



Understanding Coordinate Management in the Geodatabase

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Understanding Coordinate Management in the Geodatabase

An ESRI Technical Paper

Contents	Page
Introduction.....	1
General Concepts—Background on Spatial Reference	1
1. Coordinate System.....	2
1A. Coordinate System Horizon	5
2. Spatial Reference Domain	6
2A. Coordinate Resolution.....	6
2B. Coordinate Grid	7
2Bi. Spatial Reference Domain Extent.....	8
2Bii. "Snap to Spatial Reference" Operation.....	13
2C. Coordinate Tolerance.....	15
Coordinate Geometry Storage in the Geodatabase.....	17
High-Precision Spatial Reference (ArcGIS 9.2).....	19
Low-Precision Spatial Reference (pre-ArcGIS 9.2).....	21
Working with High- and Low-Precision Datasets in Geoprocessing.....	24
Spatial Reference Migration Strategies	25
Upgrading a Low-Precision Geodatabase.....	25
Migrating Low-Precision Datasets to High Precision	27
Migrating High-Precision Datasets to Low Precision (not recommended).....	29
Conclusion	30
Appendixes	
Appendix A: Accuracy vs. Precision.....	32
Appendix B: Glossary.....	33

Understanding Coordinate Management in the Geodatabase

Introduction

Geographic features represent elements in the real world. To make them functional and useful in geographic information system (GIS) analysis, they need to be referenced to a location on the earth's surface. This is achieved by associating coordinate system information with geographic features. It is therefore important to understand how the feature geometry of GIS data is stored and related to locations in the real world.

ArcGIS® 9.2 models spatial data in the geodatabase using high-precision spatial references. This property enables users to easily define and associate coordinate system information with their GIS data. When creating new spatial data, a user simply specifies the desired coordinate system and XY tolerance (for vector data) and they are finished. High-precision spatial references provide users with an extensive range of possible coordinate values, thus simplifying the creation and maintenance of feature coordinates in the geodatabase.

This technical paper is for users who want a more comprehensive understanding of how feature coordinates are managed within the geodatabase. It has three main objectives:

1. Provide background information on the spatial reference property of geographic features in ArcGIS.
2. Explain how feature coordinates for vector-based geographic data are stored and managed within the geodatabase.
3. Discuss data migration strategies with users who may be working with GIS data in both high-precision (ArcGIS 9.2) and low-precision (pre-ArcGIS 9.2) spatial references.

This will enable users to better manage their GIS data and help them leverage the geodatabase in their vector data migration workflows.

General Concepts— Background on Spatial Reference

A GIS organizes geographic data as a collection of thematic layers. Each thematic layer typically contains a group of homogeneous geographic features such as parcels, streets, landmarks, or raster-based imagery.

A requirement of each thematic layer accessed by ArcGIS is that it must have a spatial reference, which enables ArcGIS to relate the geographic features to a location in the real world. The term *spatial reference* refers to a collection of properties that describe the coordinate system used to store feature geometry. For raster data, the spatial reference describes the coordinate system associated with the data after an image-to-map transformation has been applied. Behind the scenes, the spatial reference is an ArcObjects™ component with properties and methods that affect coordinate management.

This document focuses on thematic layers of vector data, henceforth referred to as *feature classes*. A feature class is a collection of geographic features with the same geometry type (such as point, line, or polygon), the same attributes, and the same spatial reference. All vector-based thematic layers are feature classes. With respect to ESRI spatial data formats, a coverage is a collection of feature classes, a shapefile is a feature class, and a geodatabase can contain many feature classes.

Every feature class has an associated spatial reference. When a feature class is accessed and/or is being processed by ArcGIS, the software's geometric processing algorithms will use its spatial reference properties as inputs.¹

It is important to understand some fundamental concepts and terms associated with a spatial reference. A spatial reference has two main components: a coordinate system and a spatial reference domain. The coordinate system defines where feature coordinates are located on the earth, while the spatial reference domain controls how those coordinates are stored and processed in ArcGIS.

Below are the two spatial reference components including their characteristics:

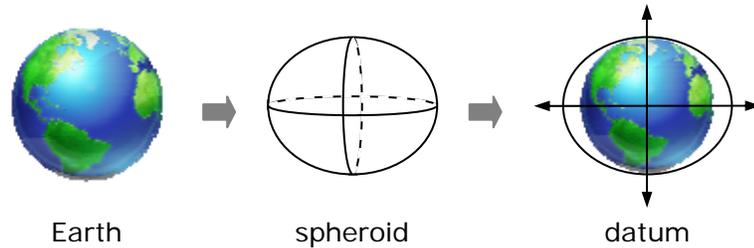
1. Coordinate System
 - 1A. Coordinate System Horizon
2. Spatial Reference Domain
 - 2A. Coordinate Resolution
 - 2B. Coordinate Grid
 - 2Bi. Spatial Reference Domain Extent
 - 2Bii. "Snap to Spatial Reference" Operation
 - 2C. Coordinate Tolerance

1. Coordinate System

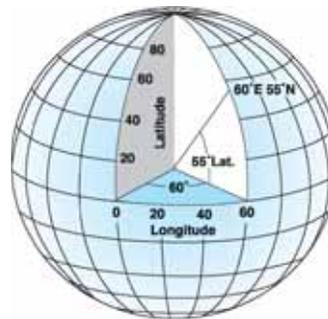
A coordinate system is a reference framework used to define the positions of points in space in either two or three dimensions. It enables spatial data to be referenced back to a location on the earth. There are two general types of coordinate systems: geographic coordinate systems (GCS) and projected coordinate systems (PCS).

A GCS uses a three-dimensional spherical surface to define locations on the earth. It includes an angular unit of measure, a prime meridian, and a datum (based on a spheroid). A spheroid approximates the shape of the earth, while a datum defines the position of the spheroid relative to the earth's center and provides a frame of reference for measuring locations on the surface of the earth (see figure 1). Alternatively, a surface-centric datum could also define the position of the spheroid relative to a location on the earth's surface (e.g., NAD27).

¹ Geodatabase feature classes have stored values for the properties of a spatial reference while coverages and shapefiles do not. Coverages and shapefiles only have a coordinate system; values for other properties are generated behind the scenes by ArcGIS when the feature class is accessed.

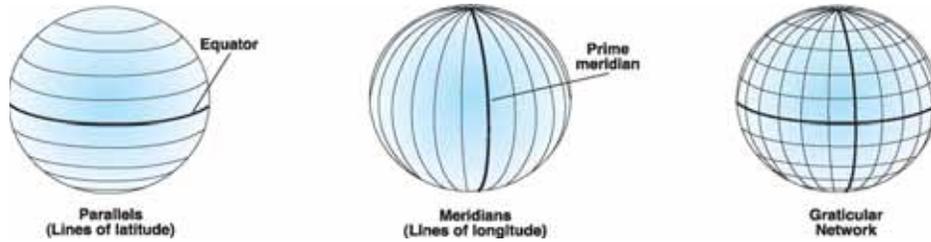
Figure 1*The Relationship between the Earth, a Spheroid, and a Datum (e.g., NAD83)*

A position on the earth is referenced by its latitude (aka east–west line) and longitude (aka north–south line) values. Latitudes are angles that are defined by dropping a perpendicular line from the earth's surface to the equatorial plane of the spheroid. If a sphere is used to approximate the shape of the earth, the line will end up at the center of the sphere (e.g., 55° latitude) as shown in figure 2. Longitudes are defined as the angles in the equatorial plane formed from the plane of the prime meridian and the plane of the local meridian (e.g., 60° longitude).

Figure 2*The Earth as a Globe Showing Latitude and Longitude Values*

Typically, latitude and longitude values are measured in either decimal degrees or in degrees, minutes, and seconds. Latitude values are measured relative to the equator and range from -90° at the South Pole to $+90^\circ$ at the North Pole. Longitude values are measured relative to the prime meridian and range from -180° traveling west to $+180^\circ$ traveling east. Both the equator and prime meridian have values of 0° ; they serve as baselines to measure against. Latitude and longitude lines encompass the entire earth and form a gridded network called a graticule (see figure 3).

Figure 3



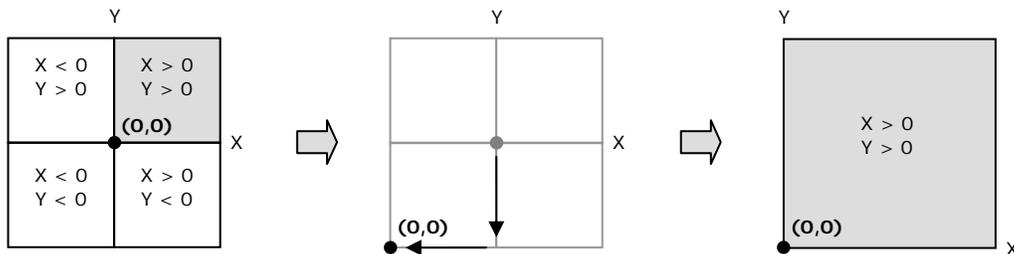
Latitude and Longitude Lines that Form a Graticular Network across the Earth

Although latitude and longitude values can locate exact positions on the surface of the earth, they are not uniform units of measure. Measurements are uniform along any given latitude (e.g., along the equator), but measurements are not uniform across a range of latitudes. For example, a degree of longitude at the equator is approximately 97 kilometers, but the measurement gradually decreases to zero as it converges at the poles. At latitudes of $\pm 45^\circ$, a degree of longitude is approximately 79 kilometers. Consequently, while a GCS is ideal for locating a position on the surface of the earth, it is not particularly well suited for GIS analysis when measurements are required.

A PCS (aka Cartesian, planimetric, or planar coordinate system) is defined on a flat, two-dimensional surface with a linear unit of measure and is always based on a GCS. A location in a PCS is referenced by x,y coordinates on a grid; the x-coordinate specifies the horizontal position, and the y-coordinate specifies the vertical position. The x,y coordinate values reference an origin at the center of the grid where $x = 0$ and $y = 0$.

There are four quadrants in a PCS that represent the four possible combinations of positive and negative x- and y-coordinates. Generally, most PCSs utilize false easting and false northing parameters (by applying a shift to the origin and creating a false origin) to ensure that all x,y coordinates in the area of interest have positive values (see figure 4).

Figure 4



Applying a False Origin to a PCS to Ensure All X,Y Coordinates Have Positive Values

One property of a PCS is a map projection, which is a mathematical transformation of coordinate values referencing a three-dimensional GCS onto a two-dimensional PCS. However, representing the earth's surface in two dimensions will always cause distortion in the shape, area, distance, and/or direction properties of the geographic data. Different projections will yield different types of distortions; some only affect one of the four spatial properties while others attempt to minimize all four. It is important to take this into consideration when selecting a PCS for GIS data and analysis.

