometimes called the sea level factor) and the scale factor are combined by multiplication into a grid or combined factor. Distances measured on the Earth's surface are converted to WCS83 grid distances by multiplying by the grid factor. Grid distances are converted to ground distances by multiplying the grid distance by the reciprocal of the grid factor.

Lines running east and west on the WCS83 grid are parallels of latitude. A Central Meridian is designated for each WCS83 zone and all other meridional lines on the WCS83 grid are constructed parallel to it. Therefore the only true geodetic north-south line on a WCS83 grid is the Central Meridian. All other north-south lines vary from geodetic North by the plane convergence angle (γ). The plane convergence angle varies with longitude, increasing as the distance from the Central Meridian increases. See Figure 6-5.

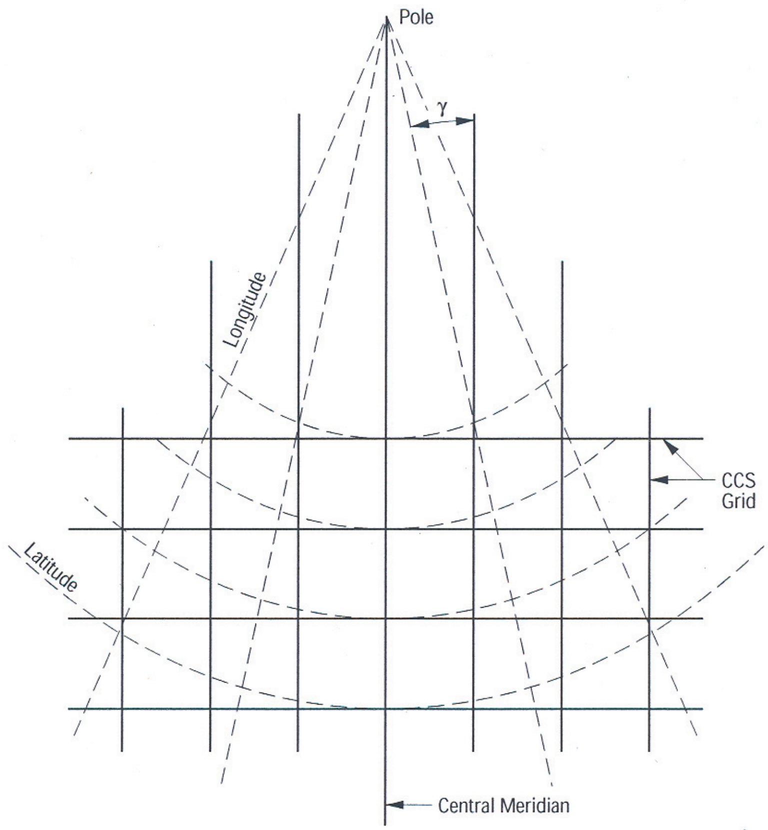


Figure 6-5

6-04.3 Coordinate Conversions

Conversions between geodetic coordinates and WCS83 coordinates are normally made using computer programs. The programs also calculate plane convergence angles and grid factors for each position. Though grid factors will differ from point to point because of change in elevation and latitude, as a general rule, a mean grid factor is selected for each project. This policy will usually cause no appreciable loss in accuracy and will eliminate confusion caused by multiple grid factors. However, for higher-order control surveys where the elevations of points vary significantly, or for projects extending to large north/south distances, assigning more than one grid factor might be appropriate.

WCS83 coordinates are specific for each zone because each WCS83 zone is a unique Lambert projection. WSDOT projects that extend from one zone into another use WCS83 coordinates based only on one zone. WCS coordinates for one zone can be easily converted to coordinates of a second zone by first converting to geodetic coordinates and then converting to WCS83 for the second zone.

In Washington, the effect of the changing datums from NAD27 to NAD83-91 was to shift and rotate geographic coordinates roughly three hundred feet to the southwest. There is no precise mathematical conversion for coordinates between WCS27 and WCS83. Conversion programs like the National Geodetic Survey's "NADCON" and the U.S. Army Corps of Engineers' "Corpscon for Windows" are only approximate conversions that are generally not accurate enough for engineering and boundary surveys. Do not use these programs to convert coordinates on survey control points between WCS27 and WCS83.

The two recommended methods for obtaining WCS83 coordinates for old WCS27 surveys are:

- Conducting a resurvey of the WCS27 survey using WA-HARN as the reference control.
- Use GPS to establish WCS83 coordinates on the original control points for the WCS27 survey and then recalculate coordinates for the entire network using the original observations.