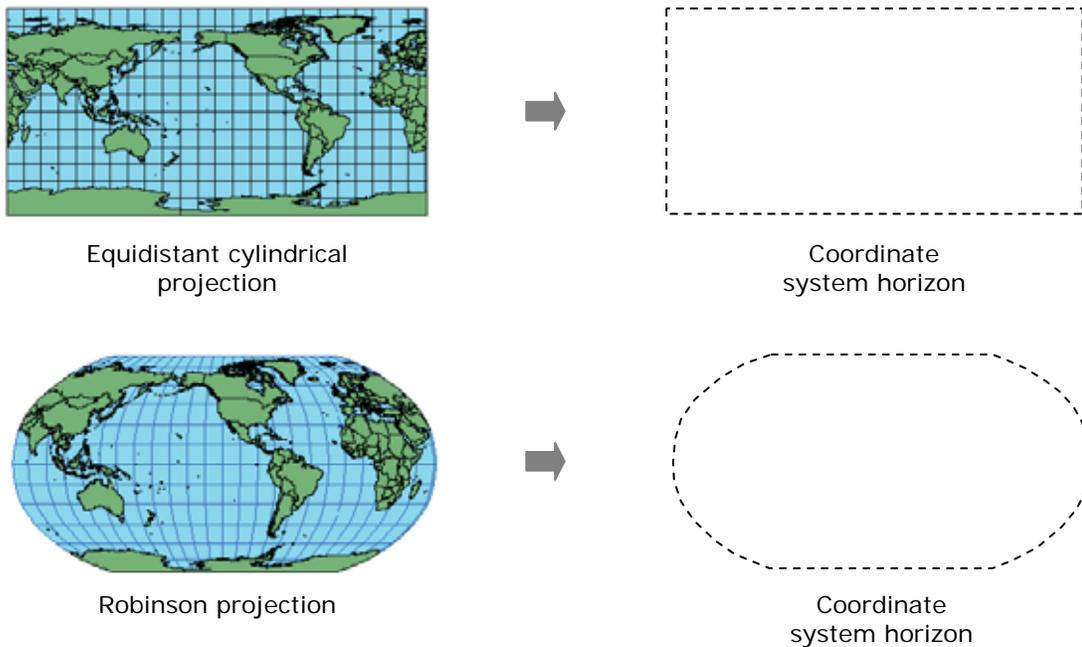
Since a PCS has x,y values that are consistent and equally spaced throughout the grid, it is ideal for GIS analysis because accurate Euclidean measurements can be made (within the definitions of the specific PCS and its associated distortions).

1A. Coordinate System Horizon

Every GCS and PCS contains a certain valid area (i.e., area that the coordinate system covers). The spatial extent of the valid area for a given GCS or PCS is known as the coordinate system horizon: it contains a set of legal x,y coordinate values in a coordinate system. Some coordinate system horizons cover the extent of the entire earth while some do not.

Figure 5 illustrates two example coordinate system horizons, where the "outer edge" of the coordinate system is the coordinate system horizon. The area inside contains valid x,y coordinate values, while the area outside does not. If users try to add features outside the coordinate system horizon using ArcGIS, they will get a "coordinates are out of bounds" error because the feature coordinates are not valid.

Figure 5



Two Example Coordinate System Horizons

2. Spatial Reference Domain

The spatial reference domain is the allowable set of values for x,y,z and m in a feature class. X,y values define a geographic position in two-dimensional space; z- and m-values are optional and are typically used for elevation and measure values (e.g., for linear referencing and dynamic segmentation), respectively.

The spatial reference domain also defines how coordinates in a feature class are managed by ArcGIS. First, it establishes the number of significant decimal places for the coordinates that compose the features in a feature class. Second, it provides an areal extent of x,y coordinate space and a set of possible x,y coordinate locations inside that space. Third, it determines the behavior of coordinates that are very close together during relational and topological processing operations. These three aspects of the spatial reference domain are closely related—a change in one will affect the others. The following sections will explain these aspects in more detail and denote the terminology used in ArcGIS to control the spatial reference domain.

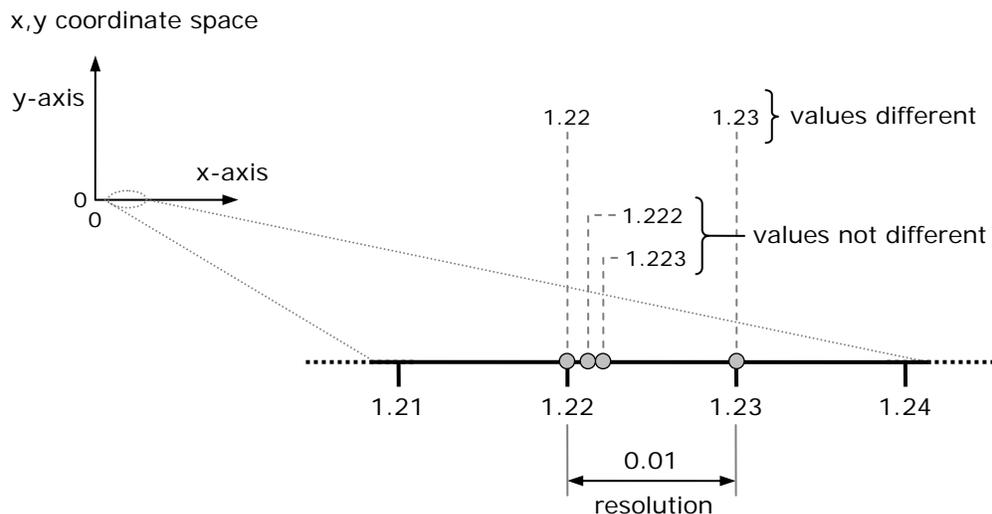
2A. Coordinate Resolution

This property refers to the detail in which a feature class depicts the location and shape of geographic features. Coordinate resolution is the numeric precision that defines the number of decimal places or significant digits used to store feature coordinates. It is the minimum distance that separates unique x,y,z- or m-values. ArcGIS uses three types of coordinate resolution:

1. XY resolution for x,y coordinates
2. Z resolution for z-values
3. M resolution for m-values

For example, if a spatial reference has an XY resolution of 0.01, then x-coordinates 1.22 and 1.23 are different, but x-coordinates 1.222 and 1.223 are not (see figure 6). The latter pair of x-coordinates are not considered different because the change in value is less than the XY resolution. The same would apply for y-coordinates.

Figure 6



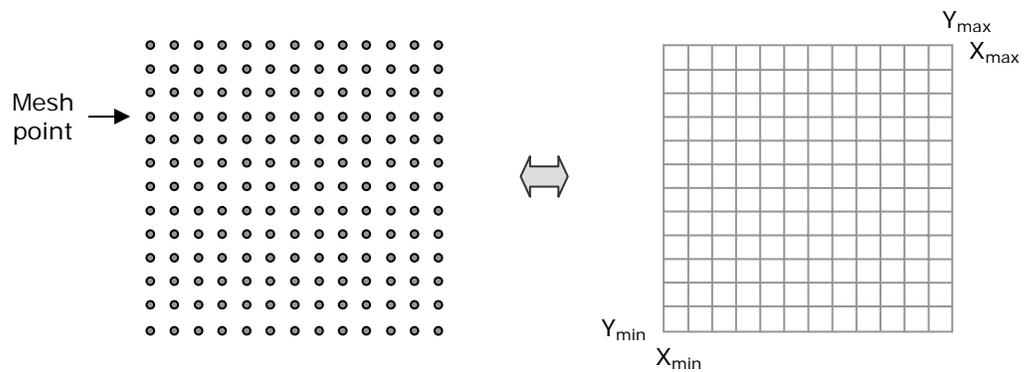
Distinguishing Different X-Coordinates with an XY Resolution Value of 0.01

XY and Z resolution values are in the same units as the associated coordinate system. For example, if a spatial reference uses a PCS with units of meters, the XY and Z resolution values are defined in meters. M resolution values can have different units than the associated coordinate system; they use the units of the measure value defined for the feature coordinates.

2B. Coordinate Grid

Every feature class accessed in ArcGIS has a spatial reference, which in turn has a coordinate grid. The structure of the grid is a mesh of points that forms a square in two-dimensional space with an origin point called a false origin (e.g., minimum x,y coordinate) and an XY resolution. The coordinate grid represents the x,y coordinate space that can be stored within a feature class. Note that it is not a visible structure within ArcGIS. Figure 7 displays the coordinate grid's mesh point structure on the left. For ease of use, it will be illustrated as a lattice structure, as shown on the right, for the remainder of this document.

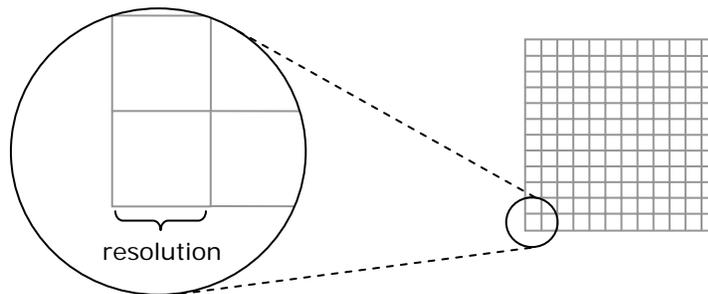
Figure 7



Coordinate Grid Conceptual Diagram

Associated with the coordinate grid is its XY resolution. As stated earlier, XY resolution is the smallest distance between different x-coordinates or different y-coordinates. Therefore, adjacent horizontal and vertical mesh points in the grid are separated by a distance equal to the XY resolution (see figure 8).

Figure 8

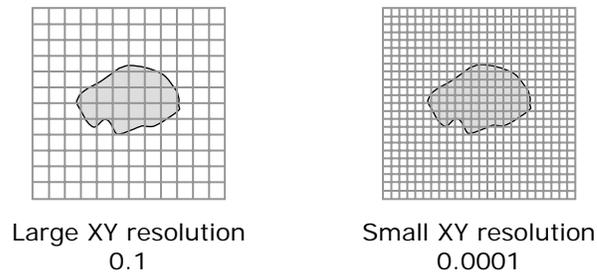


Relationship between XY Resolution and the Coordinate Grid

Feature coordinates are more precisely stored with smaller (finer) XY resolutions. However, XY resolutions that are extremely small may have a performance impact in terms of excessive disk use and decreased input/output performance. As XY resolution increases (e.g., becomes more coarse), the accuracy associated with feature coordinates diminishes; feature boundaries must be smoothed, simplified, or not shown at all.

For example, a coordinate grid with a large (coarse) XY resolution is shown on the left in figure 9; it will not be able to store a polygon feature with much precision. Conversely, a coordinate grid with a smaller (finer) XY resolution will store the polygon feature more precisely, better preserving its shape.

Figure 9



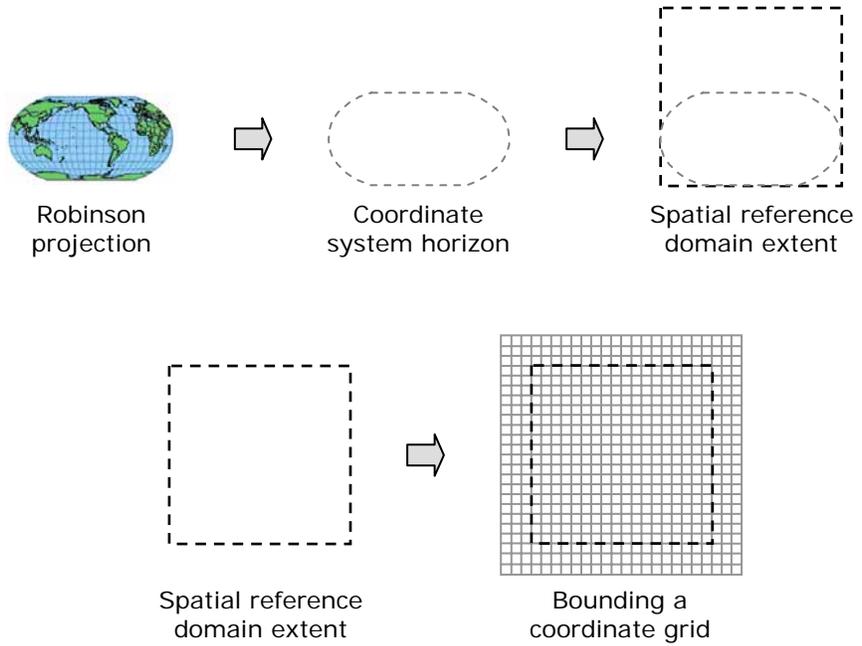
Comparison between a Coarse XY Resolution and a Fine XY Resolution

It is therefore important to strike a balance between XY resolution and the data capture resolution of the feature coordinates. The precision at which the feature coordinates were recorded should determine the appropriate XY resolution for their storage in a feature class.

2Bi. Spatial Reference Domain Extent

This property describes the x,y coordinate space boundary for a feature class and is always a square. In theory, the coordinate grid can be infinite; the spatial reference domain extent imposes a boundary on it (see figure 10). In other words, the spatial reference domain extent is the maximum allowable area (in terms of x,y coordinate values) that is covered by the coordinate grid for a given spatial reference. Ideally, the coordinate system horizon should be contained within the limits of the spatial reference domain extent.

Figure 10



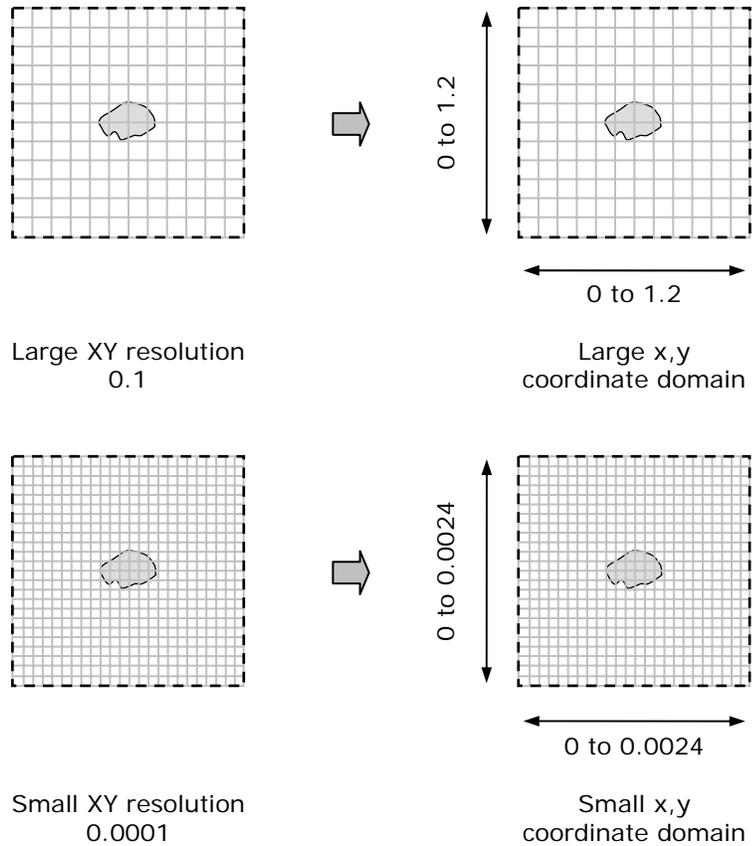
Spatial Reference Domain Extent Conceptual Diagram

Given a user-specified coordinate system (which has a coordinate system horizon) and a user-specified XY resolution, ArcGIS will automatically determine a spatial reference domain extent that includes the coordinate system horizon.²

The spatial reference domain extent is influenced by XY resolution and has a corresponding relationship with it. As XY resolution gets larger (coarser), the maximum x,y coordinate values become larger. Therefore, a spatial reference domain extent with a large (coarse) XY resolution contains more x,y coordinate area than one with a smaller (finer) XY resolution (see figure 11).

²This only applies to ArcGIS 9.2 and later releases.

Figure 11



Relationship between Spatial Reference Domain Extent and XY Resolution

Given a fixed maximum amount of storage space for each coordinate (e.g., single- or double-precision storage), there is a trade-off between spatial reference domain extent and XY resolution. Choosing a very small XY resolution (i.e., higher precision) will result in a smaller domain extent as compared to choosing a larger XY resolution (i.e., lower precision).

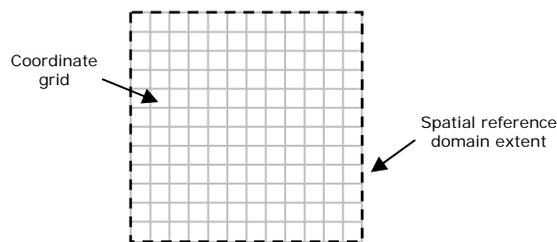
In a conceptual sense, the coordinate grid, its XY resolution, and the spatial reference domain extent imposed on it can be described as the amount of x,y coordinate area that can be represented within a feature class.

Associating Spatial Reference Properties—Putting it all Together

To review what has been discussed thus far: a feature class accessed in ArcGIS has to have a spatial reference, which consists of a coordinate system and a spatial reference domain. A coordinate system horizon contains the set of legal x,y coordinate values of a coordinate system. The spatial reference domain is composed of a coordinate grid with an XY resolution, and the coordinate grid is bounded by the spatial reference domain extent.

This section presents example figures that illustrate the relationships between the various spatial reference properties discussed. To ensure that the examples are clear and easy to understand, one relationship is not explicitly shown in the diagrams but implied: the spatial reference domain extent bounds the coordinate grid (e.g., it is a square in two-dimensional x,y coordinate space) (see figure 12).

Figure 12



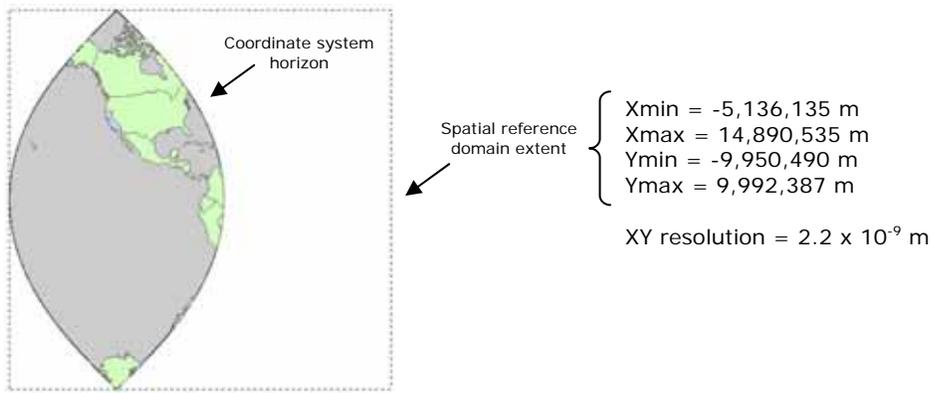
Relationship Between the Coordinate Grid and the Spatial Reference Domain Extent

A feature class of world countries is displayed for three different PCSs, with different XY resolutions, to represent data at a regional (e.g., state) map scale (figure 13)³, a continental map scale (figure 14), and global map scale (figure 15).

³ Although a Universal Transverse Mercator (UTM) zone is generally limited to 6° in longitude, the coordinate system horizon for Transverse Mercator is 90° in longitude. This is what is shown in the diagram.

Figure 13

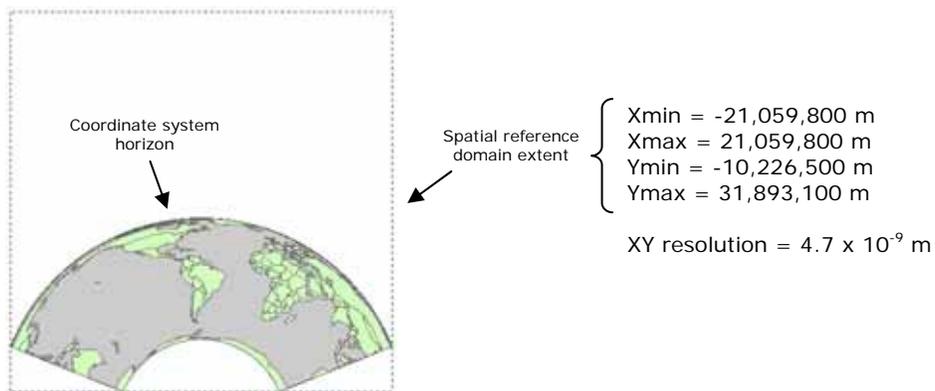
PCS: NAD 1983 UTM Zone 11



Example Spatial Reference for a Regional Dataset (California)