6-04.4 Computing Project Datum Coordinates From State Plane

Since surveyors measure on the Earth's surface and not on the mathematical Ellipsoid, a coordinate conversion is necessary to convert from Washington State Plane coordinates to a "Project Datum". Ground distances and angles can be measured and projects can be layed out and constructed working with a project datum. During location and construction of highway projects, it is much easier to work with project datum coordinates than with Washington State Plane Coordinates. The procedure is to convert the State Plane Coordinates of the initial control points to project datum coordinates, gather all of the surveying data using project datum coordinates, design the project using project datum coordinates, construct the project using project datum coordinates, then convert the project datum coordinates back to Washington State Plane Coordinates for archiving and future use.

It is very important to understand the difference between Project Datum and Washington State Plane. Surveying can be performed in Project Datum or Washington State Plane coordinates. There is however, a difference between the two datum's (depending on project location) and should never be combined or confused.

The WSDOT policy is to always use a Project Datum. Experience has shown that far fewer surveying errors occur and the data provided from the Survey crews to the Designers is consistently superior when using a project datum. Documenting the method used to determine the combined factor and the combined factor itself is critical. The combined factor shall be transferred with all data so future data collection can use the same combined factor.

Any points on the project that vary significantly in elevation as well as projects that run North and South can have an adverse affect on the combination factor. The purpose of using project datum is so that a foot will equal a foot on the ground for location and construction surveying, and to obtain the precision ratio required for the survey work at WSDOT.

At the beginning of a project, a CF (combination factor) needs to be calculated, well documented, and used throughout the project.

When using a combination factor, <u>it is always Project Specific.</u>

It is mandatory to provide a clear, well-documented explanation of the combination factor and how it derived to establish the project datum coordinates. The following questions must be answered in documenting the creation of the combined factor:

- What published control points were used for the minimum and maximum latitudes to determine the mean latitude?
- What published control points were used to derive the minimum and maximum orthometric and geoid heights to determine the mean elevation and mean geoid height?
- Were ellipsoid heights used in lieu of orthometric elevations and geoid heights?

- If scale factors were used instead of latitudes, what are the scale factors that were used (scale factors are published on the monument data sheets)?
- Were the numbers and calculations checked independently?

It is also necessary to clearly state the combined factor (**CF**), and add a constant of sufficient size to make it impossible to mistakenly believe the Project Datum coordinates to be State Plane Coordinates. WSDOT adds 100 000.000 meters to both the northing and easting coordinates to avoid confusion.

The following are items to consider in determining the projection for the project:

CONVENTIONAL SURVEY METHOD

Take the size of the project into consideration. For example, if the project is 6 miles long, find the closest published quality Control Station monuments (Wa-Harn, PRN, GPS, NGS etc. monuments) at the beginning and ending of the project. A minimum of one control station is used at each end of the project to establish the scale factor which is determined from the mean latitudes of the control stations chosen. See Figure 6-7.

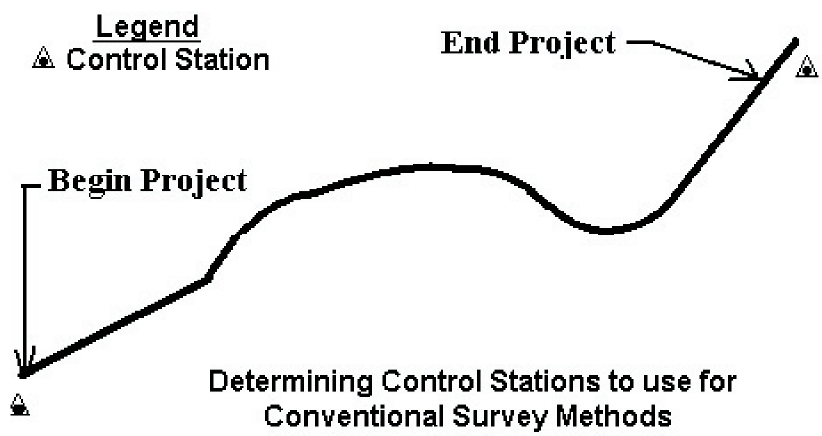


Figure 6-7

RTK SURVEY METHOD

If GPS/RTK (Real Time Kinematics) is used to survey any portion of the project, use the same control points selected for the Calibration Box of the project (a minimum of four which encompasses the project) to calculate the project datum combination factor (See Chapter 8 for procedures on Project Geometric Framework. See Figure 6-8.