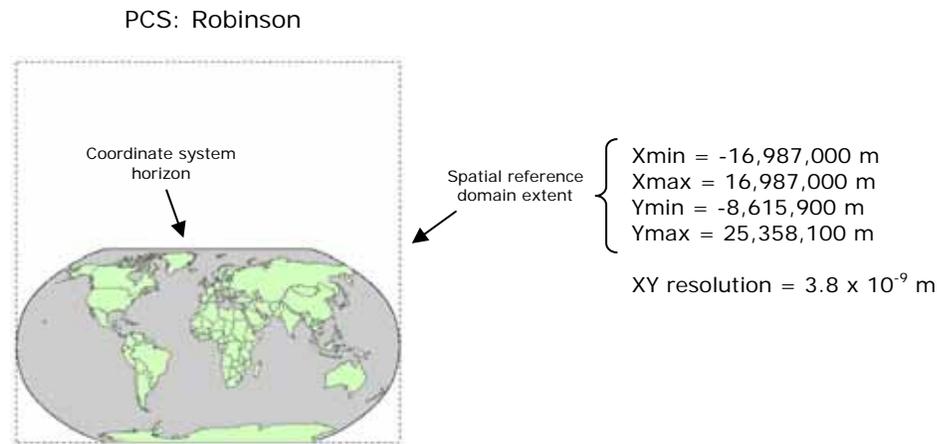
Figure 14

PCS: South America Albers Equal Area Conic



Example Spatial Reference for a Continental Dataset (South America)

Figure 15



Example Spatial Reference for a Global Dataset

For each example, several general trends can be observed:

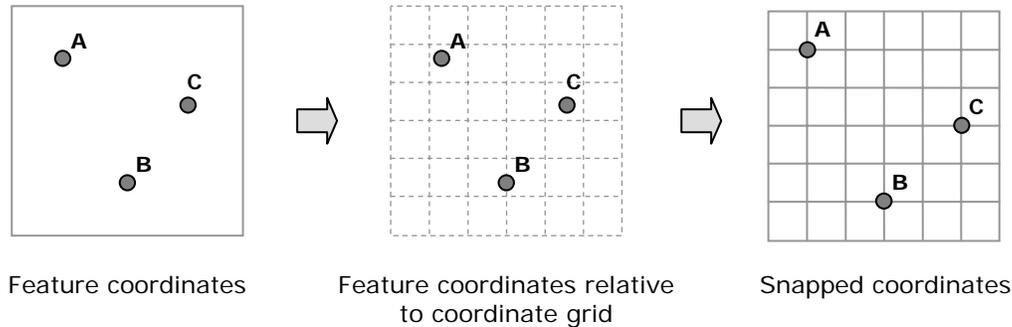
- Coordinate system horizons represent the set of legal x,y coordinate values in the coordinate system—all coordinates within are valid, all coordinates outside are not.
- Coordinate system horizons are contained within the spatial reference domain extent.
- XY resolution influences the spatial reference domain extent.

2Bii. "Snap to Spatial Reference" Operation

When a feature class is processed by ArcGIS (e.g., in geometric, relational, or topological operations), its feature coordinate values must be referenced with respect to the coordinate grid. The grid is used by the ArcGIS internal geometric algorithms during processing operations.

X,y coordinates must lie exactly on the intersections of the vertical and horizontal lines (respectively) of the coordinate grid. Recall that the intersections are the mesh points of the coordinate grid. Feature coordinates that are not situated at the mesh points of the grid will be moved ("snapped") to the nearest mesh point before they can be used in processing operations. The movement of feature coordinates in effect causes their values to be rounded from their original values to double precision values that correspond with the XY resolution. Feature coordinates aligned to the coordinate grid are termed *snapped coordinates* (see figure 16).

Figure 16



"Snap to Spatial Reference" Operation Conceptual Diagram

For example, a coordinate grid with XY resolution = 0.01 snaps the input feature coordinate (101.1234, 88.4351) to the output map coordinate (101.12, 88.44). In the context of this operation, feature coordinate movement is never greater than the XY resolution. The movement of feature coordinates to shift and align with mesh points in the coordinate grid is termed a "snap to spatial reference" operation.

ArcGIS uses integer values to perform processing operations. To transform feature coordinates into integer coordinates:

$$\text{Integer } X = \text{round} [(\text{original } X - X_{\min}) * (1/\text{XY resolution})] \text{ (equation 1)}$$

$$\text{Integer } Y = \text{round} [(\text{original } Y - Y_{\min}) * (1/\text{XY resolution})] \text{ (equation 2)}$$

When ArcGIS has completed the processing operation, coordinate values are converted back into their respective feature coordinate data units. To transform integer coordinates into snapped coordinates:

$$\text{Snapped } X = (\text{Integer } X * \text{XY resolution}) + X_{\min} \text{ (equation 3)}$$

$$\text{Snapped } Y = (\text{Integer } Y * \text{XY resolution}) + Y_{\min} \text{ (equation 4)}$$

where *round* is a function that rounds its floating point operand to the nearest integer value, and X_{\min}, Y_{\min} are the coordinates of the false origin.

Note that operations described in equations 1 to 4 comprise a single operation and intermediate integer values are never seen by the end user. Throughout the process, the precision of the feature coordinate values is maintained. Also notice that XY resolution is used to help transform the coordinate values. As stated previously, selecting an appropriate XY resolution value is critical to maintaining the precision of the feature coordinates.

2C. Coordinate Tolerance

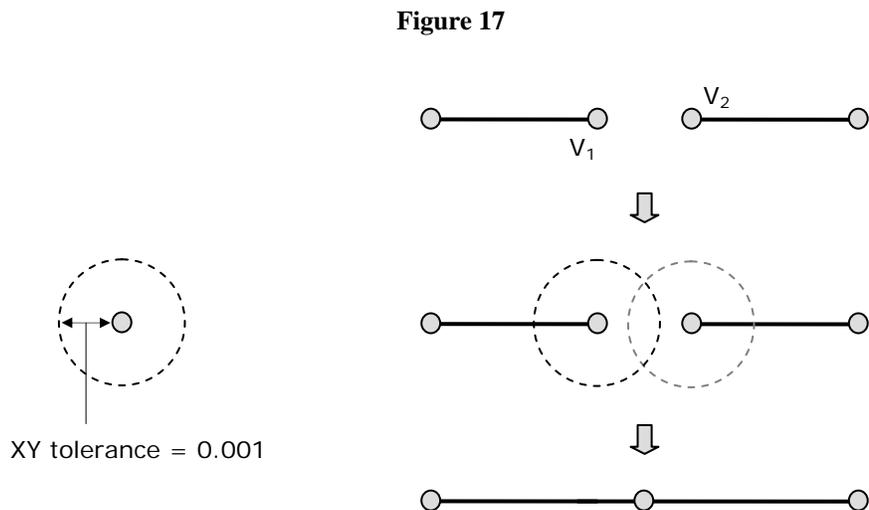
This property defines the minimum distance that a feature coordinate is allowed to move during relational (e.g., contains or touches) and topological (e.g., union or intersect) operations in ArcGIS. ArcGIS uses three types of coordinate tolerances:

1. XY tolerance⁴ for x,y coordinates
2. Z tolerance for z-values
3. M tolerance for m-values

XY and Z tolerances use distance values in map units, or its equivalent in the units of the associated coordinate system. M tolerance can have different units than the associated coordinate system; it uses the units of the measure value defined for the feature coordinates.

Of the three types, XY tolerance is the most commonly used. It is an extremely small distance that determines whether two (or more) vertices are close enough to be given the same x,y coordinate value or if they are far enough apart to each have their own x,y coordinate values. It also defines the distance that coordinates can move in x,y coordinate space during clustering operations (e.g., topology validation).

For example, figure 17 shows two line features of equal rank in the same feature class. Vertices V_1 and V_2 of those line segments are also shown. During topology validation and other geometric and geoprocessing operations, V_1 and V_2 can *each* move up to $[(\sqrt{2}) * (XY \text{ tolerance})]$ to form a cluster. That possible range of motion is shown in the middle graphic on the right side of the figure. The final clustered point is shown in the bottom right graphic.



Conceptual Diagram of XY Tolerance Behavior during Topology Validation

⁴ At ArcGIS 9.2, XY tolerance is synonymous with cluster tolerance. In certain contexts, the term *cluster tolerance* has been replaced by the term *XY tolerance*; see the ArcGIS online help for further details. XY tolerance is not equivalent to fuzzy tolerance in ArcInfo® Workstation operations.

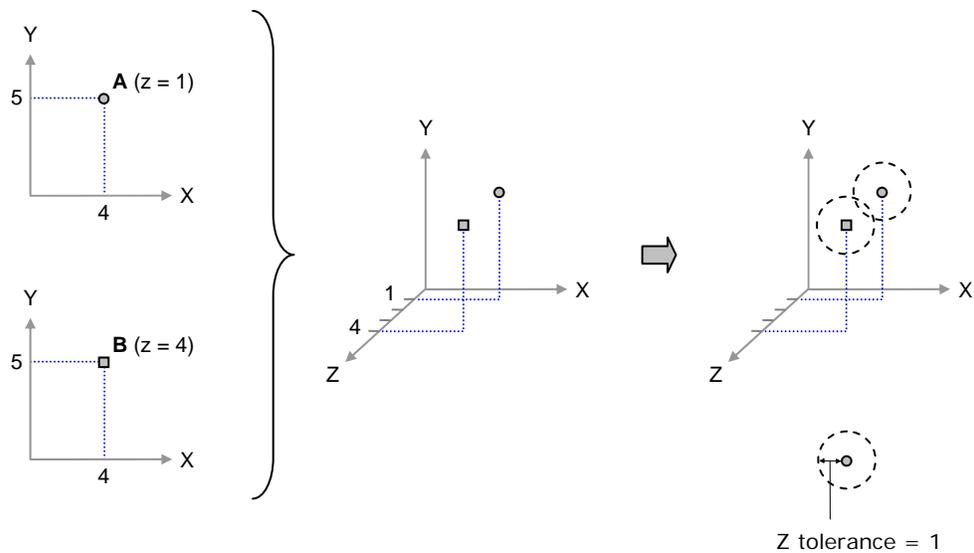
A comprehensive discussion on XY tolerance behavior is beyond the scope of this document; however, it is important to keep in mind that each vertex is allowed to move $[(\sqrt{2}) * (\text{XY tolerance})]$, and the clustering process is iterative. In some rare cases, it is possible for vertices to move more than the XY tolerance.

Different XY tolerance values can produce different results for relational and topological operations. For example, two geometries might be classified as disjoint (i.e., no points in common) with a small XY tolerance, but a larger XY tolerance value might cause them to be classified as touching. Generally, XY tolerance should be an order of magnitude greater than the XY resolution. This will ensure that data is not accidentally corrupted during processing. XY tolerance is not intended for generalizing geometry shapes but instead to be used for integrating points, lines, and boundaries during relational and topological operations.

Optionally, if feature coordinates have z- and m-values, they will also have associated tolerances. Z tolerance is the value for clustering coordinate z-values during processing. If feature coordinates are coincident and their z-values fall within the Z tolerance, their z-values will be set equal to one another (i.e., they will be clustered). M tolerance is the value for clustering coordinate m-values during processing, and the same conceptual principle for Z tolerance can also be applied.

For example, figure 18 shows two coincident points, A and B, with x,y coordinates (4,5) on the left. Both points are of equal rank in the same feature class. In the center graphic, point A has z-value = 1, and point B has z-value = 4. If the Z tolerance is 1, then the z-values for points A and B will not be clustered together because the values lie outside the Z tolerance threshold of each other (as shown in the graphic on the right).

Figure 18



Example Z Tolerance Conceptual Diagram

Coordinate Geometry Storage in the Geodatabase

The difference between coordinate resolution and coordinate tolerance is that the former is applied unconditionally: ArcGIS will snap feature coordinates to the coordinate grid before performing processing operations. While the latter may or may not have an effect on feature coordinates (e.g., alter coordinate values); it depends on the location of a feature coordinate point in relation to other feature coordinate points.

Geodatabases are data storage containers and are the native data format for ArcGIS. They provide a central location for spatial data used in GIS systems and are stored as data files or within a relational database management system (DBMS). There are three different types of geodatabases:

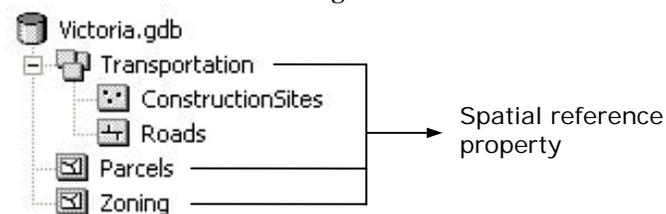
1. Personal geodatabase (Microsoft® Access™ based)
2. File geodatabase (directory of binary files)
3. ArcSDE® geodatabase (requires DBMS software)⁵

By storing spatial data within a geodatabase, users can leverage its superior data management functionalities while maintaining a GIS database. All geodatabases store feature coordinates as positive integer values.⁶ Integer values can be easily processed and compressed to consume less disk space. This enables ArcGIS to perform faster geometric operations.

Thematic layers that store vector data are modeled within the geodatabase as feature classes, which can also be grouped together within a feature dataset. Feature datasets act as containers for modeling advanced spatial associations/relationships between feature classes such as topologies, geometric networks, network datasets, survey datasets, and terrains.

In geodatabases, a spatial reference is set as a property of a stand-alone feature class or a feature dataset (see figure 19). Feature classes within a feature dataset must have the same spatial reference (and its associated properties) as the feature dataset. The one exception is that feature classes contained within a feature dataset may have different values for M resolution and M tolerance. Once a spatial reference has been defined, only its coordinate system property can be changed. All other properties are locked and cannot be changed.

Figure 19



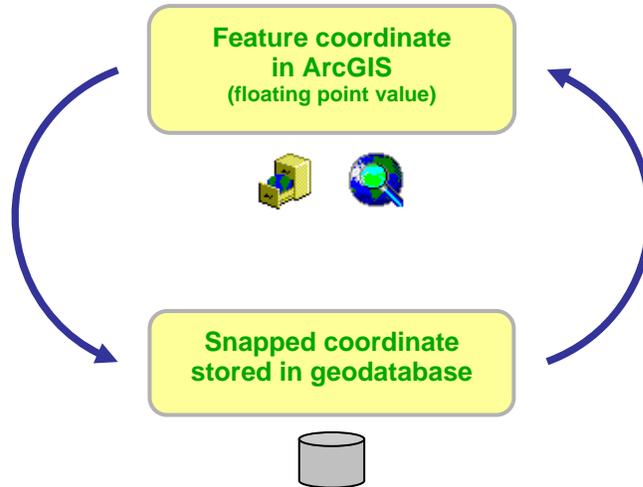
Spatial Reference—A Property of Stand-Alone Feature Classes and Feature Datasets

⁵ Both the personal geodatabase (Microsoft Access based) and file geodatabase are designed for a single user, while the ArcSDE geodatabase is designed to be scalable and utilized for multiuser data access/editing.

⁶ There are two exceptions to this: a personal geodatabase (Microsoft Access based) stores feature coordinates in the ESRI Shape data type, in a similar manner as shapefiles, and an Enterprise ArcSDE geodatabase that uses Oracle® Spatial to store geometry.

When feature coordinates are stored within the geodatabase, the "snap to spatial reference" operation is applied to them. Coordinate values are snapped to the mesh points of the coordinate grid. When feature coordinates are retrieved from the geodatabase, users will see adjusted versions of their original floating point coordinate values, but their precision is maintained. This conceptual workflow is shown in figure 20.

Figure 20



Workflow of Feature Coordinate Storage in a Geodatabase

There are two types of spatial references in geodatabases:

1. High-precision spatial reference (ArcGIS 9.2)
2. Low-precision spatial reference (before ArcGIS 9.2)

New geodatabases created with ArcGIS 9.2 can only be associated with high-precision spatial reference data and are referred to as *high-precision geodatabases*.⁷ Accordingly, geodatabases created with pre-ArcGIS 9.2 software are termed *low-precision geodatabases*. Depending on which type of geodatabase is in use, users will have different options as to how they can store and model their feature coordinate data within the geodatabase.

Note that snapping feature coordinate data to the mesh points of the coordinate grid can sacrifice precision if an inappropriate XY resolution value is used. This is especially significant for geodatabases created before ArcGIS 9.2, where stand-alone feature classes and feature datasets (both hereafter referred to collectively as *datasets*) have low-precision spatial references.

⁷ A 9.2 high-precision geodatabase that was created by upgrading a pre-ArcGIS 9.2 geodatabase can contain datasets with low-precision spatial references. See the Spatial Reference Migration Strategies section for more details.

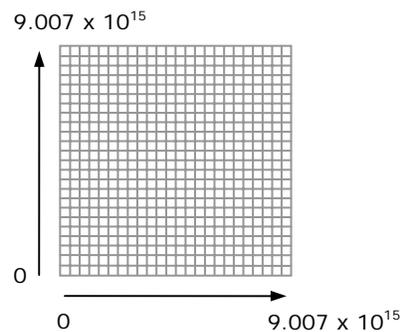
High-Precision Spatial Reference (ArcGIS 9.2)

In a new high-precision geodatabase, all newly created datasets will have high-precision spatial references. High-precision spatial references allow a large range for mesh point coordinates (i.e., a large number of grid cells in the coordinate grid) and also support very fine XY resolutions. This enables feature coordinate data in the geodatabase to span the valid horizon of any given coordinate system.

This greatly simplifies the creation and maintenance of feature coordinates in the geodatabase and has made the user experience much easier. As noted earlier, to create a new dataset in the geodatabase at ArcGIS 9.2, users need only specify the desired coordinate system and XY tolerance and they are finished. Additionally, geodatabase functionality such as historical archiving and geodatabase replication is only available using datasets with high-precision spatial references.

High-precision geodatabases store snapped feature coordinates using 53 bits, the equivalent of double-precision storage (8 bytes). The coordinate grid for a dataset is approximately 9.007×10^{15} grid cells, as shown in figure 21. Very fine distinctions between snapped coordinate values can be maintained because the minimum distance that can be represented between grid mesh points is small.

Figure 21



*High-Precision Spatial Reference
Coordinate Grid Conceptual Diagram*

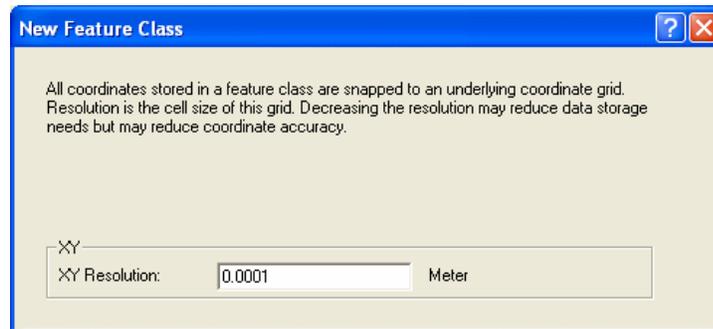
The default XY resolution for a high-precision dataset is 0.0001 meters (1/10 mm) or its equivalent in map units.⁸ For example, if the coordinate system units are feet, the default value is approximately 0.0003281 feet; if the coordinate system units are decimal degrees, the default is approximately 8.983×10^{-10} degrees. Note that the default XY resolution for a coordinate system with decimal degree units is based on the major axis of the GCS spheroid; ArcGIS uses World Geodetic System (WGS) 1984 as the default. In most cases, the default XY resolution will be adequate for most data.

At ArcGIS 9.2, users have the option to directly set a custom XY resolution value if desired (see figure 22). A dataset with a smaller (finer) XY resolution value will be stored at a higher resolution compared to a dataset with a larger (coarser) XY resolution value. For example, a dataset with an XY resolution of 0.001 millimeters is stored with higher

⁸ For unknown coordinate systems, users will have to set XY resolution values appropriate to the type of data without explicitly setting the unit of measure.

precision than a dataset with an XY resolution of 0.1 millimeters. It is recommended that custom XY resolution values be at least 10 times smaller than the data capture resolution of the data.

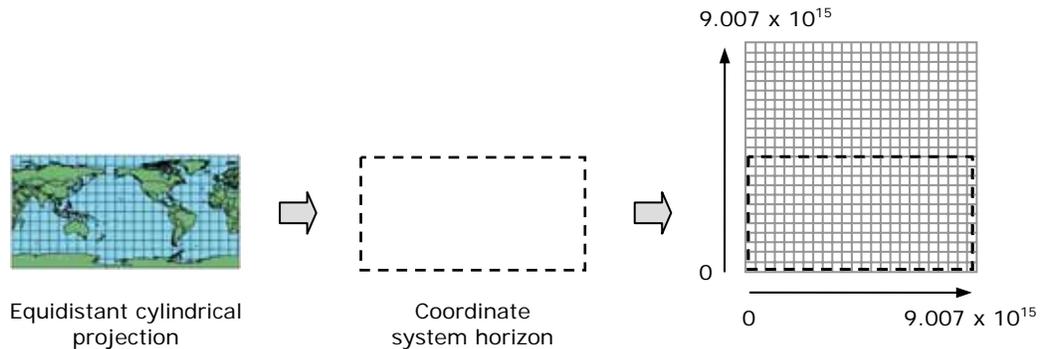
Figure 22



XY Resolution Input Dialog for Creating a New Feature Class in ArcGIS 9.2

The spatial reference domain extent is automatically set by ArcGIS based on the selected GCS or PCS. Feature data can grow to span the entire spatial reference domain extent within the valid area (i.e., coordinate system horizon) of the coordinate system (see figure 23). In effect, a high-precision spatial reference is large enough to cover the entire range of valid coordinate values for all GCSs and PCSs.

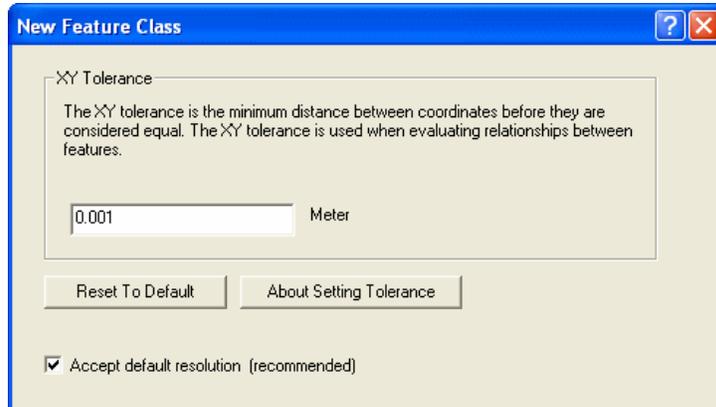
Figure 23



Example Coordinate System Horizon Placed within the Coordinate Grid of a High-Precision Spatial Reference

The default XY tolerance value is 0.001 meters, 10 times the default XY resolution. Users can set a custom XY tolerance value (see figure 24), but it should never approach the data capture resolution, and the minimum allowable XY tolerance value is twice the XY resolution.

Figure 24



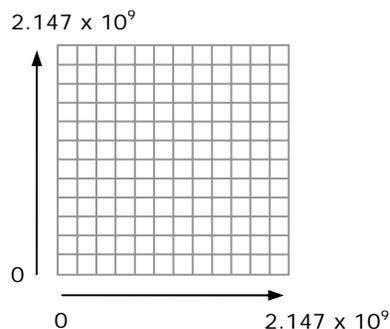
XY Tolerance Input Dialog for Creating a New Feature Class in ArcGIS 9.2

High-precision spatial references can also support a vertical coordinate system (VCS) as an optional property. A VCS is a framework that georeferences z-values and consists of a linear unit of measure, a vertical or geodetic (e.g., horizontal) datum, a direction, and an optional vertical shift. A common application of a VCS is for z-values to represent elevations or depths. These coordinate values are not associated with a coordinate grid and therefore do not snap during processing. At ArcGIS 9.2, this property is stored as metadata with the feature classes' spatial reference, where the measure unit of a VCS is used by ArcGlobe™ for displaying vector features and when extruding multipatch features.

***Low-Precision
Spatial Reference
(pre-ArcGIS 9.2)***

In releases prior to ArcGIS 9.2, all datasets in the geodatabase have low-precision spatial references. Low-precision geodatabases store snapped feature coordinates using 31 bits, the equivalent of single-precision storage (4 bytes). The coordinate grid for datasets with a low-precision spatial reference is approximately 2.147×10^9 grid cells, as shown in figure 25. It stores a smaller range of mesh point coordinate values (i.e., has a smaller areal extent) than the coordinate grid of high-precision spatial references.

Figure 25



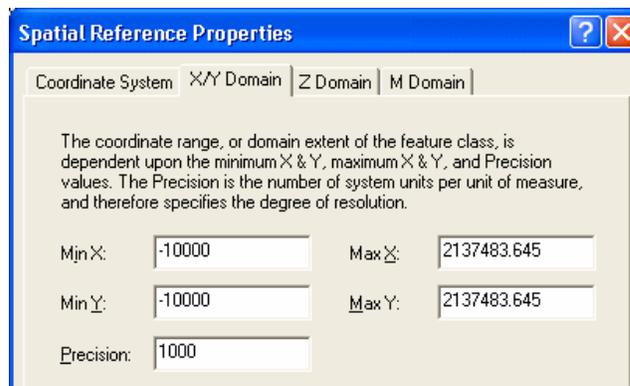
*Low-Precision Spatial Reference
Coordinate Grid Conceptual Diagram*

In low-precision geodatabases, when creating a new dataset using pre-ArcGIS 9.2 software, users specify the reciprocal of the XY resolution; this value is labeled *Precision* on the user interface (see figure 26).

$$\textit{Precision} = 1/\textit{XY resolution} \text{ (equation 5)}$$

If a small precision value is entered, feature coordinate data is stored with a large (coarse) XY resolution, hence low precision. If a large precision value is entered, feature coordinate data is stored with a small (fine) XY resolution, therefore high precision. For example, a precision value of 10 will have an XY resolution of 0.1, while a precision value of 100 will have an XY resolution of 0.01.

Figure 26



Spatial Reference Properties Dialog Box in pre-ArcGIS 9.2 Software

Although the coordinate grid of low-precision spatial references has a smaller mesh point range, large spatial reference domain extents are possible with large (coarse) XY resolutions. However, snapped feature coordinate data is stored with low precision. Storing snapped feature coordinates with a smaller (and therefore finer) XY resolution would require undersized spatial reference domain extents that may be too small for many GCSs and PCSs. As a consequence, users need to plan carefully when defining their spatial references in a low-precision geodatabase.

Since users must balance the trade-off between spatial reference domain extent and the XY resolution, there are two approaches (using pre-ArcGIS 9.2 software) for defining the spatial reference domain of a low-precision spatial reference:

1. Set the minimum x,y and maximum x,y coordinates.

In this approach, the spatial reference domain extents are explicitly specified, and the XY resolution will be calculated by ArcGIS. Using this method, the XY resolution will be maximized within the specified x,y coordinate extent. It ensures that all features within the feature class will fit inside the spatial reference domain with the highest possible precision.

2. Set the minimum x,y coordinate and the precision.

Alternatively, by specifying the minimum x,y coordinate and the precision, the spatial reference domain extent will be determined by ArcGIS. The advantage of this option over the first approach is that it provides the maximum spatial reference domain extent that supports the required data resolution.

First, the desired XY resolution of the coordinate grid is selected. An appropriate precision corresponding to the XY resolution is then determined (using equation 5). As with high-precision spatial references, an XY resolution value that is at least 10 times smaller than the data capture resolution of the data is recommended.

Consider the following examples:

Data Collection Method	Coordinate System Unit	Equipment Precision	Recommended XY Resolution
Digitize 1:250,000 paper map	feet	+/- 416 feet	1 foot
Professional GPS	meters	+/- 0.5 meters	0.05 meters
Survey with theodolite	meters	+/- 5 millimeters	0.0005 meters

The following table presents appropriate precision values for the examples above.⁹

Data Collection Method	Coordinate System Unit	Recommended XY Resolution	Precision
Digitize 1:250,000 paper map	feet	1 foot	1
Professional GPS	meters	0.05 meters	20
Survey with theodolite	meters	0.0005 meters	2000

To validate if a desired precision will work for a study area:

1. Calculate the range of the data:

$$\text{Dataset width} = (\text{MaximumX} - \text{MinimumX}) \text{ (equation 6)}$$

$$\text{Dataset height} = (\text{MaximumY} - \text{MinimumY}) \text{ (equation 7)}$$

2. Use the larger of the width or height for the range; multiply the range * precision.
3. Determine if (range * precision) < 2,147,483,645.

If the result is less than 2,147,483,645 (i.e., the snapped coordinate range of the coordinate grid), the data will fit within the low-precision spatial reference with the desired XY resolution. If the result is greater, the desired XY resolution for that particular dataset cannot be supported by the low-precision spatial reference. An alternate XY resolution will need to be selected.

The term *XY tolerance* is not used in releases prior to ArcGIS 9.2. Instead, the term *cluster tolerance* is used to describe the distance range in which all vertices and

⁹ In this instance, "precision" refers to the input *Precision* value in the Spatial Reference Properties dialog box (in pre-ArcGIS 9.2 software) shown in figure 26.

boundaries in a shapefile or feature dataset are considered identical or coincident. In pre-ArcGIS 9.2 software, cluster tolerance is only set as a property of a topology and used during topology validation. A general rule of thumb is to set the cluster tolerance to a value that is an order of magnitude less than the data capture resolution. The topology property cluster tolerance is now called *XY tolerance* at ArcGIS 9.2.

With respect to ArcGIS relational and topological processing operations, before ArcGIS 9.2, the cluster tolerance of datasets was fixed to be two times the XY resolution. At ArcGIS 9.2, the cluster tolerance (now called XY tolerance in the user interface and set as a property of a dataset) with low-precision spatial references defaults to the same value but can be changed by users.

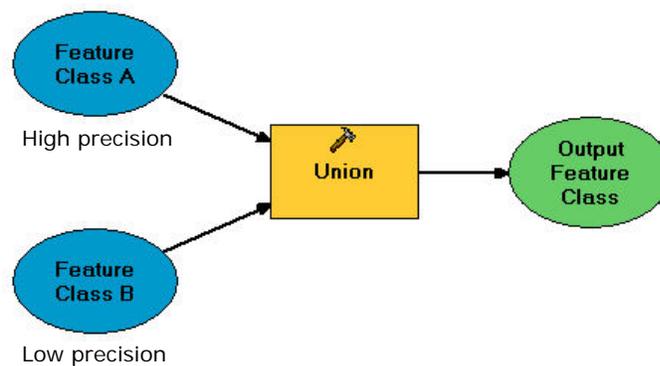
Based on the discussion above, the setup and management of datasets with low-precision spatial references can potentially be complicated because of its limited spatial reference domain extent. In addition, datasets with low-precision spatial references do not support ArcGIS 9.2 geodatabase functionality such as historical archiving and geodatabase replication. For these reasons, users are strongly encouraged to take advantage of datasets with high-precision spatial references available in ArcGIS 9.2.

Working with High- and Low-Precision Datasets in Geoprocessing

ArcGIS 9.2 enables users to work with both high- and low-precision spatial reference data simultaneously in GIS analysis. Note that earlier versions of ArcGIS software do not support datasets with high-precision spatial references. When two (or more) feature classes with different types of spatial references are input into an ArcGIS geoprocessing operation, the output feature class' spatial reference type will depend on the output workspace location.

For example, feature class A has a high-precision spatial reference, feature class B has a low-precision spatial reference, and both are input into the Union geoprocessing tool (see figure 27).

Figure 27



Example ModelBuilder™ Workflow of Two Input Feature Classes into the Union Geoprocessing Tool

One of two results will occur:

- Case 1: The output feature class will have a high-precision spatial reference if it is located in a high-precision geodatabase.¹⁰
- Case 2: It will have a low-precision spatial reference if it is located in a low-precision geodatabase.

At execution time, the geoprocessing tool will create the output feature class. All processing will be done in the output feature class' spatial reference.

Spatial Reference Migration Strategies

In some instances, users may be working with both high- and low-precision datasets. This section discusses some migration strategies and options available for integrating the datasets with different types of spatial references into a unified GIS database. There are three general migration topics:

1. Upgrade a low-precision geodatabase.
2. Migrate low-precision datasets to high precision.
3. Migrate high-precision datasets to low precision (not recommended).

Upgrading a Low-Precision Geodatabase

The upgrade of a pre-ArcGIS 9.2 geodatabase and its contents from low-precision spatial references to high-precision spatial references requires two steps; designed to give users the ability to manage spatial reference precision on a per-dataset basis. Both steps can easily be performed in ArcCatalog™.

1. Upgrade the geodatabase.

This operation will update the geodatabase schema (e.g., update internal system tables) and version number. Once a geodatabase has been upgraded, older ArcGIS clients (e.g., before ArcGIS 9.2) will be unable to access its contents. Datasets within the geodatabase before the upgrade was performed will still have a low-precision spatial reference with its associated limitations.

New datasets created after the upgrade will have high-precision spatial references, with one exception: if a new feature class is created inside an existing low-precision feature dataset, it will have a low-precision spatial reference. This enables users to have the option to continue to work with low-precision feature classes within a high-precision geodatabase.

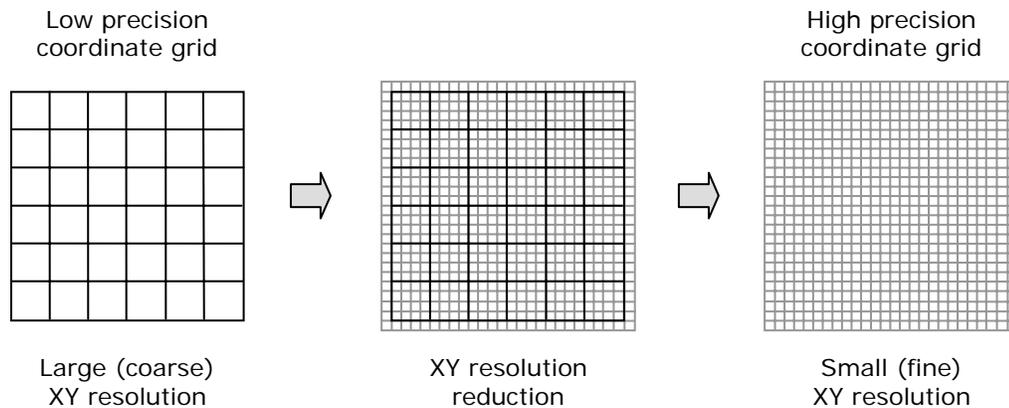
2. Upgrade the spatial reference of individual datasets.

Next, for each existing stand-alone feature class and feature dataset, their spatial references need to be individually upgraded. Two things occur when a spatial reference is converted to high precision. First, the XY resolution value is made finer (smaller): snapped coordinate values can be stored closer together within a finer coordinate grid. Note that for each mesh point of the original low-precision coordinate grid, there is a corresponding mesh point in the high-precision coordinate grid (see figure 28). The XY tolerance property of the upgraded spatial reference will be 2 * (the XY resolution of the

¹⁰ There is one exception to this statement: in a high-precision geodatabase, the output feature class can have a low-precision spatial reference if it is located within a feature dataset with a low-precision spatial reference. Refer to the Spatial Reference Migration Strategies section for more details.

original low-precision dataset). Second, the minimum and maximum x,y coordinate values of the spatial reference domain extent are expanded to cover the coordinate system's horizon.

Figure 28



Low- to High-Precision Spatial Reference Upgrade Causes XY Resolution Reduction

When deriving a smaller (finer) XY resolution value for the upgrade to high precision, ArcGIS attempts to generate a default value of 0.1 millimeters (or the adjusted equivalent to the dataset's coordinate system unit of measure). The original low-precision XY resolution value is divided iteratively until a new XY resolution value equal to 0.1 millimeters (or a value close to it) is reached. If the low-precision XY resolution is 0.1 millimeters, then it will be unchanged when upgraded to high precision. The default XY resolution for high precision works well and is recommended for most datasets.

Alternatively, users have the option to specify a custom smaller (finer) XY resolution value. The custom XY resolution value must divide evenly into the original XY resolution and be based on a power of 2. For example, if the original XY resolution is 0.001 meters, possible smaller XY resolution values for high precision include 0.0005, 0.00025, or 0.000125. These values divide evenly into 0.001 and are based on powers of 2: $0.001/(2^1) = 0.0005$, $0.001/(2^2) = 0.00025$, and $0.001/(2^3) = 0.000125$. This ensures that feature coordinates are not affected by the spatial reference upgrade process.

If the dataset has z- and m-values, their Z and M resolutions will also be changed as part of the spatial reference upgrade process. By default, their resolutions will be improved (made smaller) by a factor of four.

Note that feature coordinate values will not be altered (in terms of accuracy) by upgrading the geodatabase or upgrading the spatial reference. Therefore, all data types can be safely migrated to high-precision spatial references including topologies, geometric networks, network datasets, survey datasets, and versioned data. Versioned data does not have to be compressed to perform the upgrade to high precision.

Migrating Low-Precision Datasets to High Precision

There is also an implicit spatial reference upgrade when datasets are transferred (e.g., copy/paste or export/import) from a low-precision geodatabase to a high-precision geodatabase. Their spatial references are automatically converted to high precision, which includes a new default XY resolution value and an expanded coordinate grid.

There are three ArcGIS operations that will implicitly upgrade low-precision datasets to high precision:

- ArcCatalog copy/paste commands
- Export/Import of XML workspace document
- Use of export/import geoprocessing tools

All three methods will yield the same default XY resolution for the output dataset. They utilize the same approach to reduce the XY resolution as the upgrade spatial reference process (for individual datasets) described previously. Note that only the third method allows users to specify a custom XY resolution value, while the first two generate a default XY resolution value.¹¹

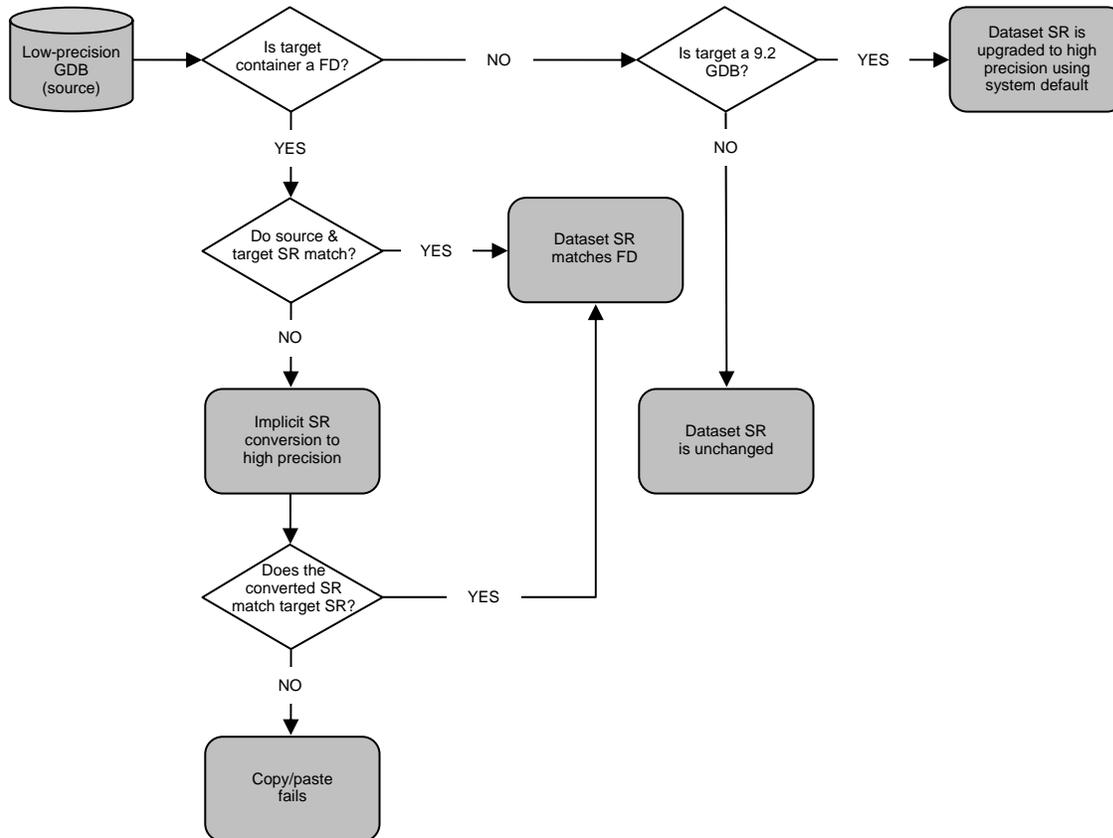
The next several figures contain flowcharts of the three dataset migration methods. They illustrate the spatial reference migration analysis process that is performed by ArcGIS. Figure 29 applies to the ArcCatalog copy/paste commands (note this workflow is also applicable to data extraction), figure 30 applies to the export/import of an XML workspace document, and figure 31 applies to the export/import geoprocessing tools.

The following abbreviations are applicable for all three flowcharts:

- FD = feature dataset
- GDB = geodatabase
- GP = geoprocessing
- SR = spatial reference

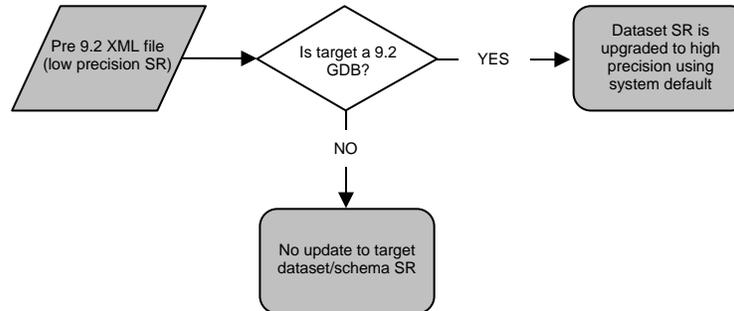
¹¹ A custom XY resolution value can be set for the export/import geoprocessing tools in the ArcToolbox™ geoprocessing environment settings.

Figure 29



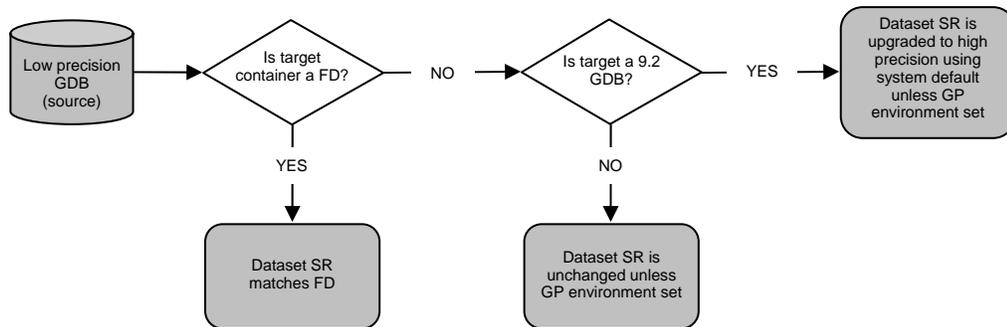
ArcCatalog Copy/Paste Commands Workflow for Migrating Low- to High- Precision

Figure 30



Export/Import of XML Workspace Document Workflow for Migrating Low- to High- Precision

Figure 31



Export/Import Geoprocessing Tools Workflow for Migrating Low- to High- Precision

Migrating pre-ArcGIS 9.2 datasets to high precision is not mandatory. If existing datasets with low-precision spatial references meet current business model and workflow needs, then users can leave them in low precision. However, upgrading them to high precision will enable users to take advantage of the new functionality available in high-precision geodatabases such as historical archiving and geodatabase replication.

Migrating High-Precision Datasets to Low Precision (not recommended)

When datasets are transferred (e.g., copy/paste or export/import) from a high-precision geodatabase to a low-precision geodatabase, there is an implicit spatial reference downgrade. In other words, high-precision spatial references are converted to low precision.

This occurs when any of the following ArcGIS operations are executed:

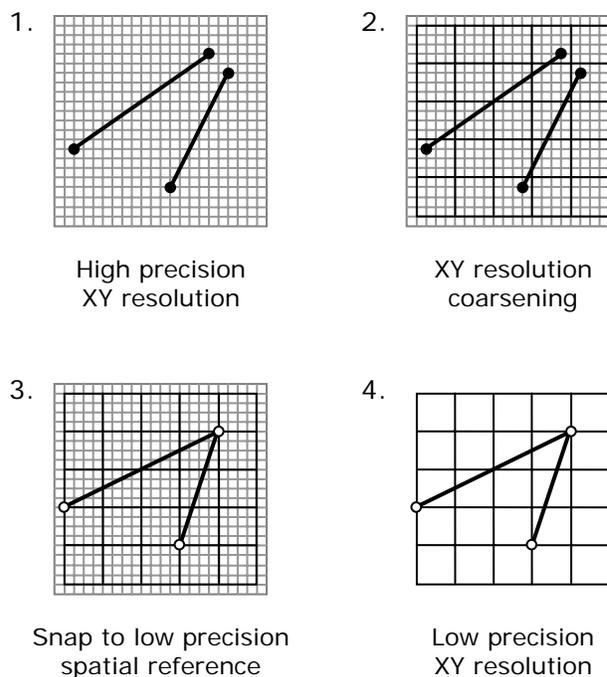
- ArcCatalog copy/paste commands
- Export/Import of XML workspace document
- Use of export/import geoprocessing tools

ArcGIS will coarsen (i.e., will increase the value of) the XY resolution until features fit within the low-precision spatial reference. Feature coordinates will be snapped to the

mesh points of the new, smaller coordinate grid. However, this will likely result in feature coordinates shifting and possibly corrupting feature data.

For example, in figure 32, diagram 1, there are two lines in a high-precision coordinate grid. Diagram 2 shows the coarsening of the high-precision coordinate grid to low precision; note that the XY resolution becomes larger. Diagram 3 displays the two line features being snapped to the mesh points of the low-precision coordinate grid. Observe that the two upper vertices become coincident at the same mesh point. Last, in diagram 4, the two lines appear to converge, which was not the case originally.

Figure 32



Example Conceptual Diagram of Migration from High Precision to Low Precision (e.g., coarsening the XY resolution) that May Possibly Result in Data Corruption

In addition, depending on the coordinate system horizon, some features may not lie within the smaller, low-precision coordinate grid range. Therefore, features near the spatial reference domain boundaries may cause the dataset migration process from high to low precision to fail. For these reasons, migration from high-precision to low-precision spatial references is not a recommended procedure.

Conclusion

Understanding the spatial reference property of feature classes in ArcGIS is beneficial to successfully implementing and managing a GIS database. A spatial reference consists of two main components: a coordinate system and a spatial reference domain. The former defines where feature coordinates are located on the earth, while the latter controls how those coordinates are stored and processed in ArcGIS.

Feature coordinates in the geodatabase can be stored with either a high- or low-precision spatial reference, depending on the ArcGIS release (e.g., ArcGIS 9.2 versus ArcGIS 9.1 and earlier, respectively). High-precision spatial references enable users to easily associate coordinate system information to geographic features in a feature class.

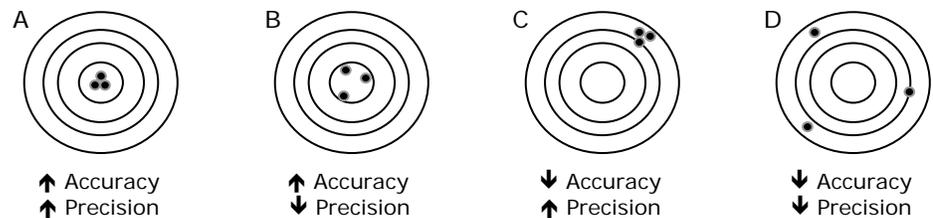
Regardless of the spatial reference type (high or low precision), the accuracy of feature coordinates stored in the geodatabase is always maintained by ArcGIS when accessed and/or being processed. Understanding the differences between the two types of spatial references will enable geodatabase administrators and GIS managers to better manage their GIS spatial data in migration workflows.

Appendix A: Accuracy vs. Precision

It is important to clarify and distinguish between two common terms that are frequently associated with the spatial references of feature classes: accuracy and precision. Accuracy is the degree to which a measured value conforms to true or accepted values; in other words, how close a measure value is to the actual value. GIS data accuracy is determined by the method in which it was collected. For example, survey data is likely to be more accurate than digitizing a paper map. Precision is the closeness of a repeated set of observations of the same quantity to one another; in other words, for a collection of measured values, how close they are to each other. Sometimes accuracy and precision are inappropriately thought of as being synonymous.

Figure A1 illustrates the differences between the concepts of accuracy versus precision using a dartboard analogy. It contains four different scenarios that contrast the two terms. Diagram A: three darts hit the target center and are very close together = high accuracy and precision. Diagram B: three darts hit the target center but are not very close together = high accuracy, low precision. Diagram C: three darts do not hit the target center but are very close together = low accuracy, high precision. Lastly, diagram D: three darts do not hit the target center nor are they close together = low accuracy and precision.

Figure A1



Accuracy vs. Precision—Dartboard Analogy Conceptual Diagram

It is important to understand the distinction between the two terms because when GIS data is stored in the geodatabase as feature classes, the data accuracy is not changed, only the precision at which the data is stored is affected. This is determined by the coordinate resolution spatial reference property: the numeric precision that defines the number of decimal places or significant digits used to store feature coordinates. It is the minimum distance that separates unique x,y,z- or m-values.

Appendix B: Glossary

Accuracy

The degree to which a measured value conforms to a true or accepted value.

Coordinate grid

A structure that consists of a mesh of points that forms a square in two-dimensional space and is bounded by the spatial reference domain extent. It represents the x,y coordinate space that can be stored within a feature class.

Coordinate resolution

The minimum distance that separates unique x,y,z- or m-values in a spatial reference. It is the numeric precision that defines the number of decimal places or significant digits used to store feature coordinates in a feature class.

Coordinate system

A reference framework used to define the positions of points in space in either two or three dimensions. It enables spatial data to be referenced back to a location on the earth.

Coordinate system horizon

The spatial extent of the valid area for a given GCS or PCS, and it contains a set of legal x,y coordinate values in a coordinate system.

Coordinate tolerance

The minimum distance that a feature coordinate is allowed to move during relational (e.g., contains or touches) and topological (e.g., union or intersect) operations in ArcGIS. It may or may not have an effect on feature coordinates (e.g., alter coordinate values); it depends on the location of a feature coordinate point in relation to other feature coordinate points.

Data capture resolution

The measure accuracy of feature coordinates when they are recorded/stored in digital form. This is highly dependent on the method by which the feature coordinates are acquired.

Feature class

A collection of geographic features with the same geometry type (such as point, line, or polygon), the same attributes, and the same spatial reference.

Feature dataset

A container in the geodatabase that collects feature classes, all of which have the same spatial reference. It is typically used to enable the modeling of geospatial relationships between feature classes such as topologies, networks, and terrains.

Geodatabase

A container of spatial and attribute data; the native data format for ArcGIS. It provides a central location for spatial data used in GIS systems and can be stored as data files or within a relational DBMS.

Geographic coordinate system (GCS)

A type of coordinate system that uses a three-dimensional spherical surface to define locations on the earth. It includes an angular unit of measure, a prime meridian, and a datum (based on a spheroid).

High-precision spatial reference

Available at ArcGIS 9.2, it is associated with stand-alone feature classes and feature datasets. It stores snapped feature coordinates using 53 bits, the equivalent of double-precision storage (8 bytes). It allows a large range for mesh point coordinates (i.e., a large number of grid cells in the coordinate grid) and also supports very fine XY resolutions. This enables feature coordinate data in the geodatabase to span the valid horizon of any given coordinate system.

Low-precision spatial reference

Available before ArcGIS 9.2, it is associated with stand-alone feature classes and feature datasets. It stores snapped feature coordinates using 31 bits, the equivalent of single-precision storage (4 bytes). It stores a smaller range of mesh point coordinate values (i.e., has a smaller areal extent) than in high-precision spatial references.

Map projection

A mathematical transformation of coordinate values referencing a three-dimensional GCS onto a two-dimensional PCS.

Precision

The closeness of a repeated set of observations of the same quantity to one another. It is the number of significant digits used to store values.

Projected coordinate system (PCS)

A type of coordinate system that is defined on a flat, two-dimensional surface with a linear unit of measure and is always based on a GCS. It references locations with x,y coordinates on a grid, where x specifies the horizontal position and y specifies the vertical position.

"Snap to spatial reference" operation

The movement of feature coordinates to shift and align with the mesh points in the coordinate grid.

Spatial reference

For vector data: It is a collection of properties that describe the coordinate system used to store feature geometry. For raster data: It describes the coordinate system associated with the data after an image-to-map transformation has been applied.

Spatial reference domain

The allowable set of values for x,y,z and m in a feature class. It defines how coordinates in a feature class are managed by ArcGIS in three ways: (1) it establishes the number of significant decimal places for coordinates, (2) it provides an areal extent of x,y coordinate space and a set of possible x,y coordinate locations inside that space, and (3) it determines the behavior of coordinates that are very close together during relational and topological operations in ArcGIS.

Spatial reference domain extent

The maximum allowable area (in terms of x,y coordinate space) that is covered by the coordinate grid for a given spatial reference.

Vertical coordinate system (VCS)

A type of coordinate system that georeferences z-values and consists of a linear unit of measure, a vertical or geodetic (e.g., horizontal) datum, a direction, and an optional vertical shift.