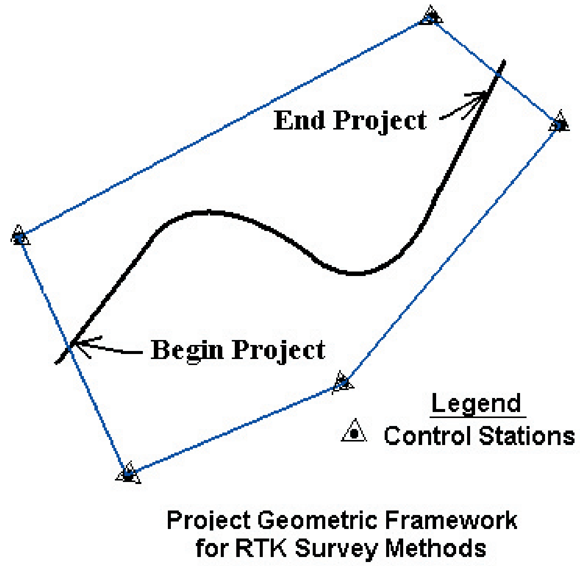


Figure 6-8

If possible, try not to exceed 6 miles of total project length when developing the "Project Datum Combination Factor". If the project exceeds 6 miles and/or there is a large difference in elevation within the project, separate combination factors within the project area may need to be used. Generally, this is not recommended due to the potential confusion and errors it can create. It is always best to only have one combination factor per project whenever possible.

DETERMINING THE COMBINED FACTOR

Determining a Combined Factor is a two-step process.

First you determine the project Scale Factor (SF) and the project Elevation Factor (EF).

The SF is determined based on the mean scale factors of the project control that has been established surrounding the project. See appendix A for a worksheet to help you calculate the SF.

The EF is determined based on the mean elevation of the project. See appendix A for a worksheet to help you calculate the EF.

Then you calculate a Combined Factor (CF). Multiplying the SF by the EF does this. See appendix A for a worksheet to help you calculate the CF.

APPLYING THE COMBINED FACTOR TO YOUR CONTROL POINTS

First, state plane grid coordinates values (in metric) on ALL of your initial control points are divided by your combined factor (**CF**). See appendix A for a worksheet to help you apply the CF.

Now add 100,000 meters to the northing and easting values of all of your control points to make their appearance very different from WSPC. We do not want State Plane coordinates and Project Datum coordinates to be confused. See appendix A for a worksheet to help you apply the 100,000 meters.

For the conversion of coordinates from metric to english units, 1 meter is equal to 39.37 inches (RCW 58.20.190). Therefore, since WSDOT typically works in english units; a conversion from metric to english is necessary. See appendix A for a worksheet to help you convert from metric to english units.

Apply these steps to any project control. The process of projecting state plane coordinates to a project datum needs to only be done once at the start of a survey project and ALL data gathered on the project will use the original CF.

After applying the CF to the control points, the surveyor will gather all of the data for the project with a scale factor of 1.0000000 in their data collectors, designers will design the project with no scale factors, construction will be accomplished with no scale factors.

When the project is completed and ready for archiving, the conversion from project datum coordinates to Washington State Plane Coordinates are calculated in the reverse order. So, English units are converted to metric, subtract 100,000 meters from each coordinate, then multiply the coordinate values by the combined factor. The result is the entire project is then based on the Washington State Plane Coordinates system and ready for archiving, GIS, transfer to others, etc.

Computer spreadsheets have been developed for ease of these calculations.

Check with the Regional Survey Coordinator or the State CAE Survey Coordinator for help with the computer conversion spreadsheets.

APPENDIX A

WORK SHEET FOR CONVERTING STATE PLANE COORDINATES TO PROJECT DATUM

Project Name	**Zone** (North or South)	**Minimum Latitude**	**Maximum Latitude**	**Mean Latitude**	**Mean Elevation**	**Mean Geoid Height**

(SF)	**(EF)**	**(CF)**	**(N) and (E)** Project Datum	Conversion to US Survey Foot
Obtained by using the mean latitude from the table k value	$E.F. = \frac{R}{R+N+H}$ R = assumed radius of earth of 6,372,000 (meters) H = mean elevation from sea level for project (meters) N = mean Geoid height for project (meters)	$SF \times EF = CF$	$N = \frac{Y}{CF} + 100{,}000$ $E = \frac{X}{CF} + 100{,}000$	$N \times \frac{39.37}{12}$ $E \times \frac{39.37}{12}$

Point ID	**(Y) State Plane Northing** (meters)	**(X) State Plane Easting** (meters)	**(SF) Mean Scale factor** (8 significant digits)	**(EF) Mean Elevation factor** (8 significant digits)	**(CF) Combined Factor** (8 significant digits)	**(N) Project Datum Northing** (meters)	**(E) Project Datum Easting** (meters)	**Project Datum Northing** (feet)	**Project Datum Easting** (feet)

Calculated By:

Checked By: