Unit 012 - Position on the Earth

by Kenneth E. Foote, Department of Geography, University of Texas at Austin, USA

Unit Topics

- Five topics are highlighted in this section:
  - Unit 013 - Coordinate Systems Overview, by Peter Dana
  - Unit 014 - Latitude and Longitude, by Anthony Kirvan
  - Unit 015 - The Shape of the Earth, by Peter Dana
  - Unit 016 - Discrete Georeferencing, by David Cowen
  - Unit 017 - Global Positioning Systems Overview, by Peter Dana
- These cover topics that are fundamental to understanding the systems of locational reference used in GIS.
- The units have been written as overviews, but additional references and materials are provided for instructors wishing to extend their presentations of these important topics.

Intended Learning Outcomes of this Section

- Determine location and calculate distances using global coordinate systems (latitude-longitude and UTM).
- Determine location and calculate distances in the local coordinate system employed most commonly in the student's state, region, or nation.
- Understand why different coordinate systems have been developed to record location.
- Select a coordinate system suited to a particular GIS project.
- Explain how the shape of the earth is related to geographic position and to the measurement of distance.
- Understand how geographic coordinates can be assigned to street address and postal codes using discrete georeferencing.
- Identify the difficulties and errors that arise in discrete geocoding.
- Explain how a GPS receiver computes position and time from GPS signals and list major types of error.
- State the methodological differences between single-user and differential GPS.

Describe the practical differences between using GPS for low-precision and high-precision positioning.
- See also the detailed learning outcomes listed below by unit.

Metadata and Revision History

Position on the Earth

1. The Importance of Position

- Accurate referencing of geographic location is fundamental to all GIS.
  - The management, analysis, and reporting of all GIS data requires that it be carefully referenced by position on the Earth's surface.
  - Mispositioned data can disrupt and even invalidate a GIS dataset and all modeling based upon that dataset.
- Many different coordinate systems are used to record location.
  - Some systems such as latitude and longitude are global systems that can be used to record position anywhere on the Earth's surface.
  - Other systems are regional or local in coverage and intended to provide accurate positioning over smaller areas.
  - Position is sometimes recorded in other ways, for instance by using postal codes and cadastral reference systems.
  - The system of locational reference used in a particular GIS project will depend on the purpose of the project and how the positions of the source data have been recorded.
- It is sometimes the case that the data needed for a particular GIS project will be recorded in two or more of these reference systems.
  - Combining the information of these sources will require that positions be carefully converted, transformed, or projected from one system to another.
  - This is a reason why GIS practitioners must usually be familiar with a variety of commonly used coordinate systems.
- Geographic position is related to the shape of the Earth.
  - This shape is not a perfect sphere but rather an irregular ellipsoid.
  - Positions are sometimes reported in spherical units, but are more commonly are adjusted to account for Earth shape using what are called geodetic datums.
    - Spherical distances and measurements differ from those that use geodetic datums to adjust for Earth shape.
  - Accurate positioning requires knowledge of the datum used to construct a given coordinate system.
    - Transforming locations from one coordinate system to another will often also require shifting datums as well.
- Phenomena whose positions are recorded by street address or postal code can also referenced using geographic coordinates.
  - The process of matching street addresses and postal codes to geographic

coordinate systems is called discrete georeferencing.
- Precise positioning of natural and human phenomena can be a very demanding task.
  - The level of precision with which position is recorded in a GIS dataset will vary from project to project.
    - Some engineering applications demand centimeter precision, some demographic and marketing applications require much lower precision to accomplish their objectives.
  - High precision positioning usually requires the use of staff well trained in surveying, geodesy, and photogrammetry.
- The Global Positioning System (GPS) is now used routinely for both low-precision and high-precision positioning.
  - Low-precision GPS positioning can be attained by users with little knowledge of the underlying GPS technology and inexpensive equipment.
  - High-precision GPS positioning requires both a thorough knowledge of the technology and more specialized equipment.

2. Overview of the Section Units

- The units are intended to provide an overview to the most important issues in determining position.
- These overviews still contain much technical information.
  - Lecturing from these units may occasionally require studying some of the reference materials.
- Instructors are encouraged to adapt these materials to their audiences.
  - Students often benefit from having these topics explained using local examples.
  - Students often benefit from exercises and activities that require them to practice using different coordinate systems.
- Instructors may find it useful to teach these units in conjunction with those on map projections and on uncertainty in spatial databases.
- The contents and interrelationships of the units in this section are described below.

2.1. Unit 013 - Coordinate Systems Overview

- This unit provides an overview of coordinate systems used for georeferencing, including:
  - A description of basic coordinate systems
  - A description of the shape of the Earth
  - Some examples of global and regional systems used for precise positioning, navigation, and geographic information systems
- The overview discusses the rationale behind these systems and how they are used
- After learning the material covered in this unit, students should be able to:
  - List the major global georeferencing systems
  - Explain how the UTM georeferencing system is organized
  - Locate a given local landmark in three or more global or regional coordinate systems
  - Express the location of the student's home in UTM and one regional coordinate system

    - Identify the georeferencing system used most widely in the student's locality.
    - Differentiate between different global systems of georeferencing including UTM, MGRS, and GEOREF systems.
    - Collect examples of regional and local coordinate systems employed by nations or states not mentioned in the text.
    - Find and plot one example of a metes-and-bounds survey
    - Plan a regional GIS project that spans two or more UTM or SPC zones.

2.2. Unit 014 - Latitude and Longitude

- This unit focuses on the most widely used global reference system, latitude and longitude.
- It defines, explains, and illustrates:
    - Earth rotation, the North and South Poles, and the Equator
    - Parallels of latitude and meridians of longitude
    - Determination of north or south position with latitude
    - The use of longitude to determine east or west position
    - The measurement of latitude and longitude with degrees, minutes, and seconds
- After learning the material covered in this unit, students should gain an appreciation for:
    - The relationship between plane and earth coordinate geometries
    - The importance of the earth's rotation and poles to measurement and point location
    - The use of latitude and longitude to determine locations on the earth's surface
    - The differences and relationships between latitude and longitude
    - Using latitude and longitude to measure distances

2.3. Unit 015 - The Shape of the Earth

- This unit focuses on the shape of the Earth, and how this shape is related to location.
- The unit provides an overview of the following concepts:
    - Geodetic datums
    - Geometric Earth models
    - Reference ellipsoids
    - Earth surfaces
- After learning the material covered in this unit, students should gain an appreciation for:
    - The various methods of describing the size and shape of the earth
    - The evolution of a flat earth model into an accurate spherical representation.

2.4. Unit 016 - Discrete Georeferencing

- GIS often must assign geographic coordinates to data recorded by street address or postal code using discrete georeferencing.
- This unit provides an overview of discrete georeferencing, including:
    - Description of how georeferencing is used to create GIS databases
    - Applications that rely on georeferencing
    - The level of geographic resolution possible for various alternatives of georeferencing

  - Sources of base maps for georeferencing
  - Software for georeferencing address files
  - Problems associated with handling addresses
  - Internet resources for georeferencing
- After learning the material covered in this unit, students should understand:
  - The importance of georeferencing as a way to create GIS databases
  - The limitations of the approach and the benefits of certain alternatives
  - The mechanics of how to use GIS software to perform georeferencing tasks
  - Sources of software and data for performing geocoding operations

2.5. Unit 017 - Global Positioning Systems Overview

- The Global Positioning System (GPS) is now widely used for both low-precision and high-precision positioning.
- This unit provides an overview of the GPS including:
  - A description of the space, control and user components of the system.
  - A description of the basic services provided by GPS.
  - A discussion of position and time determination from GPS signals.
  - A discussion of GPS error sources and methods for overcoming some GPS errors.
- The overview discusses GPS project planning and costs.
- The overview does not discuss details of GPS signals and data formats, but does provide references to relevant sources.
- After learning the material covered in this unit, students should be able to:
  - List the major GPS segments as defined by the Department of Defense.
  - Explain how a GPS receiver computes position and time from GPS signals.
  - Describe the major error sources for GPS positioning projects.
  - Explain the various forms of Differential GPS.
  - Propose suitable equipment and processes for various levels of positioning accuracy.

Last revised: November 30, 1998.

Unit 012 - Position on the Earth

Table of Contents

Advanced Organizer

- Topics Covered
- Intended Learning Outcomes
- Metadata and Revision History

1. The importance of position

2. Overview of section units

   2.1 Unit 013 - Coordinate systems overview
   2.2 Unit 014 - Latitude and Longitude
   2.3 Unit 015 - The Shape of the Earth
   2.4 Unit 016 - Discrete Georeferencing
   2.5 Unit 017 - Global Positioning Systems Overview

Back to the Unit

Position on the Earth

Metadata and Revision History

Page contents

1. About the main contributors
2. Details about the file
3. Key words
4. Index words
5. Prerequisite units
6. Subsequent units
7. Revision history

---

1. About the main contributors

- author: Kenneth E. Foote, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098

2. Details about the file

- last revision date: 15 November 1998
- unit title: Position on the Earth
- unit key number: Unit 012w

3. Key words

- Coordinate Systems
- Latitude
- Longitude
- Discrete Georeferencing
- Global Positioning System (GPS)
- Georeferencing
- Precise Positioning
- Location

- See also the key words listed in individual units.

4. Index words

- Geodetic datum
- Postal code
- Ellipsoid
- Geocoding

- See also the index words listed in individual units.

5. Prerequisite units

- None

6. Subsequent or concurrent units

- 019 - Projections and transformations
- 020 - Maps as representations of the world
- 096 - Handling uncertainty, including units:
  - 097 - Storing uncertainty information
  - 098 - Uncertainty Propagation in GIS
  - 099 - Detecting and Evaluating Errors by Graphical Methods
  - 100 - Data Quality Measurement and Assessment
  - 187 - Managing Uncertainty in GIS

7. Revision history

- 15 November 1998. Draft completed.
- 30 November 1998. Posted to NCGIA website.

- Back to the Unit: Position on the Earth

Unit 013 - Coordinate Systems Overview

by Peter H. Dana, Department of Geography, University of Texas at Austin, USA

This section was edited by Kenneth Foote, Department of Geography, University of Texas Austin.

Advanced Organizer

Topics covered in this unit

- This unit provides an overview of coordinate systems used for georeferencing, including:
  - a description of basic coordinate systems
  - a description of the shape of the Earth
  - some examples of global and regional systems used for precise positioning, navigation, and geographic information systems
- The overview discusses the rationale behind these systems and how they are used

Learning Outcomes

- After learning the material covered in this unit, students should be able to:
  - List the major global georeferencing systems
  - Explain how the UTM georeferencing system is organized
  - Locate a given local landmark in three or more global or regional coordinate systems
  - Express the location of the student's home in UTM and one regional coordinate system
  - Identify the georeferencing system used most widely in the student's locality.
  - Differentiate between different global systems of georeferencing including UTM, MGRS, and GEOREF systems.
  - Collect examples of regional and local coordinate systems employed by nations or states not mentioned in the text.
  - Find and plot one example of a metes-and-bounds survey
  - Plan a regional GIS project that spans two or more UTM or SPC zones.

Full Table of Contents

Instructors' Notes

Metadata and Revision History

Unit 013 - Coordinate Systems Overview

1. Basic Coordinate Systems

- There are many basic coordinate systems familiar to students of geometry and trigonometry.
  - These systems can represent points in two-dimensional or three-dimensional space.
- René Decartes (1596-1650) introduced systems of coordinates based on orthogonal (right angle) axes.
  - These two and three-dimensional systems used in analytic geometry are often referred to as ***Cartesian systems***.
- Similar systems based on angles from baselines are often referred to as ***polar systems***.

1.1. Plane Coordinate Systems

- Two-dimensional coordinate systems are defined with respect to a single plane, as demonstrated in the following figures:
  - Figure 1. A Point Described by Cartesian Coordinates in a Plane
  - Figure 2. A Line Defined by Two Points in a Plane
  - Figure 3. Distance Between Two points (Line Length) from the formula of Pythagoras
  - Figure 4. A Point Described by Polar Coordinates in a Plane
  - Figure 5. Conversion of Polar to Cartesian Coordinates in a Plane

1.2. Three-Dimensional Systems

- Three-dimensional coordinate systems can be defined with respect to two orthogonal planes.
  - Figure 6. A Point Described by Three-Dimensional Cartesian Coordinates
  - Figure 7. A Point Described by Three-Dimensional Polar Coordinates
  - Figure 8. Conversion of Three-Dimensional Polar to Three Dimensional Cartesian Coordinates

---

2. Earth-Based Locational Reference Systems

- Reference systems and map projections extend the ideas of Cartesian and polar coordinate systems over all or part of the earth.
  - Map projections portray the nearly spherical earth in a two-dimensional

representation.

- Earth-based reference systems are based on various *models* for the size and shape of the earth.
    - Earth shapes are represented in many systems by a *sphere*
    - However, precise positioning reference systems are based on an *ellipsoidal earth* and *complex gravity models*.

2.1. Reference Ellipsoids

- Ellipsoidal earth models are required for precise distance and direction measurement over long distances.
    - Ellipsoidal models account for the slight flattening of the earth at the poles. This flattening of the earth's surface results at the poles in about a twenty kilometer difference between an average spherical radius and the measured polar radius of the earth.
    - The best ellipsoidal models can represent the shape of the earth over the smoothed, averaged sea-surface to within about one-hundred meters.
- Reference ellipsoids are defined by either:
    - *semi-major* (equatorial radius) and *semi-minor* (polar radius) axes, or
    - the relationship between the semi-major axis and the flattening of the ellipsoid (expressed as its *eccentricity*).
    - Figure 9. Reference Ellipsoid Parameters
- Many reference ellipsoids are in use by different nations and agencies.
    - Table 1. Selected Reference Ellipsoids
- Reference ellipsoids are identified by a name and often by a year
    - for example, the Clarke 1866 ellipsoid is different from the Clarke 1858 and the Clarke 1880 ellipsoids.

2.2. Geodetic Datums

- Precise positioning must also account for irregularities in the earth's surface due to factors in addition to polar flattening.
- **Topographic** and **sea-level models** attempt to model the physical variations of the surface:
    - The *topographic surface* of the earth is the actual surface of the land and sea at some moment in time.
        - Aircraft navigators have a special interest in maintaining a positive height vector above this surface.
    - *Sea level* can be thought of as the average surface of the oceans, though its true definition is far more complex.
        - Specific methods for determining sea level and the temporal spans used in these calculations vary considerably.
        - Tidal forces and gravity differences from location to location cause even this smoothed surface to vary over the globe by hundreds of meters.
- **Gravity models** and **geoids** are used to represent local variations in gravity that change the local definition of a level surface
    - *Gravity models* attempt to describe in detail the variations in the gravity field.

        - The importance of this effort is related to the idea of *leveling*. Plane and geodetic surveying uses the idea of a plane perpendicular to the gravity surface of the earth which is the direction perpendicular to a plumb bob pointing toward the center of mass of the earth.
        - Local variations in gravity, caused by variations in the earth's core and surface materials, cause this gravity surface to be irregular.
    - *Geoid models* attempt to represent the surface of the entire earth over both land and ocean as though the surface resulted from gravity alone.
- **Geodetic datums** define reference systems that describe the size and shape of the earth based on these various models.
    - While cartography, surveying, navigation, and astronomy all make use of geodetic datums, they are the central concern of the science of ***geodesy***.
- Hundreds of different datums have been used to frame position descriptions since the first estimates of the earth's size were made by the ancient greeks.
    - Datums have evolved from those describing a spherical earth to ellipsoidal models derived from years of satellite measurements.
    - Modern geodetic datums range from
        - *flat-earth* models, used for plane surveying
        - to *complex* models, used for international applications, which completely describe the size, shape, orientation, gravity field, and angular velocity of the earth.
- Different nations and international agencies use different datums as the basis for coordinate systems in geographic information systems, precise positioning systems, and navigation systems.
    - In the United States, this work is the responsibility of the National Geodetic Survey (http://www.ngs.noaa.gov/).
    - Links to some of the NGS's counterparts in other nations are listed below in Section 7.2 (Web References).
- Linking geodetic coordinates to the wrong datum can result in position errors of hundreds of meters.
    - The diversity of datums in use today and the technological advancements that have made possible global positioning measurements with sub-meter accuracies requires careful datum selection and careful conversion between coordinates in different datums.
- For the purposes of this unit, reference system can be divided into two groups:.
    - *Global systems* can refer to positions over much of the Earth.
    - *Regional systems* have been defined for many specific areas, often covering national, state, or provincial areas.

---

3. Global Systems

3.1. Latitude, Longitude, Height

- The most commonly used coordinate system today is the latitude, longitude, and height system.
- The ***Prime Meridian*** and the ***Equator*** are the reference planes used to define latitude

and longitude.
    - Figure 10. Equator and Prime Meridian
- There are several ways to define these terms precisely. From the geodetic perspective these are:
    - The ***geodetic latitude*** of a point is the angle between the equatorial plane and a line normal to the reference ellipsoid.
    - The ***geodetic longitude*** of a point is the angle between a reference plane and a plane passing through the point, both planes being perpendicular to the equatorial plane.
    - The ***geodetic height*** at a point is the distance from the reference ellipsoid to the point in a direction normal to the ellipsoid.
    - Figure 11. Geodetic Latitude, Longitude, and Height

3.2. ECEF X, Y, Z

- **E**arth **C**entered, **E**arth **F**ixed (ECEF) Cartesian coordinates can also be used to define *three dimensional positions*.
- ECEF X, Y, and Z Cartesian coordinates define three dimensional positions *with respect to the center of mass of the reference ellipsoid*.
    - The Z-axis points from the center toward the North Pole.
    - The X-axis is the line at the intersection of the plane defined by the prime meridian and the equatorial plane.
    - The Y-axis is defined by the intersection of a plane rotated 90° east of the prime meridian and the equatorial plane.
    - Figure 12. ECEF X, Y, and Z
    - Table 2. ECEF X, Y, Z Coordinates Example

3.3. Universal Transverse Mercator (UTM)

- **U**niversal **T**ransverse **M**ercator (UTM) coordinates define two dimensional, horizontal, positions.
- Each UTM zone is identified by a number
    - UTM zone *numbers* designate individual 6° wide longitudinal strips extending from 80° South latitude to 84° North latitude.
    - (Military UTM coordinate systems also use a *character* to designate 8° zones extending north and south from the equator, see below).
    - Figure 13. UTM Zones
- Each zone has a ***central meridian***.
    - For example, Zone 14 has a central meridian of 99° west longitude.
        - The zone extends from 96 to 102° west longitude.
    - Figure 14. UTM Zone 14
- Locations within a zone are measured in meters eastward from the central meridian and northward from the equator. However,
    - Eastings increase eastward from the central meridian which is given a *false* easting of 500 km so that only positive eastings are measured anywhere in the zone.
    - Northings increase northward from the equator with the equator's value differing

in each hemisphere
    - in the Northern Hemisphere, the Equator has a northing of 0
    - for Southern Hemisphere locations, the Equator is given a false northing of 10,000 km
  - Figure 15. UTM Zone 14 Example Detail
  - Table 3. UTM Coordinate Example

3.4. Military Grid Reference System (MGRS)

- The **M**ilitary **G**rid **R**eference **S**ystem (MGRS) is an extension of the UTM system. A
- UTM zone number and an additional zone character are used to identify areas 6° in east-west extent and 8° in north-south extent.
  - A few special UTM zones do not match the standard configuration (see Figure 13)
    - between 0° and 42° east longitude, above 72° north latitude in the area of the Greenland and Barents Seas, and the Arctic Ocean.
    - in zones 31 and 32 between 56° and 64° north latitude including portions of the North Sea and Norway.
- UTM zone number and character are followed by two characters designating the eastings and northings of 100 km square grid cells.
  - Starting eastward from the 180° meridian, the characters A to Z are assigned consecutively to up to 24 strips covering 18° of longitude (characters I and O are omitted to eliminate the possibility of confusion with the numerals 1 and 0). The sequence begins again every 18°.
  - From the equator northward, the characters A to V (omitting characters I and O) are used to sequentially identify 100 km squares, repeating the sequence every 2,000 km.
    - for *odd* numbered UTM easting zones, northing designators normally begin with 'A' at the equator
    - for *even* numbered UTM easting zones, the northing designators are offset by five characters, starting at the equator with 'F'.
    - South of the equator, the characters continue the pattern set north of the equator.
    - Complicating the system, ellipsoid junctions ("spheroid junctions" in the terminology of MGRS) require a shift of 10 characters in the northing 100 km grid square designators. Different geodetic datums using different reference ellipsoids use different starting row offset numbers to accomplish this.
  - Figure 16. Military Grid Reference System
- For a full MGRS location, UTM zone number and character and the two grid square designators are followed by an even number of digits representing more precise easting and northing values.
  - 2 digits give a coordinate precision of 10 km.
  - 10 digits give a coordinate precision of 1 m.
  - Table 4. MGRS Example
- MGRS and UTM systems are often employed in products produced by the US National Imagery and Mapping Agency (http://www.nima.mil/), formerly the Defense Mapping

Agency.

3.5. World Geographic Reference System (GEOREF)

- The World **Geo**graphic **Ref**erence System is used for aircraft navigation.
- GEOREF is based on latitude and longitude.
- The globe is divided into twelve bands of latitude and twenty-four zones of longitude, each 15° in extent.
  - Figure 17. World Geographic Reference System Index
- These 15° areas are further divided into one degree units identified by 15 characters.
  - Figure 18. GEOREF 1 Grid
  - Table 5. GEOREF Example

---

4. Regional Systems

- Several different systems are used regionally to identify geographic location
- Some of these are true coordinate systems, such as those based on UTM and UPS systems
- Others, such as the metes and bounds and Public Land Survey systems describe below, simply partition space

4.1. Transverse Mercator Grid Systems

- Many nations have defined grid systems based on Transverse Mercator coordinates that cover their territory.

4.1.1. An example - the British National Grid (BNG)

- The British National Grid (BNG) is based on the National Grid System of England, administered by the British Ordnance Survey
- The BNG has been based on a Transverse Mercator projection since the 1920s.
  - The modern BNG is based on the Ordnance Survey of Great Britain Datum 1936.
- The true origin of the system is at 49° north latitude and 2 degrees west longitude.
  - The false origin is 400 km west and 100 km north.
- Scale factor at the central meridian is 0.9996012717.
- The first BNG designator defines a 500 km square.
- The second designator defines a 100 km square.
  - Figure 19. British National Grid 100 km Squares
- The remaining digits define 10 km, 1 km, 100 m, 10 m, and 1 m eastings and northings.
  - Table 6. British National Grid Example

4.2. Universal Polar Stereographic (UPS)

- The **U**niversal **P**olar **S**tereographic (UPS) projection is defined above 84° north latitude and south of 80° south latitude.

- The eastings and northings are computed using a polar aspect stereographic projection.
- Zones are computed using a different character set for south and north Polar regions.
- Figure 20. North Polar Area UPS Grid
    - Table 7. North Polar UPS Example
- Figure 21. South Polar Area UPS Grid
    - Table 8. South Polar UPS Example

4.3. State Plane Coordinates (SPC)

- State plane systems were developed in order to provide local reference systems that were tied to a national datum.
- In the United States, the **State Plane System 1927** was developed in the 1930s and was based on the North American Datum 1927 (NAD-27).
    - NAD-27 coordinates are in English units (feet).
    - Figure 22. NAD-27 State Plane Coordinate Example
- The **State Plane System 1983** is based on the North American Datum 1983 (NAD-83).
    - NAD-83 coordinates are metric.
    - Table 9. NAD-83 State Plane Coordinate Example
    - While the NAD-27 State Plane System has been superceded by the NAD-83 System, maps in NAD-27 coordinates are still in use.
- Most USGS 7.5 Minute Quadrangles show several coordinate system grids including latitude and longitude, UTM kilometer tic marks, and applicable State Plane coordinates.
    - Figure 23. Three Coordinate Systems on the Austin, East USGS 7.5' Quadrangle
- Each state has its own State Plane system with specific parameters and projections.
    - Software is available for easy conversion to and from latitude and longitude.
    - A popular public domain software package, CORPSCON is maintained by the US Army Corps of Engineers
- Some smaller states use a single state plane zone while larger states are divided into several zones.
    - State plane zone boundaries often follow county boundaries.
    - Figure 24. State Plane Zone Example
- Two projections are used in all State Plane systems, with one exception:
    - *Lambert Conformal Conic* projections are used for regions with a larger east-west than north-south extent.
        - examples are Nebraska and North Carolina
    - *Transverse Mercator* projections are used for regions with a larger north-south extent.
        - examples are New Hampshire and Illinois
    - Some states use both projections
        - in Florida, the Lambert Conformal Conic projection is used for the North zone while the Transverse Mercator projection is used for the East and West zones.
    - The exception is one State Plane zone in Alaska which uses an *Oblique Mercator* projection for a thin diagonal area.
        - Figure 25. Alaska State Plane Zone 5001

4.4. Public Land Rectangular Surveys (USPLS)

- Public Land Rectangular Surveys have been used since the 1790s to identify public lands in the United States.(USPLS = US Public Land Survey)
  - The system is based on **principal meridians** and **baselines**.
- **Townships**, square with six miles on each side, are numbered with reference to a baseline and principal meridian.
  - actually, few townships are truly square due to convergence of the meridians.
- **Ranges** are the distances and directions from baseline and meridian expressed in numbers of townships.
- Every four townships, a new baseline is established so that orthogonal meridians can remain north oriented.
  - Figure 26. U.S. Rectangular Survey
- **Sections**, approximately one mile square, are numbered from 1 to 36 within a township.
  - Figure 27. Township Sections
  - Sections are divided into quarter sections.
  - Quarter sections are divided into 40-acre, quarter-quarter sections.
  - Quarter-quarter sections are sometimes divided into 10-acre areas.
  - Figure 28. Subdivided Section
  - Fractional units of section quarters, designated as numbered lots, often result from irregular claim boundaries, rivers, lakes, etc.
- Abbreviations are used for Township (T or Tps), Ranges (R or Rs), Sections (Sec or Secs), and directions (N, E, S, W, NE, etc.).
  - Table 10. A Township and Range Property Description

4.5. Metes and Bounds

- Metes and Bounds identify the boundaries of land parcels by describing lengths and directions of a sequence of lines forming the property boundary.
  - Lines are described with respect to natural or artificial monuments and to baselines drawn from these monuments.
- The metes and bounds survey is based on a point of beginning, an established monument.
  - Line lengths are measured along a horizontal level plane.
  - Directions are bearing angles measured with respect to the previous line in the survey.
  - Table 11. Metes and Bounds Example
  - Figure 28a. Metes and Bounds graphic
- Metes and bounds descriptions are also referred to as **COGO** (**Co**ordinate **Geo**metry) when used in GIS and CAD systems

---

5. Summary

- This overview has introduced a number of global and regional coordinate systems. A single point on the Earth can be described in a variety of systems. Each GIS project may require the use of a specific locational reference system. It is important to be aware of the variety of systems in use.

- As an example of a point that could be referred to by a number of different system, one of the horizontal control monuments used in the survey network maintained by the National Geodetic Survey (the star in the hand of the statue of the Goddess of Liberty on top of the state capitol building in Austin, Texas) has been used throughout this overview.
    - Figure 29. The Texas Capitol Building
    - Figure 30. The Star in the Hand of The Goddess of Liberty
- This horizontal control monument can be described by many different locational reference systems.
    - Table 12. One Location Described by a Variety of Systems

---

6. Review and Study Questions

6.1. Essay and Short Answer Questions

- In what ways does the long and widespread use of SPC, UTM, COGO, and USPLS reference systems limit the possibility of building regional and state-wide GIS?
- What is metes and bounds surveying and how is it used to measure and record land records?
- The US Public Land Survey is a method of cadastral partitioning. How has it influenced the appearance of the American landscape and why?
- What is the rationale behind both the State Plane Coordinate and Universal Transverse Mercator coordinate systems?
- From the standpoint of locational reference systems (SPC and UTM) and methods of cadastral partitioning (USPLS, metes and bounds, etc.), why is Texas such an unusual state?
- Describe the Township and Range land surveying system. Use a diagram.
- What is a false origin? In practice, why are they always placed outside of the map zone being used?
- In a state of Texas's size, why can't SPC or UTM coordinates be used for mapping and GIS projects that span the entire state?
- Why was the State Plane Coordinate System such an important advance for mapping in the US?

6.2. Multiple-choice questions

Choose the best or most appropriate answer(s) to the question.

- Which of the following statements are true of **both** SPC and UTM coordinate systems?
    1. both SPC and UTM are for mapping in the US
    2. both SPC and UTM employ conformal, equidistant projections
    3. within the US both systems yield horizontal coordinates of equal precision
    4. UTM zones correspond to state boundaries, whereas SPC zone are aligned with

county boundaries

- Which system incorporates a false origin to measure position within a Cartesian grid?
    1. metes and bounds
    2. State Plane Coordinate System (SPC)
    3. Universal Transverse Mercator (UTM)
    4. Township and Range
    5. long lots

- Which of the following are true about the SPC?
    1. accuracy is 1 part in 10000
    2. the system is best used in regional and statewide GIS projects
    3. city governments resist using the SPC because of cost
    4. both A and B
    5. none of the above

---

7. Reference Materials

7.1. Print References

Bugayevskiy, Lev M. and John P. Snyder. 1995. *Map Projections: A Reference Manual*. London: Taylor and Francis.
This book contains a general exposition on map projection theory followed by sections on particular types of projection. Projections are classified by those whose parallels are straight, in the shape of concentric circles, or in the shape on non-concentric circles. Other types map projections and current map projection research are discussed. This is an excellent resource especially when paired with Snyder's *Map Projections* 1987.

Clarke, Keith C. 1995. *Analytical and Computer Cartography*, 2nd ed. Englewood Cliffs, NJ: Prentice Hall.
This book contains descriptions of most coordinate systems used in GIS along with enough technical details (including source code examples and a diskette) to work out many coordinate system conversions including computer raster graphic transformations not included in many other books on map projections.

Defense Mapping Agency. 1977. *The American Practical Navigator: Publication No. 9,* Defense Mapping Agency Hydrographic Center.
A venerable reference work containing many practical details for using maps and navigation systems. While primarily useful for working with nautical charts, the book contains sections on numerous navigation aids, from sextants to GPS.

Defense Mapping Agency. 1991. *World Geodetic System 1984 (WGS 84) - Its Definition and Relationships with Local Geodetic Systems,* 2nd Edition. Washington, DC: Defense Mapping Agency (DoD).
The primary source for WGS-84 information, including lists of reference ellipsoids, geodetic datums, and the simple three-parameter datum shift values required for datum

transformation approximations.

Laurila, Simo H. 1976. *Electronic Surveying and Navigation.* New York: John Wiley & Sons.
An excellent source for geodetic formulas, including details on latitude, longitude, height systems, rectangular coordinate systems and ellipsoidal geodesics. The book, while somewhat dated now, provides a good background on many surveying and navigation systems in use today.

Muehrcke, P.C and Juliana O. Muehrcke. 1992. *Map Use.* Madison, WI: JP Publications.
While not a technical manual for mapping transformations, the book has very clear descriptions of most coordinate systems as well as discussions of many more detailed GIS issues relating to terrain surfaces and statistical evaluations.

Maling, D.H. 1992. *Coordinate systems and map projections.* 2nd ed. New York: Pergamon Press.
A reference manual containing algorithms and formulas for conversion between different coordinate systems and map projections.

Robinson, Arthur H., Joel L. Morrison, Phillip C. Muehrcke, A. Jon Kimerling, and Stephen C. Guptill. 1995. *Elements of Cartography*. 6th ed. New York: John Wiley and Sons, 41-58, 91-111.
A book that has served as the basis for cartography courses for more than 40 years. An indispensable reference book covering all phases of map making and map reading.

Snyder, John P. 1987. *Map Projections: A Working Manual.* Washington, DC: US Government Printing Office.
The best single reference for details on map projection methods, the book includes numerical examples for help in producing map projection code.

US Army. 1967. *TM 5-241-1 Grids and Grid References.* Washington, DC: Department of the Army.
A complete description of MGRS and UTM, including maps of the world with the MGRS preferred "spheroids" and MGRS row offsets. This old edition is out of print and does not contain WGS-84-based MGRS details.

7.2. Web References

7.2.1. US Federal Agencies

- US Army Corps of Engineers, http://www.tec.army.mil/
  - maintains the CORPSCON program

- US Geological Survey, http://www.usgs.gov/
  - National Mapping Division
  - Global Land Information System

- US National Geodetic Survey, http://www.ngs.noaa.gov/
    - Geodetic Control Subcommittee
- US National Imagery and Mapping Agency (NIMA)

7.2.2. Non-US Federal Agencies

- Australian Surveying and Land Information Group (AUSLIG),
    - AUSLIG Geodesy Division
- British Geological Survey, http://www.bgs.ac.uk/
- Geomatics Canada/Gomatique Canada
    - National Atlas Information Service
    - Geodetic Survey of Canada/Division des levés géodésiques, http://www.geod.nrcan.gc.ca/
- Geographical Survey Institute of Japan
- Institut Géographique National (France)
- National Survey and Cadastre (Denmark), http://www.kms.dk/index_en.html
- Ordnance Survey (United Kingdom)
- Ordnance Survey of Northern Ireland, http://www.osni.gov.uk/
- Sistema Nactional de Informação Geográphica (Portugal)
- Statens Kartverk (Norway), http://www.statkart.no/

7.2.3. Other relevant webpages

- The following are related sections by the same author in *The Geographer's Craft Project* at the University of Texas Austin:
    - Dana, Peter H. 1995. Geodetic Datum Overview, http://www.colorado.edu/geography/gcraft/notes/datum/datum_f.html
    - Dana, Peter H. 1995. Coordinate Systems Overview, http://www.colorado.edu/geography/gcraft/notes/coordsys/coordsys_f.html
    - Dana, Peter H. 1995. Map Projections Overview, http://www.colorado.edu/geography/gcraft/notes/mapproj/mapproj_f.html

---

Citation

To reference this material use the appropriate variation of the following format:

> Dana, Peter H. (1997) Coordinate Systems Overview, *NCGIA Core Curriculum in GIScience*, http://www.ncgia.ucsb.edu/giscc/units/u013/u013.html, posted (today).

Created: June 10, 1996. Last revised: July 7, 2000.

Coordinate Systems Overview

Table of Contents

Advanced Organizer

- Topics Covered in this Unit
- Learning Outcomes
- Instructors' Notes
- Metadata and Revision History

1. Basic Coordinate Systems

- 1.1 Plane Coordinate Systems
- 1.2 Three Dimensional Coordinate Systems

2. Earth-Based Locational Reference Systems

- 2.1 Reference Ellipsoids
- 2.2 Geodetic Datums

3. Global Systems

- 3.1 Latitude, Longitude, Height
- 3.2 ECEF X, Y, Z
- 3.3 Universal Transverse Mercator (UTM)
- 3.4 Military Grid Reference System (MGRS)
- 3.5 World Geographic Reference System (GEOREF)

4. Regional Systems

- 4.1 Transverse Mercator Grid Systems
  - 4.1.1 British National Grid
- 4.2 Universal Polar Stereographic (UPS)
- 4.3 State Plane Coordinates
- 4.4 Public Land Rectangular Surveys
- 4.5 Metes and Bounds

5. Summary

6. Review and Study Questions

- 6.1 Essay and Short Answer Questions
- 6.2 Multiple-choice Questions

7. References

- 7.1 Print References
- 7.2 Web References
    - 7.2.1 US Federal Agencies
    - 7.2.2 Non-US Federal Agencies
    - 7.2.3 Other Relevant Webpages

Last revised May 20, 1997.

Coordinate Systems Overview

Instructors' Notes

Several techniques can be used to help students gain a working knowledge of coordinate systems. Indeed, this 50-minute module can readily be expanded to include another 50-minute coordinate system "workshop" using maps and mapping reading problems.

Illustrations

It is useful to teach this unit using sets of maps that employ different coordinate systems. Build a collection of local maps as well as maps from other states, provinces, or nations. These can be used for illustration or assigned to individual students for coordinate "readouts."

Practice

Have students practice using both global and local coordinate systems to find locations. Present them with problems where they must both locate positions on maps from coordinates and read coordinates from maps.

Projects

Develop projects that present problems with respect to the use of coordinate systems. These might involve GIS projects that span different UTM or SPC zones, or projects that involve collating information recorded in several different coordinate systems.

Back to the Unit

Coordinate Systems Overview

Metadata and Revision History

Page contents

1. About the main contributors
2. Details about the file
3. Key words
4. Index words
5. Prerequisite units
6. Subsequent units
7. Revision history

---

1. About the main contributors

- author: Peter H. Dana, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098
- editor: Kenneth E. Foote, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098

2. Details about the file

- last revision date: 21 May 1997
- unit title: Coordinate System Overview
- unit key number: Unit 013w

3. Key words

- Coordinate Systems
- Georeferencing
- Precise Positioning
- Location

4. Index words

- reference ellipsoid ("reference ellipsoid")
- geodetic datum ("geodetic datum")
- Cartesian coordinates ("Cartesian coordinates")
- Earth Centered, Earth Fixed Coordinates ("ECEF")
- Universal Transverse Mercator ("UTM")
- Military Grid Reference System ("MGRS")
- World Geographic Reference Systems ("GEOREF")
- Universal Polar Stereographic Coordinates ("UPS")
- British National Grid ("BNS")
- State Plane Coordinate System ("SPC")
- US Public Land Survey System ("USPLS")

5. Prerequisite units

- 008 - Representing the Earth

6. Subsequent units

- 018 - Mapping the Earth
- 066 - Populating the GISystem
- 082 - Kinds of Geospatial Data
- 096 - Handling Uncertainty
- 136 - Making it Work

7. Revision history

- 28 February 1997. 12 tables converted from gif to html format. New tables placed in /tables subdirectory below unit root. Figures renumbered.
- 2 March 1997. Web references added to text and bibliography.
- 13 March 1997. Major format revision. Bold and italics added for definitions and technical terms. Frame version and short table of contents created.
- 25 March 1997. Editorial changes made in sections 2.1 (Reference Ellipsoids); 2.2 (Geodetic Datums); 3.3 (UTM); and 4.5 (Metes and Bounds). Additional technical and definitional terms highlighted. NAME annotations corrected to properly anchor text.
- 21 May 1997. Further editorial changes made. File posted to NCGIA website.
- 4 July 1997. Figure 3 replaced.
- 7 July 2000. External links updated.

- Back to the Unit: Coordinate System Overview

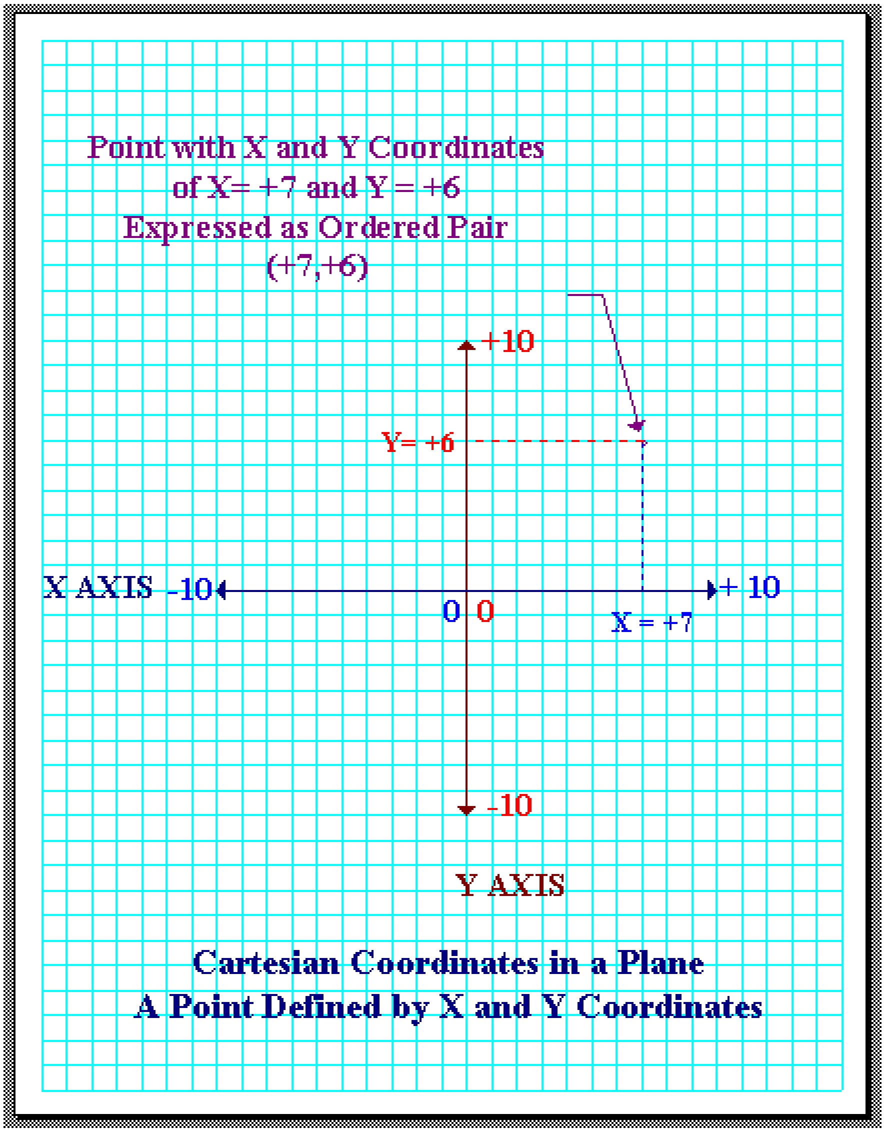


Figure 1. A Point Described by Cartesian Coordinates in a Plane

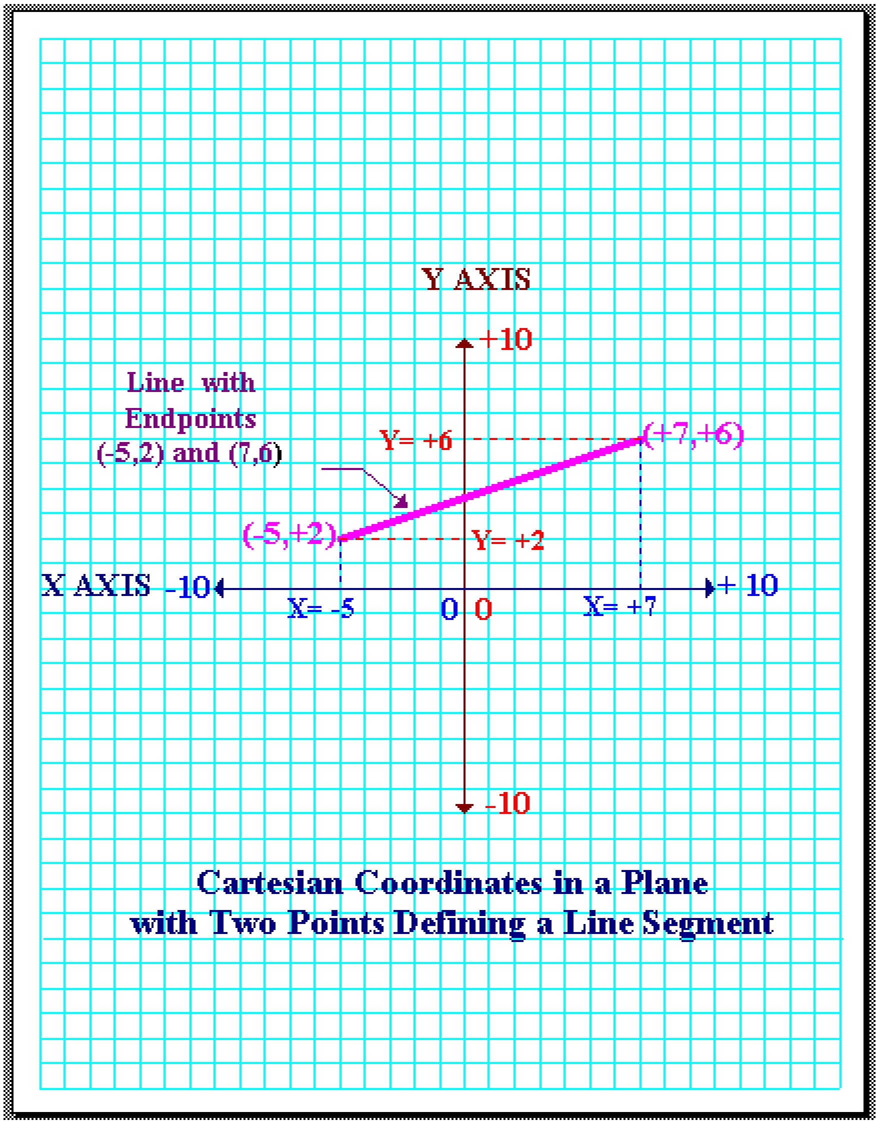


Figure 2. A Line Defined by Two Points in a Plane

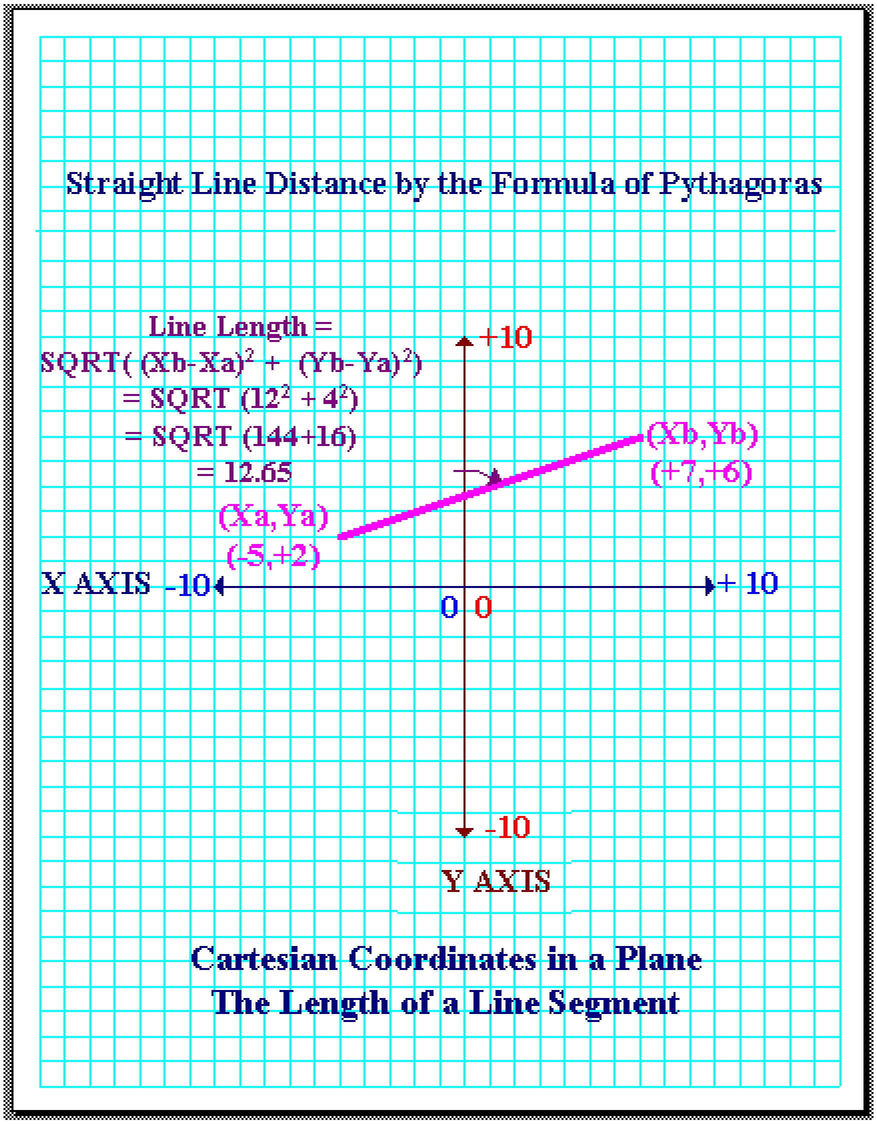


Figure 3. Distance Between Two points (Line Length) from the formula of Pythagoras

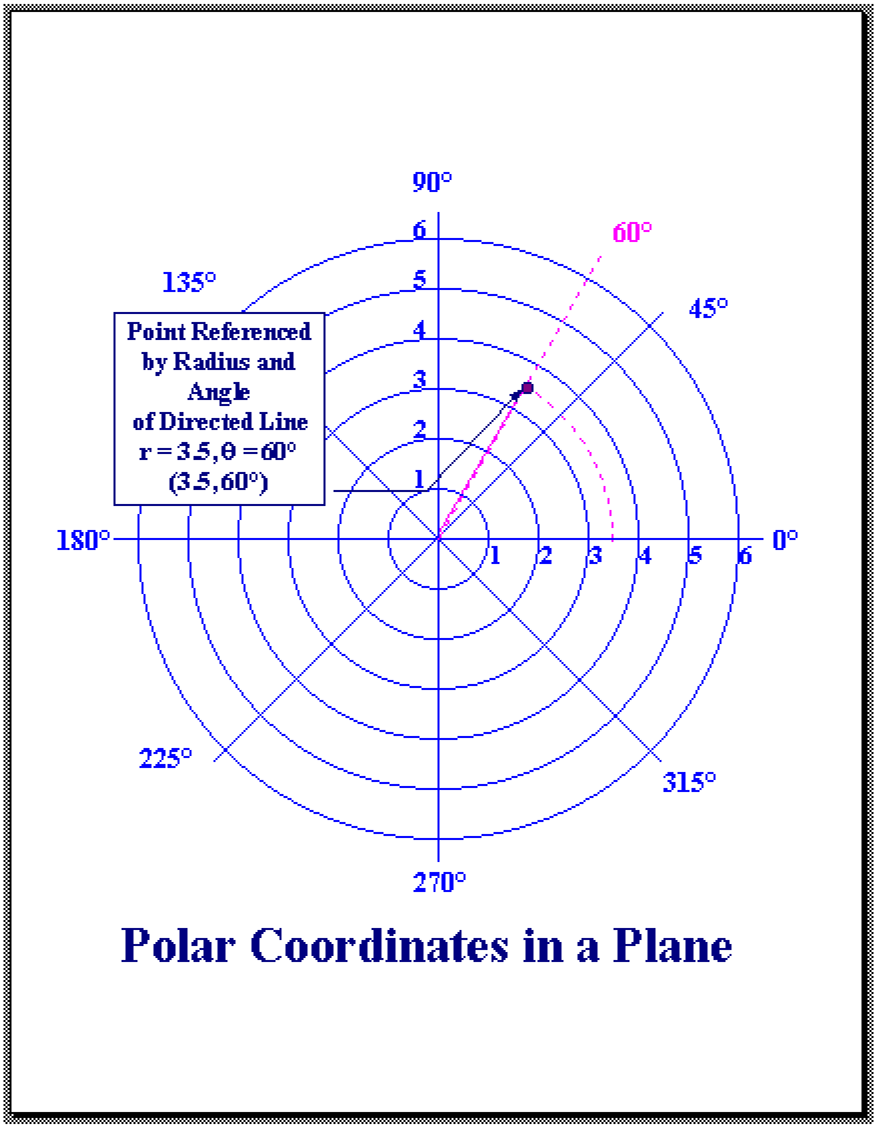


Figure 4. A Point Described by Polar Coordinates in a Plane

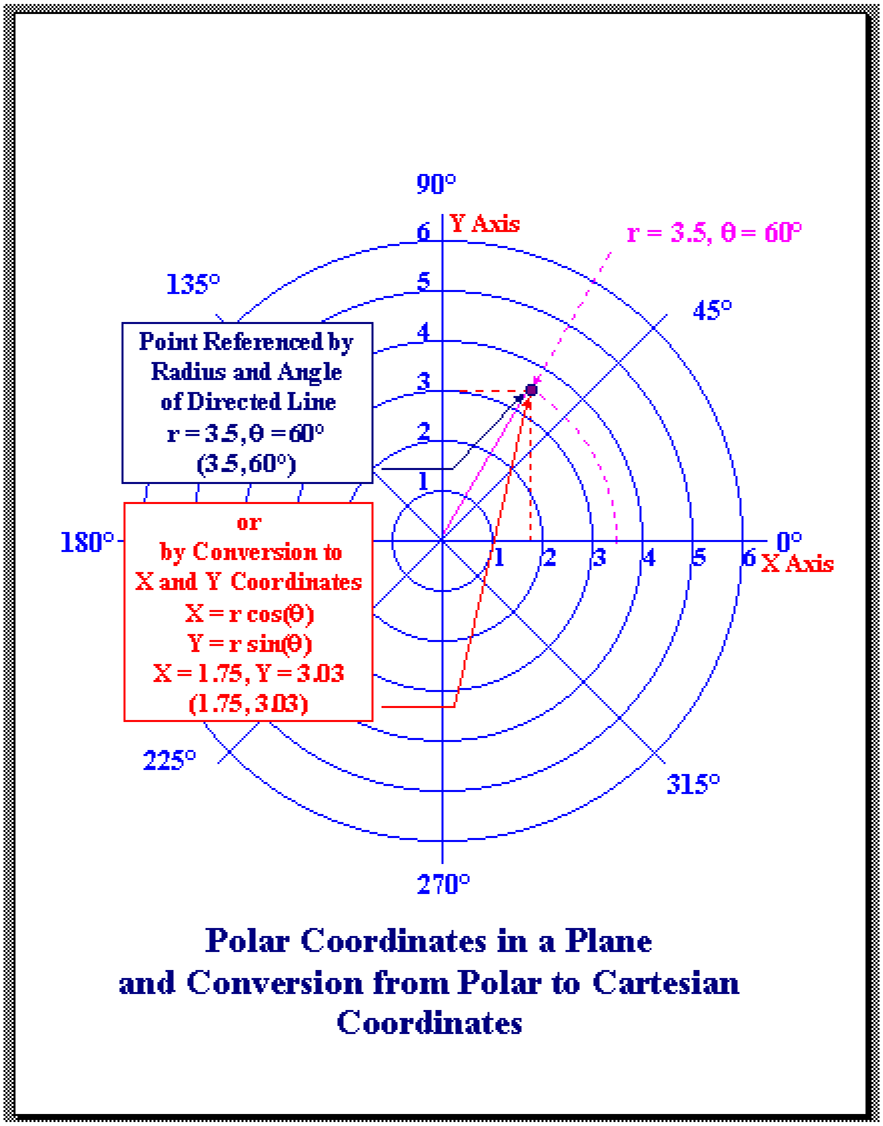


Figure 5. Conversion of Polar to Cartesian Coordinates in a Plane

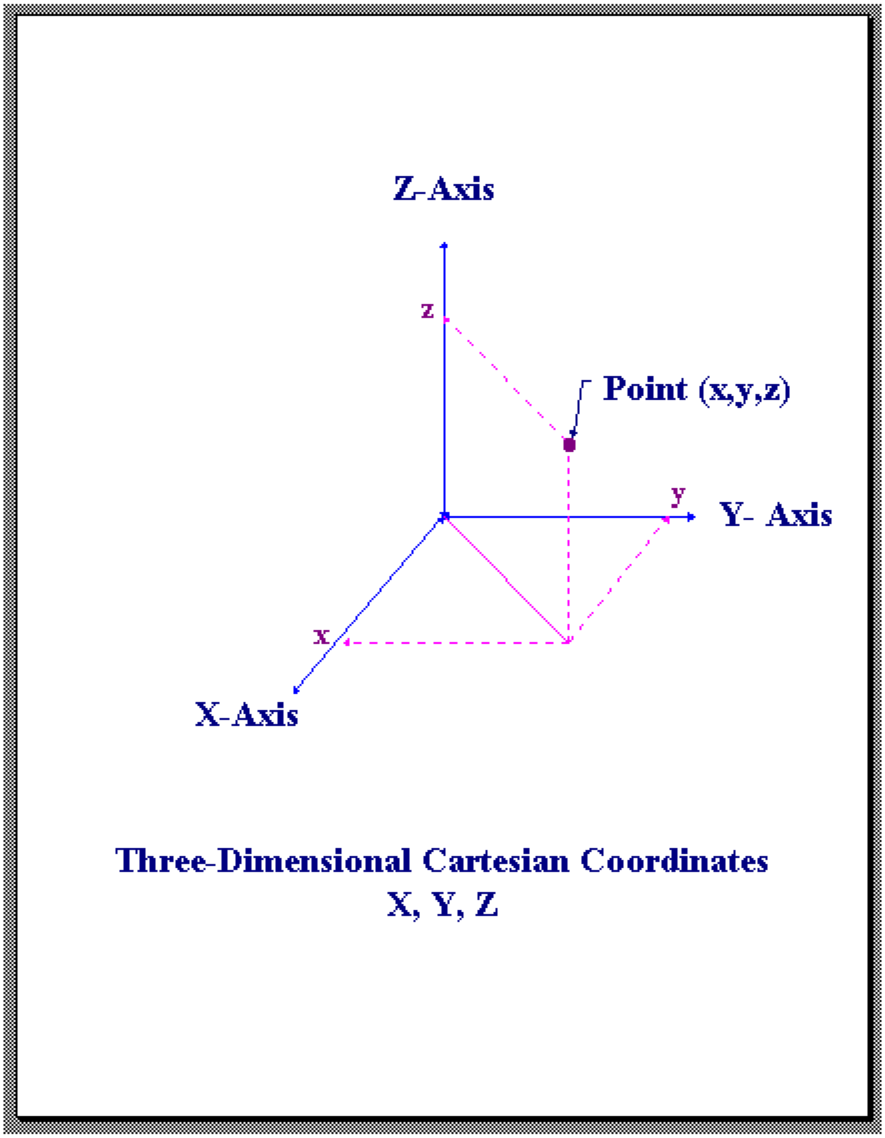


Figure 6. A Point Described by Three-Dimensional Cartesian Coordinates

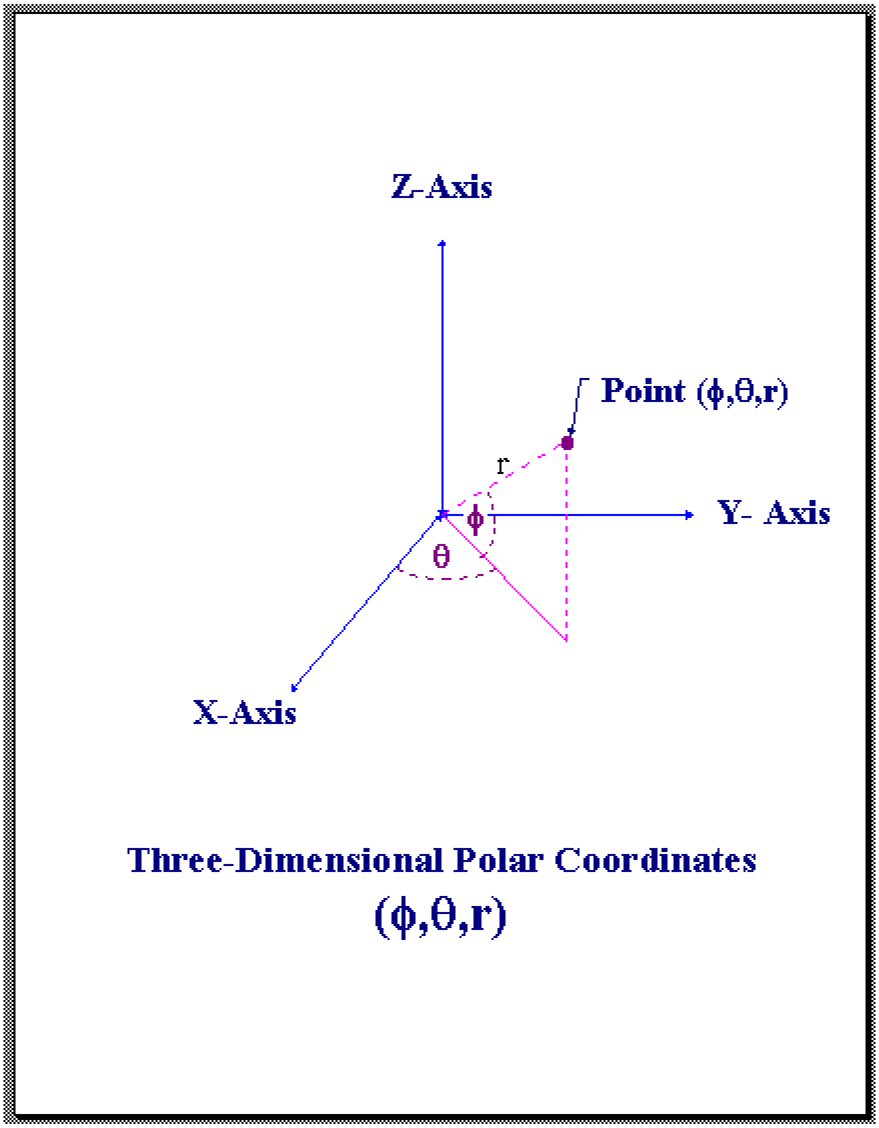


Figure 7. A Point Described by Three-Dimensional Polar Coordinates

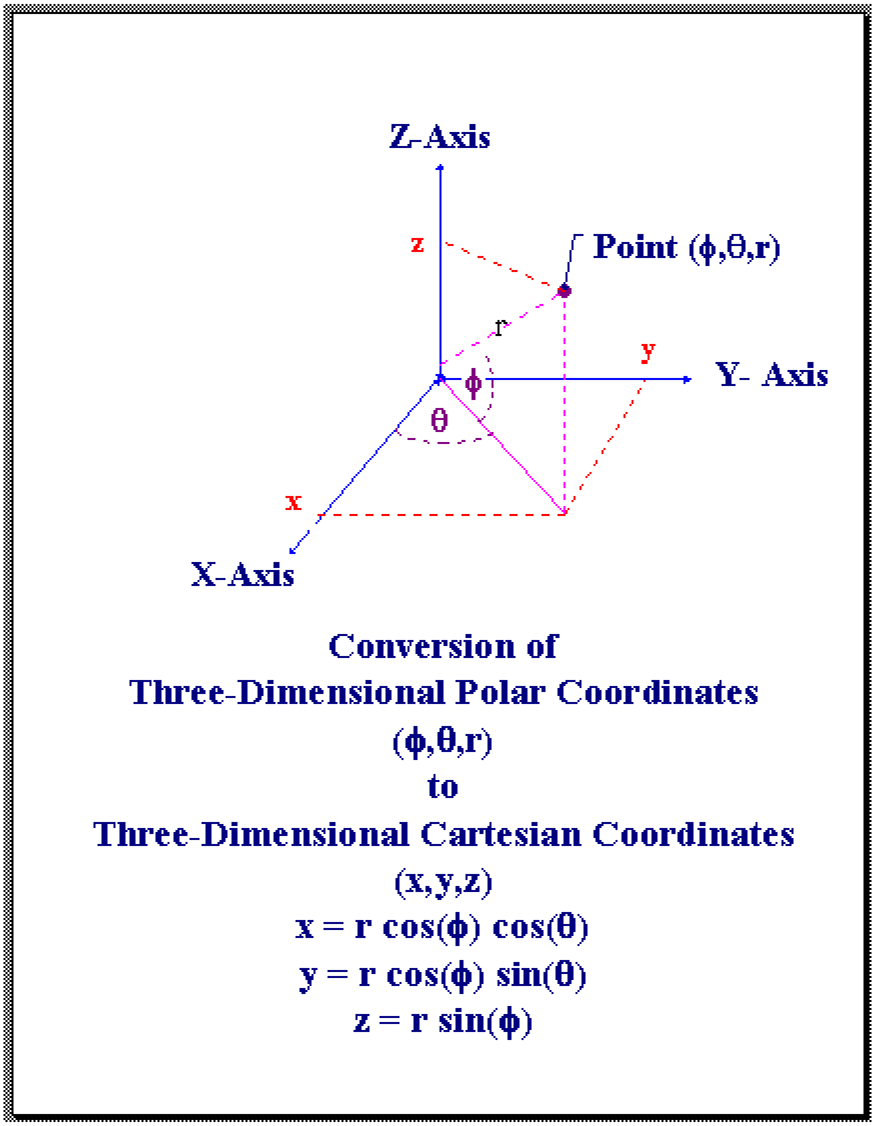


Figure 8. Conversion of Three-Dimensional Polar to Three Dimensional Cartesian Coordinates

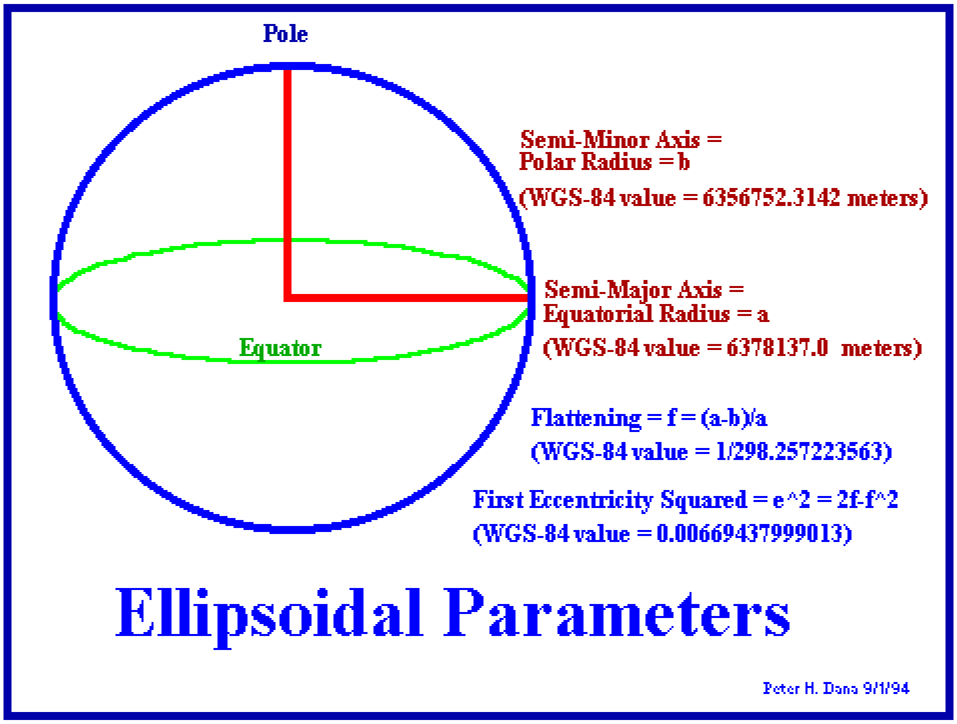


Figure 9. Reference Ellipsoid Parameters

Selected Reference Ellipsoids

Ellipse	Semi-Major Axis	Flattening
Airy 1830	6377563.396	299.3249646
Bessel 1841	6377397.155	299.1528128
Clarke 1866	6378206.4	294.9786982
Clarke 1880	6378249.145	293.465
Everest 1830	6377276.345	300.8017
Fischer 1960 (Mercury)	6378166	298.3
Fischer 1968	6378150	298.3
G R S 1967	6378160	298.247167427
G R S 1975	6378140	298.257
G R S 1980	6378137	298.257222101
Hough 1956	6378270	297.0
International	6378388	297.0
Krassovsky 1940	6378245	298.3
South American 1969	6378160	298.25
WGS 60	6378165	298.3
WGS 66	6378145	298.25
WGS 72	6378135	298.26
WGS 84	6378137	298.257223563

Table 1. Selected Reference Ellipsoids

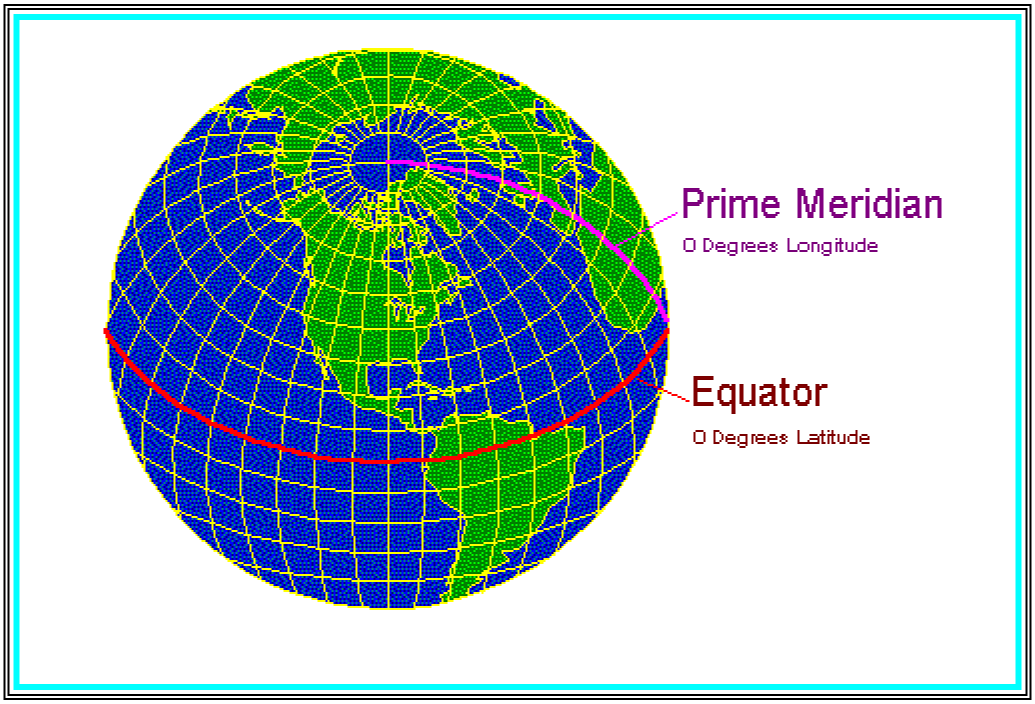


Figure 10. Equator and Prime Meridian

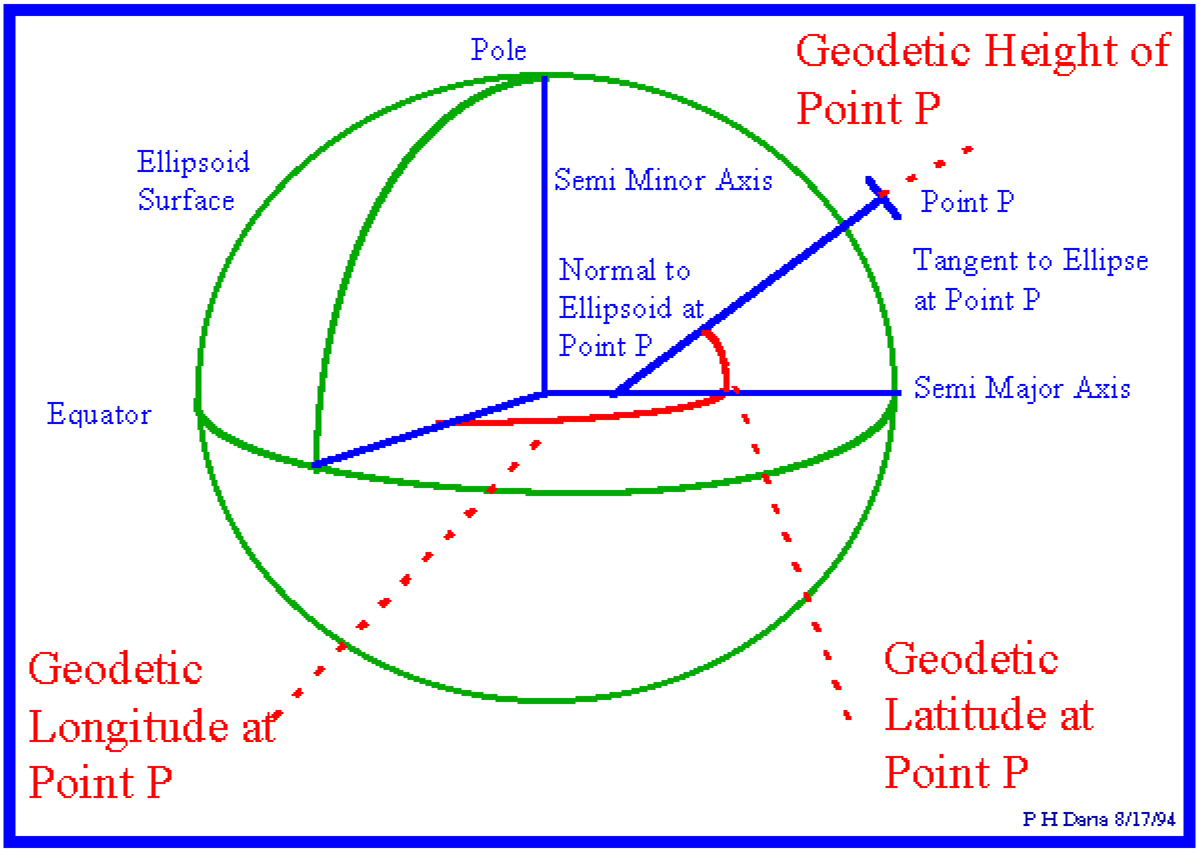


Figure 11. Geodetic Latitude, Longitude, and Height

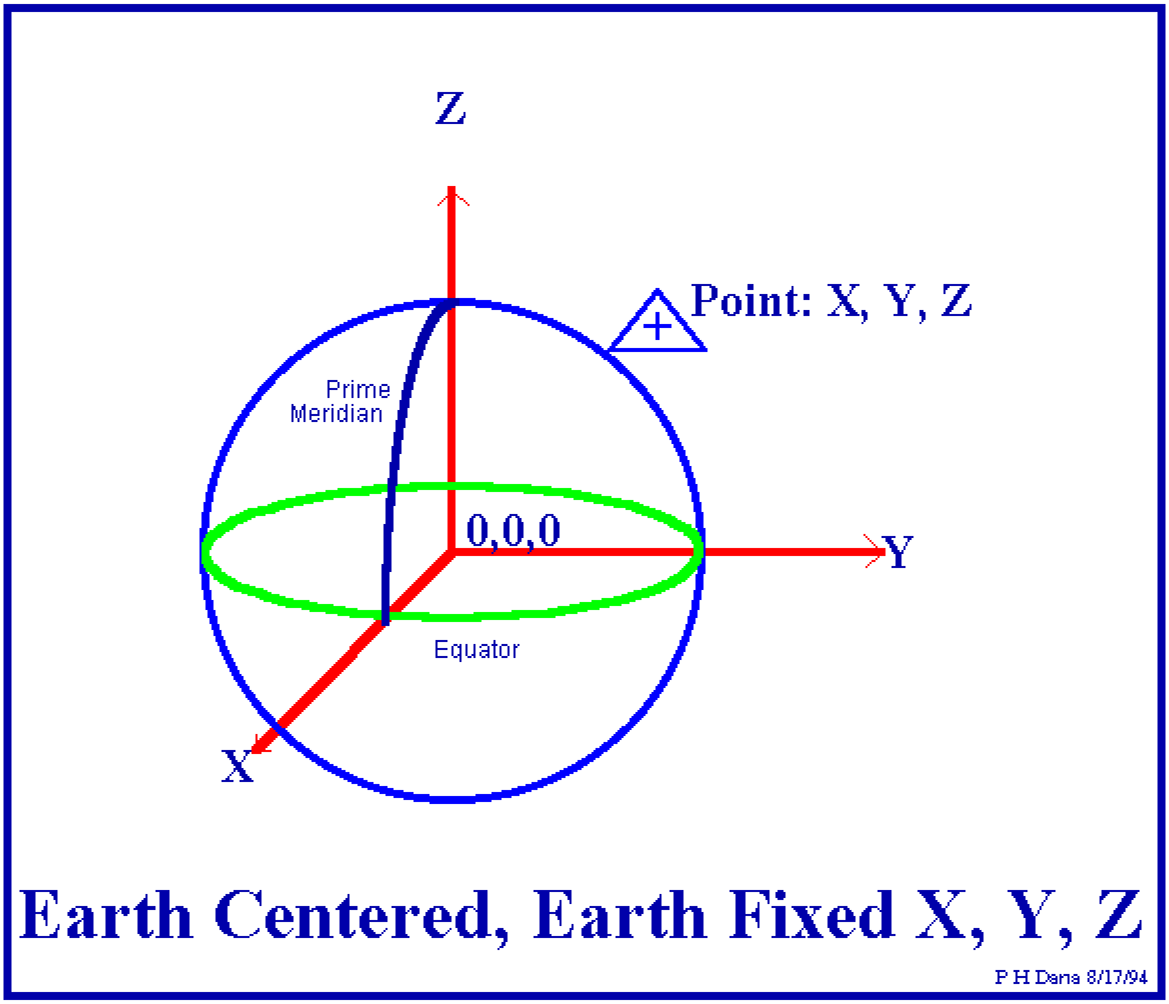


Figure 12. ECEF X, Y, and Z

Earth Centered, Earth Fixed (ECEF) X, Y, Z Example

NAD-83 Latitude, Longitude of 30:16:28.82 N 97:44:25.19 W

is

X = -742507.1

Y = -5462738.5

Z = 3196706.5

Table 2. ECEF X, Y, Z Coordinates Example

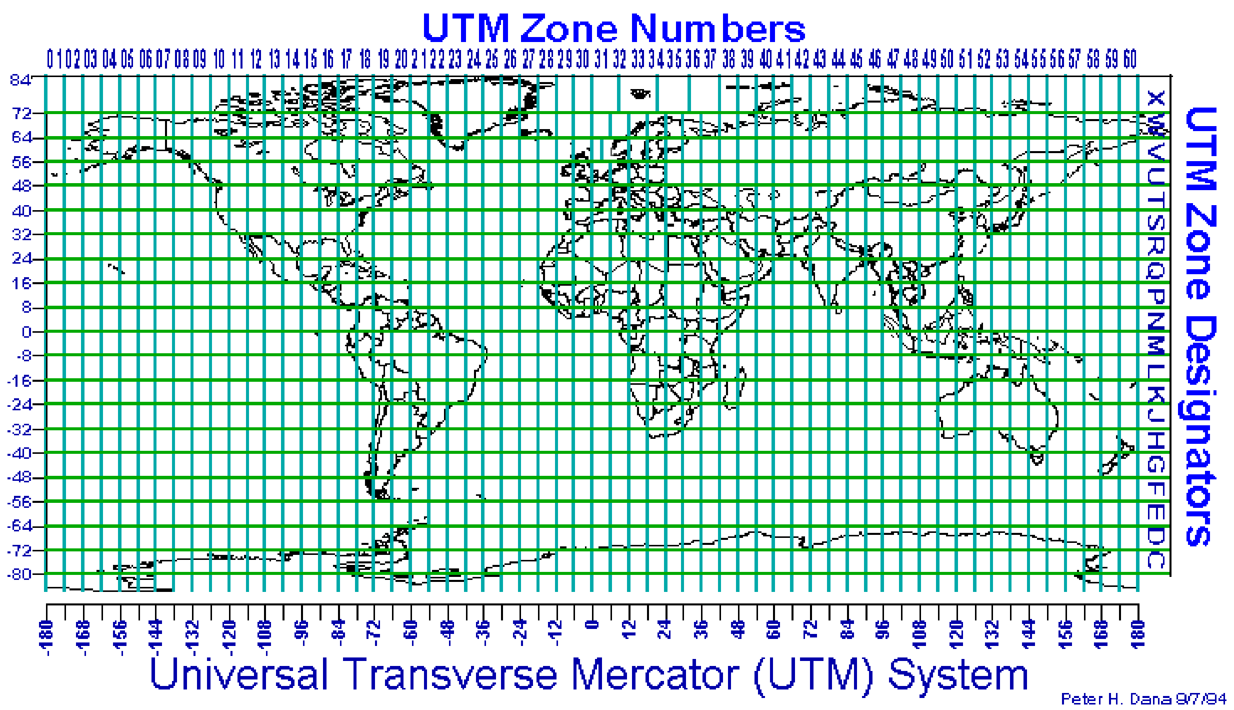


Figure 13. UTM Zones

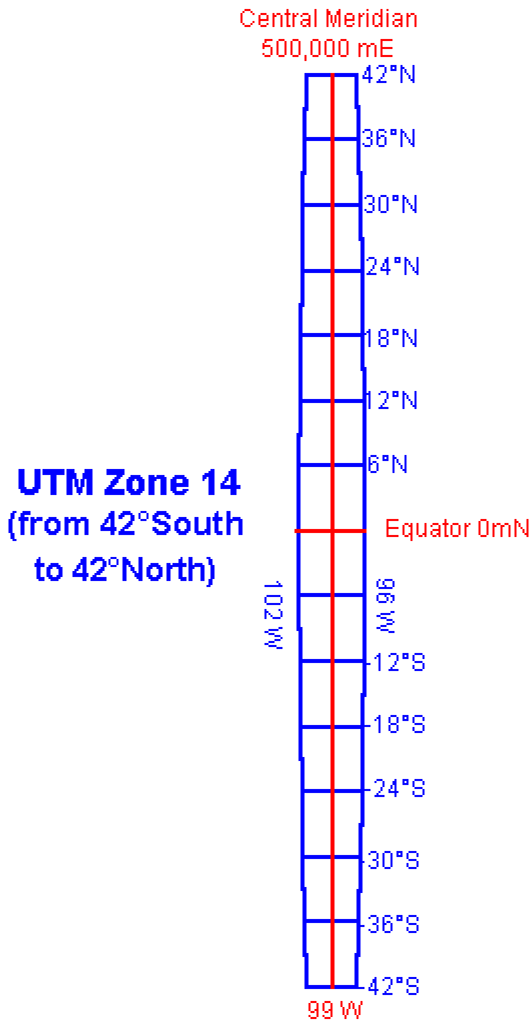


Figure 14. UTM Zone 14

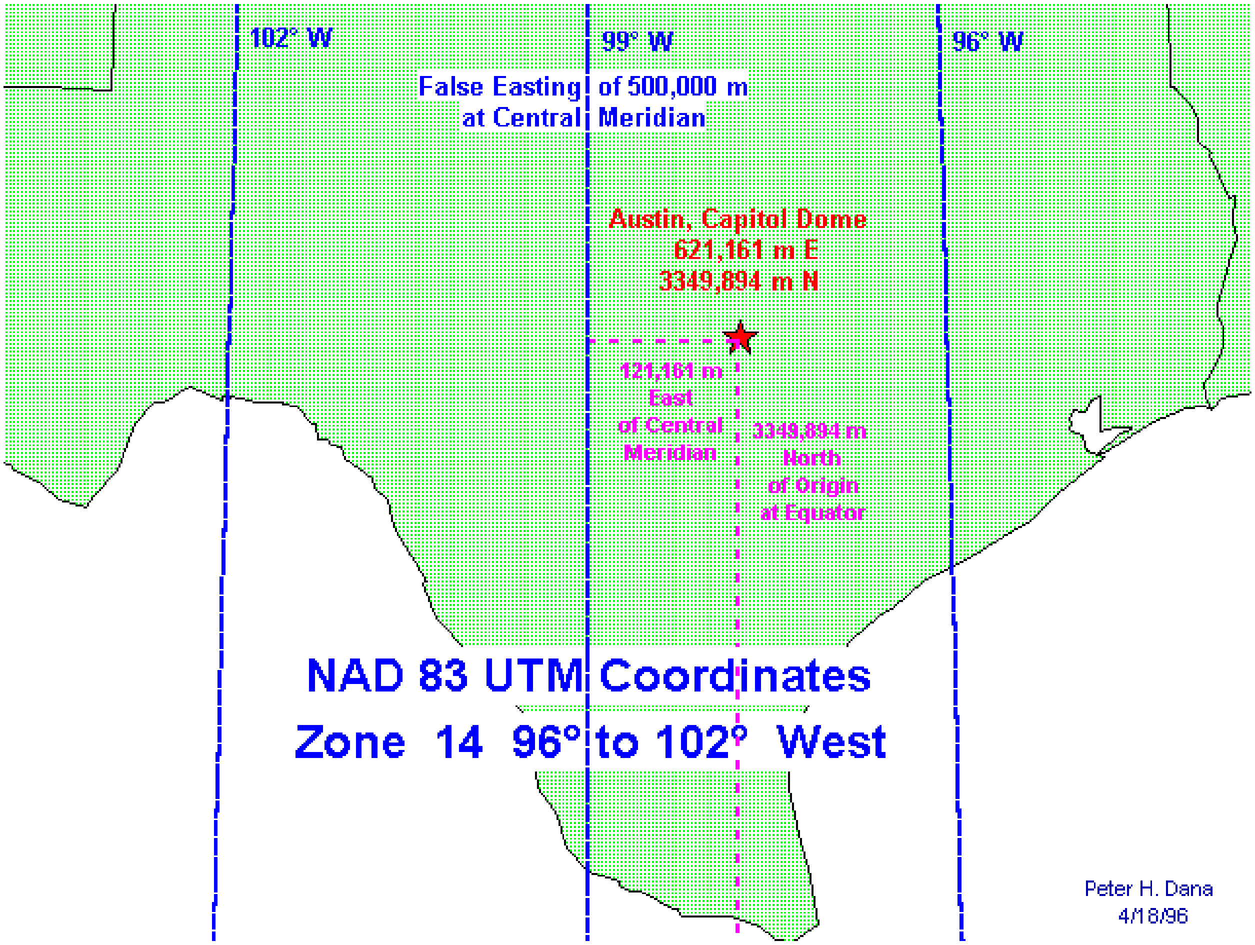


Figure 15. UTM Zone 14 Example Detail

Universal Transverse Mercator (UTM) Example

NAD-83 Latitude, Longitude of 30:16:28.82 N 97:44:25.19 W **is** **NAD-83 UTM Easting, Northing** **621160.98m 3349893.53m** **Zone 14 R**

Table 3. UTM Coordinate Example

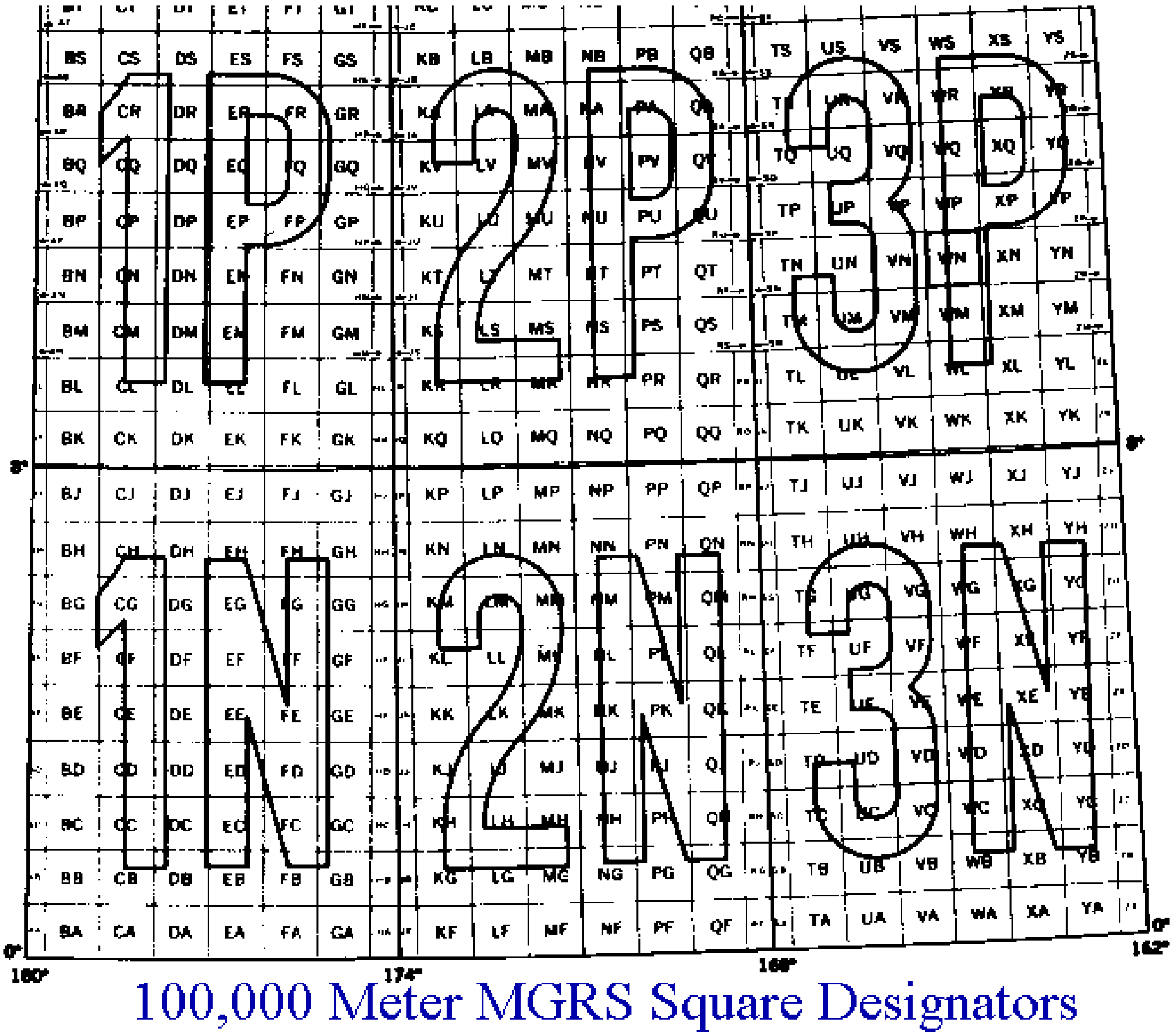


Figure 16. Military Grid Reference System

Military Grid Reference System (MGRS) Example

NAD-83 Latitude, Longitude of 30:16:28.82 N 97:44:25.19 W
is
NAD-83 Military Grid Reference
14RPU2116149894

Table 4. MGRS Example

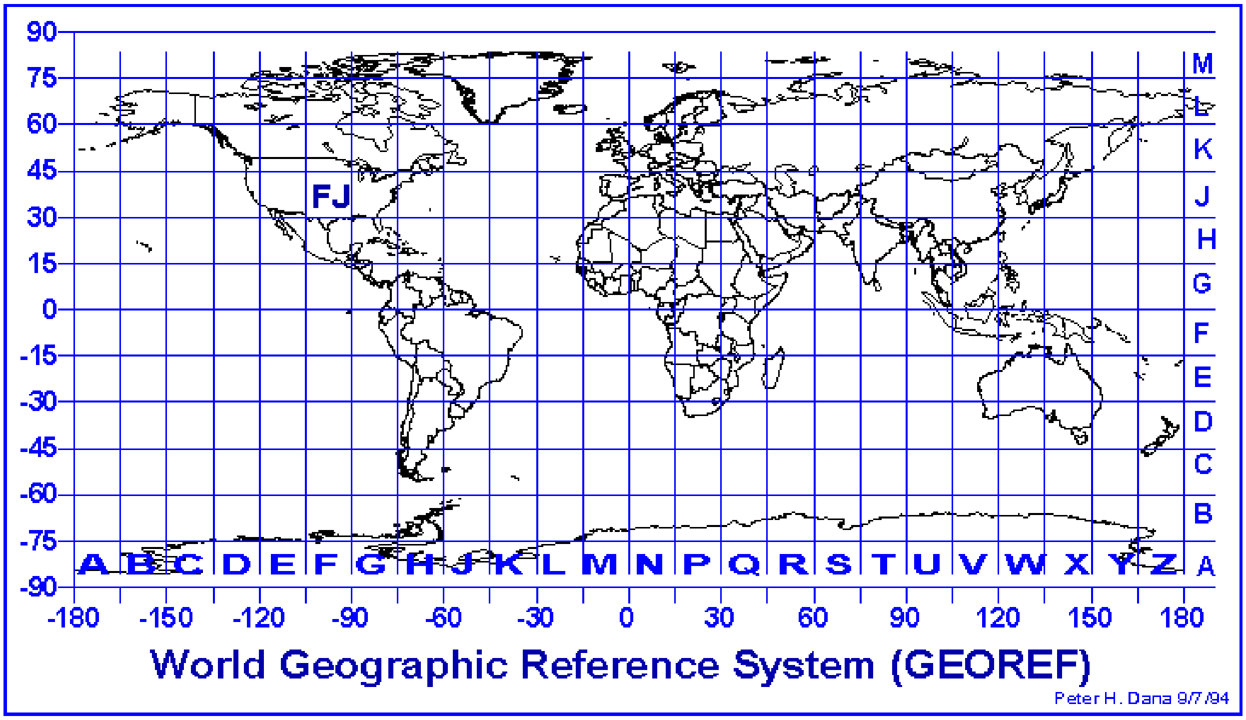


Figure 17. World Geographic Reference System Index

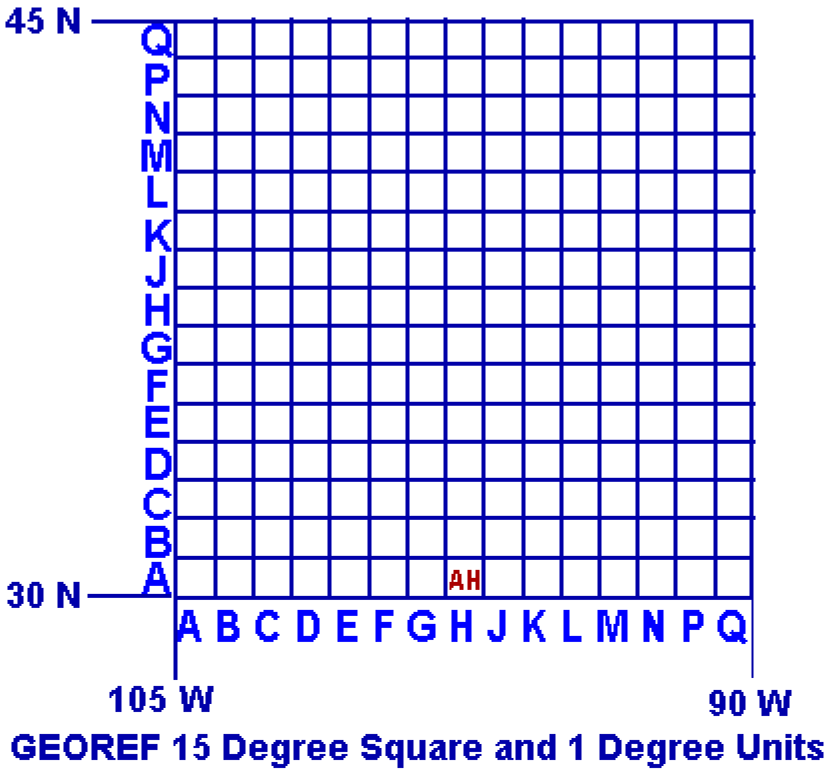


Figure 18. GEOREF 1 Grid

World Geographic Reference (GEOREF) System Example

NAD-83 Latitude, Longitude of 30:16:28.82 N 97:44:25.19 W
is
World Geographic Reference System
FJHA1516

Table 5. GEOREF Example

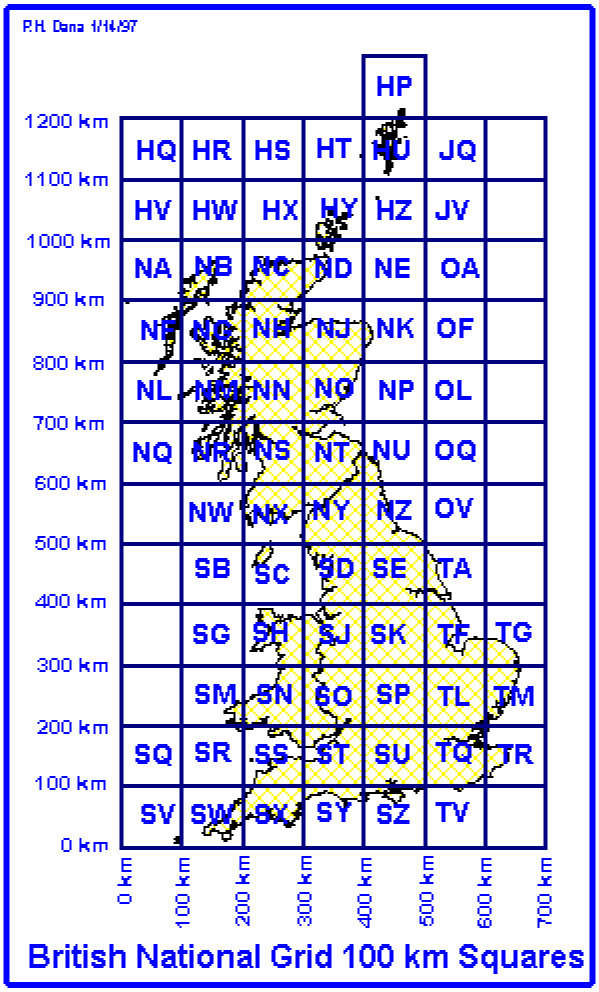


Figure 19. British National Grid 100 km Squares

British National Grid Example

OS36 Latitude, Longitude of 54:30:52.55 N 1:27:55.75 W
is
British National Grid
NZ3460013400

Table 6. British National Grid Example

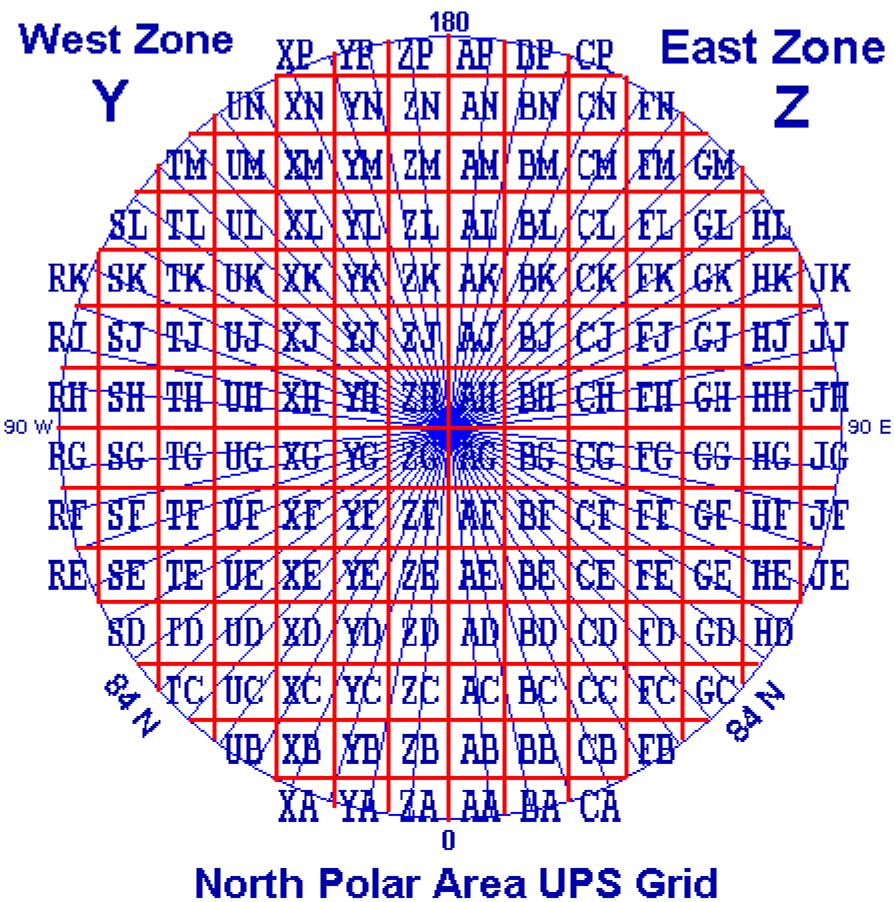


Figure 20. North Polar Area UPS Grid

North Polar Area UPS Example

NAD-83 Latitude, Longitude of 85:40:30.0 N 85:40:30.0 W

is

Universal Polar Stereographic

ZGG7902863771

Table 7. North Polar UPS Example

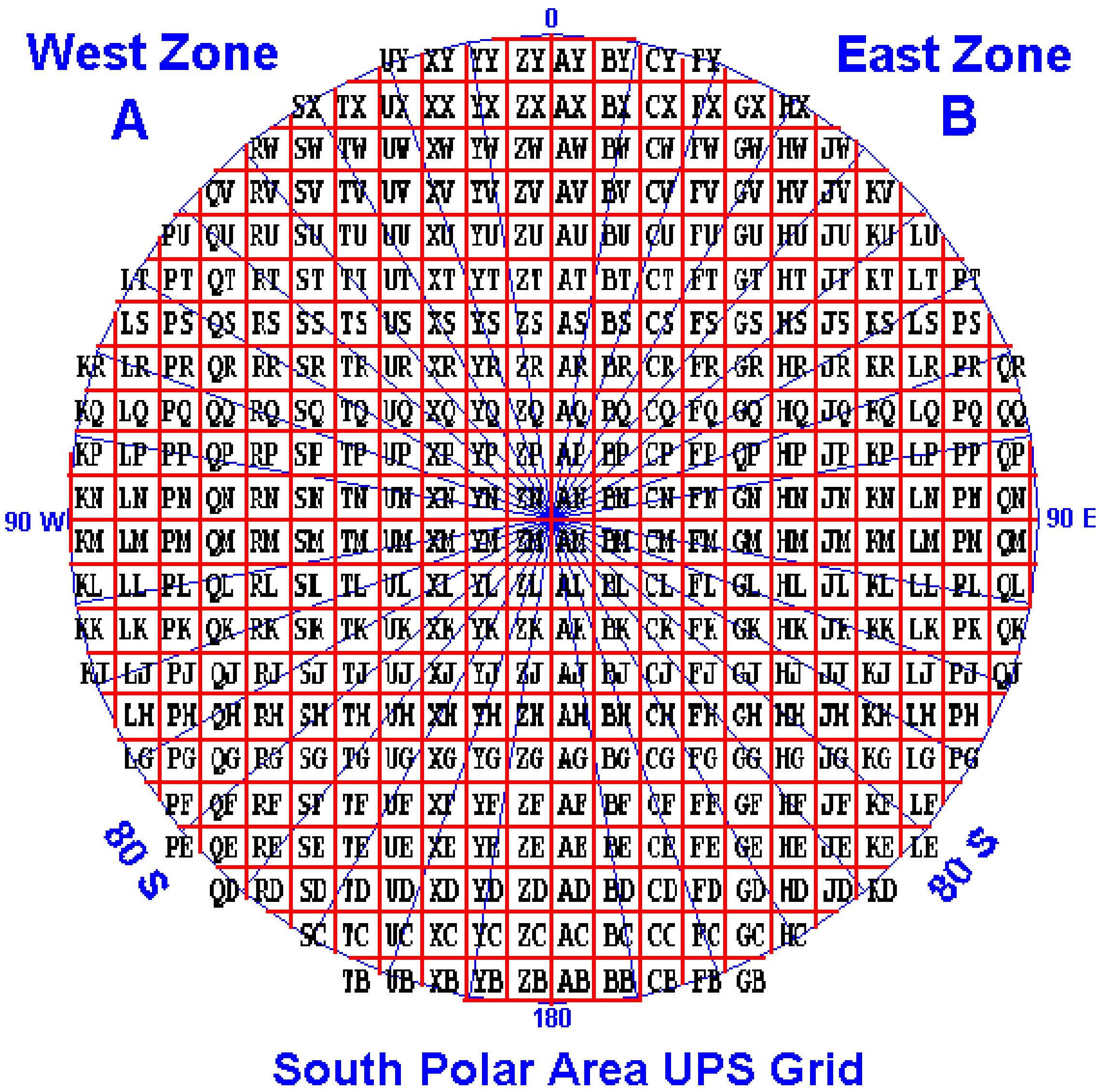


Figure 21. South Polar Area UPS Grid

South Polar Area UPS Example

NAD-83 Latitude, Longitude of 85:40:30.0 S 85:40:30.0 W
is
Universal Polar Stereographic
ATN2097136228

Table 8. South Polar UPS Example

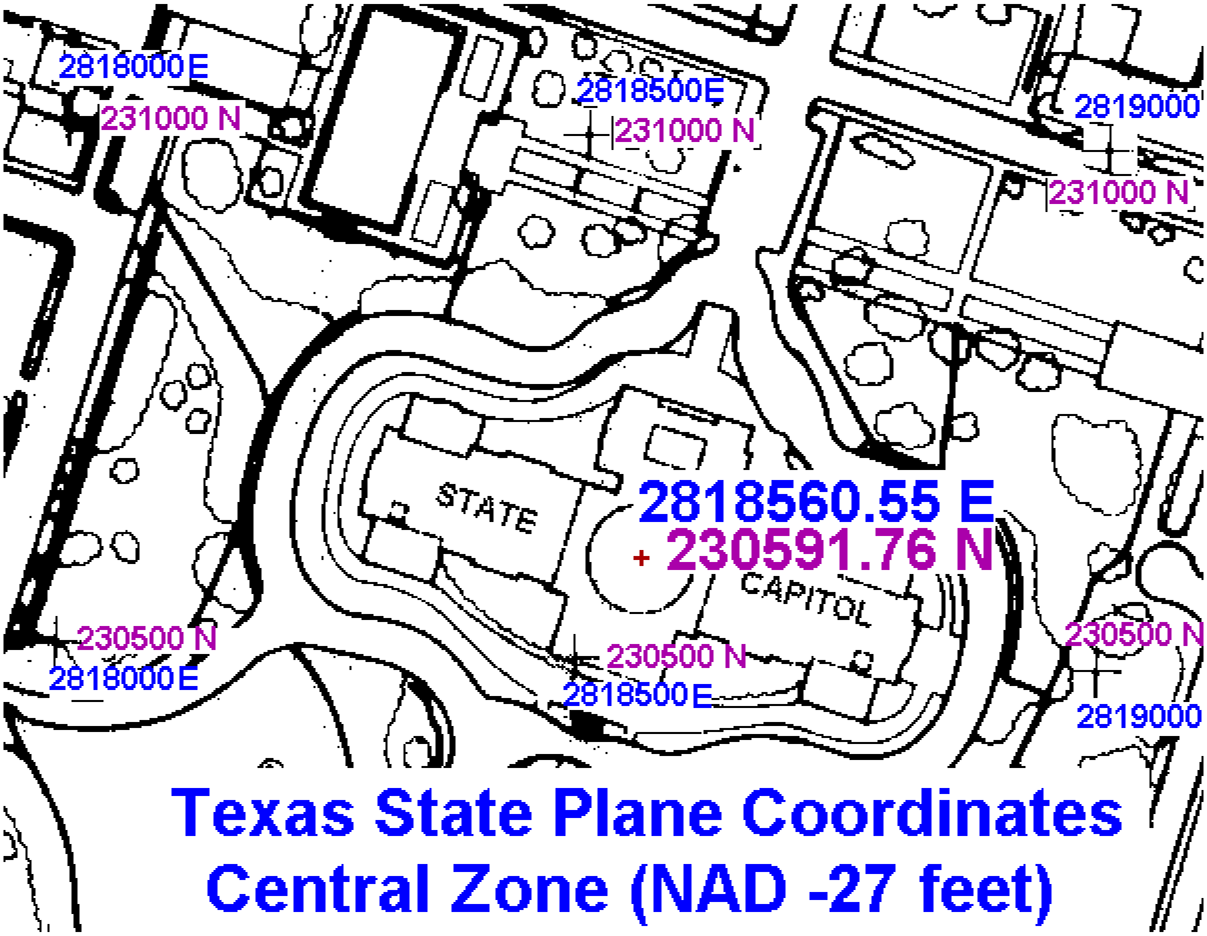


Figure 22. NAD-27 State Plane Coordinate Example

State Plane Coordinate System Example

NAD-83 Latitude, Longitude of 30:16:28.82 N 97:44:25.19 W

is

NAD-83 Texas Central Zone

State Plane Coordinates, Easting and Northing

949465.059m, 3070309.475m

Table 9. NAD-83 State Plane Coordinate Example

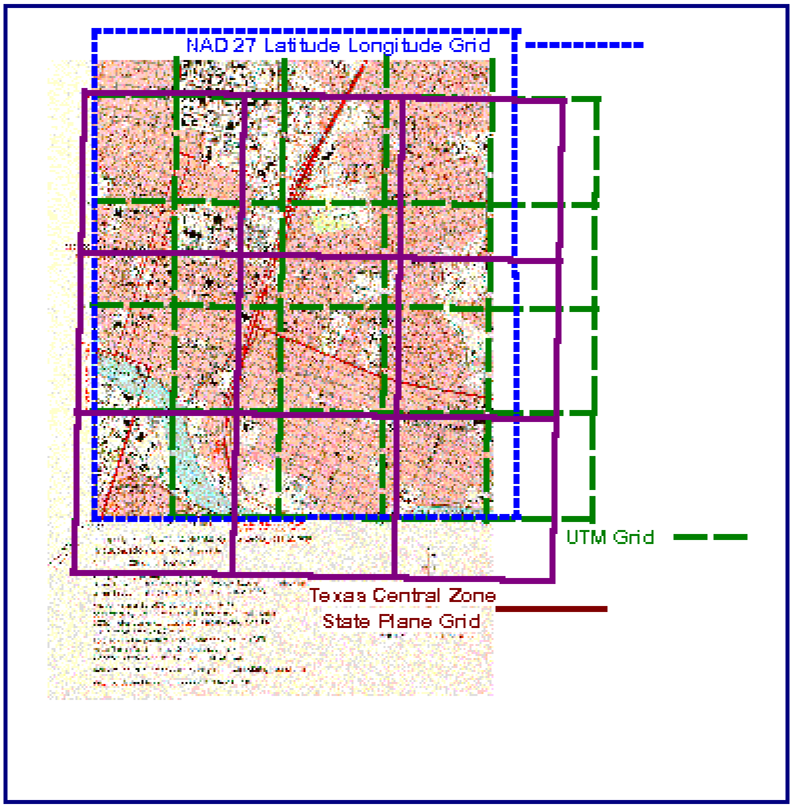


Figure 23. Three Coordinate Systems on the Austin, East USGS 7.5' Quadrangle

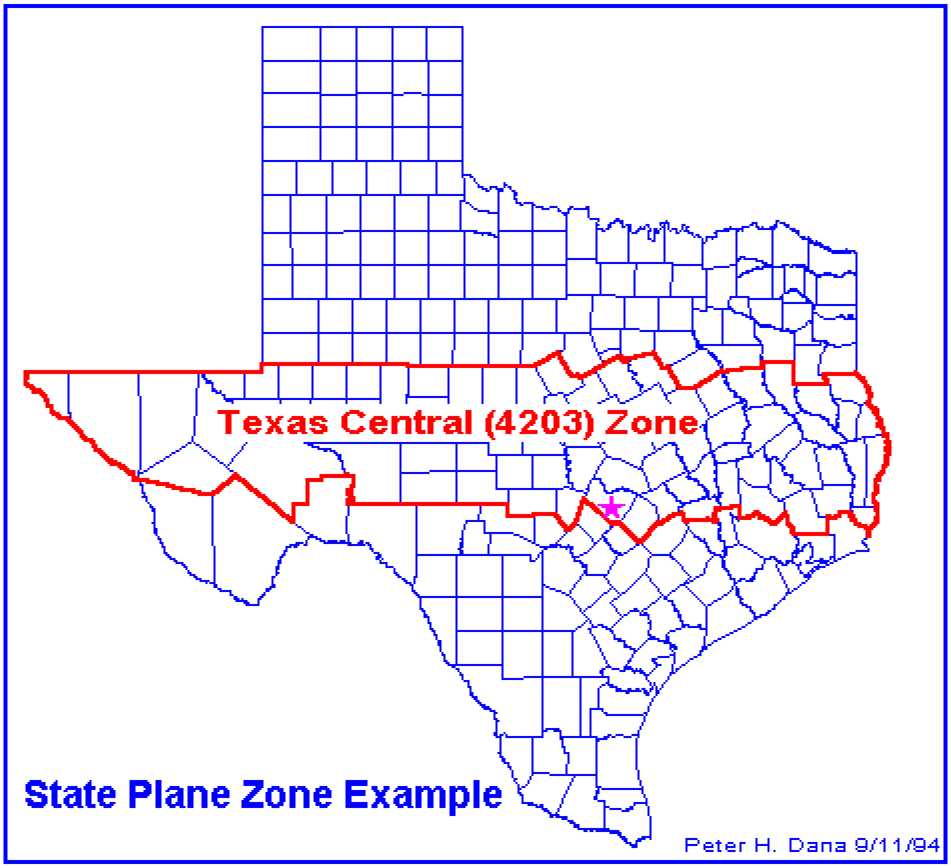


Figure 24. State Plane Zone Example

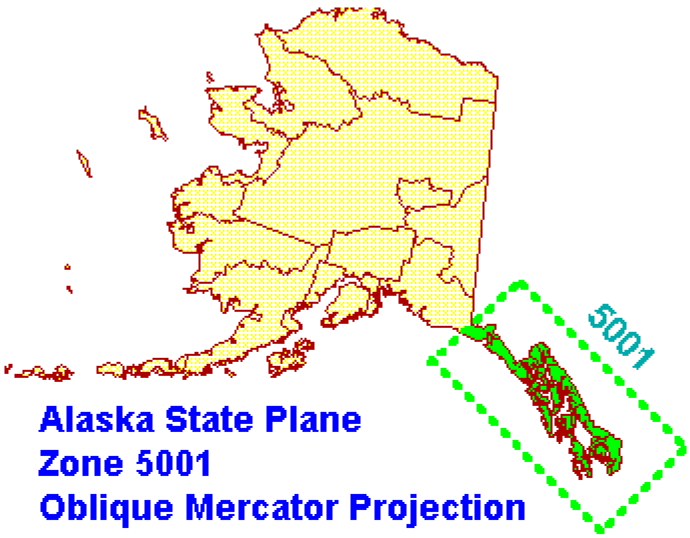


Figure 25. Alaska State Plane Zone 5001

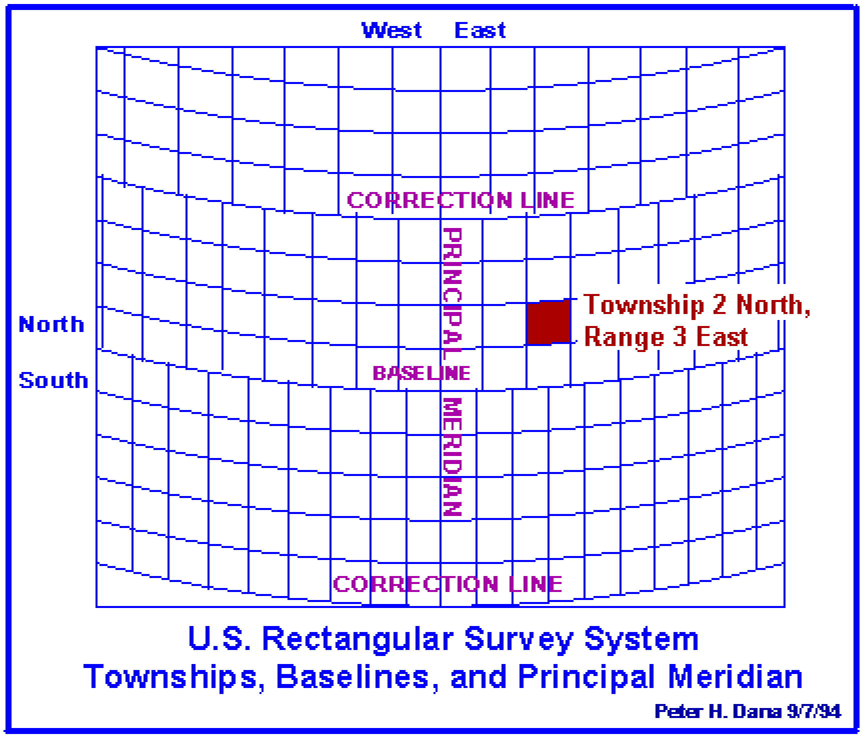


Figure 26. U.S. Rectangular Survey

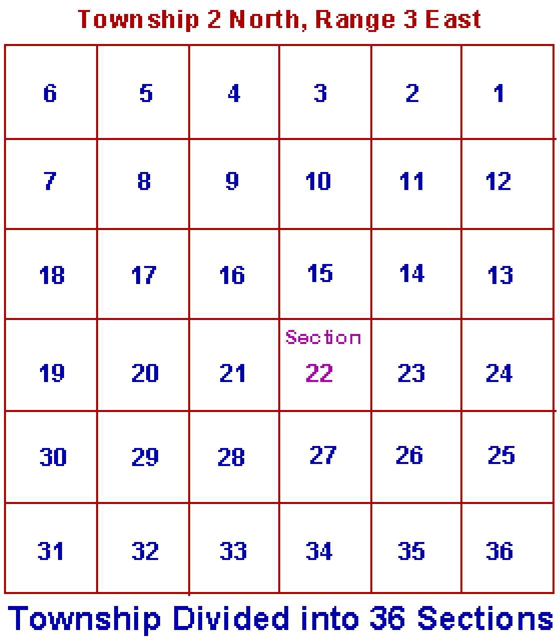


Figure 27. Township Sections

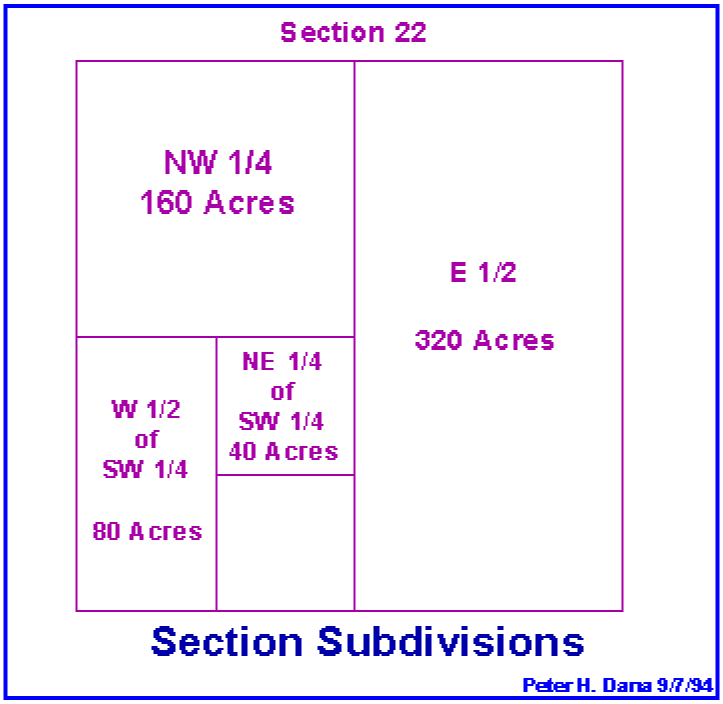


Figure 28. Subdivided Section

Land Description based on US Public Land Survey

Black Hills Meridian

T.3 S., R. 1 E.,

sec. 8, SE1/4;

sec. 21;

sec. 28, E1/2, N1/2NW1/4 and NE1/4SW1/4

sec. 31, lots 2 and 4, NW1/4NE1/4, NE1/4NW1/4, and SE1/4;

sec. 34, W1/2NE1/4, W1/2, W1/2SE1/4, and W1/2SE1/4

Table 10. A Township and Range Property Description

Example of Metes and Bounds Description

A right of way 40 ft. wide, the center line of which is described as follows:

Beginning at station No.1, on the boundary between the United States Military Reservation and Land Court application 1000 (amended), from which the azimuth and distance to United States Military Reservation Monument No. 80 is 182°36'40", 6.55 ft.

From station No. 1, by azimuths and distances,

109°55'48", 444.2 ft. to station No. 2;

159°44'10", 183.8 ft. to station No. 3;

209°07'56", 208.3 ft. to station No. 4;

139°02'05", 414.6 ft. to station No. 5;

173°38'45", 325.5 ft. to station No. 6;

201°43'50", 505.9 ft. to station No. 7;

156°57'40", 435.1 ft. to station No. 8;

186°41'20", 477.9 ft. to station No. 9;

165°16'45", 345.4 ft. to station No. 10;

187°43'20", 1092.1 ft. to station R 1, at the southern intersection of the center of the HonoluluWaialua road with the Military Reservation boundary between monuments No. 79 and No.80, and being determined by the following azimuths and distances;

To monument No. 79, 351°53'12", 2179.0 ft.;

To monument No. 80, 171°53'12", 3930.2 ft.;

(Specifications for Descriptions of Tracts of Land for Use in Land Orders and Proclamations, U. S. Dept,. of the Interior 1976)

Table 11. Metes and Bounds Example

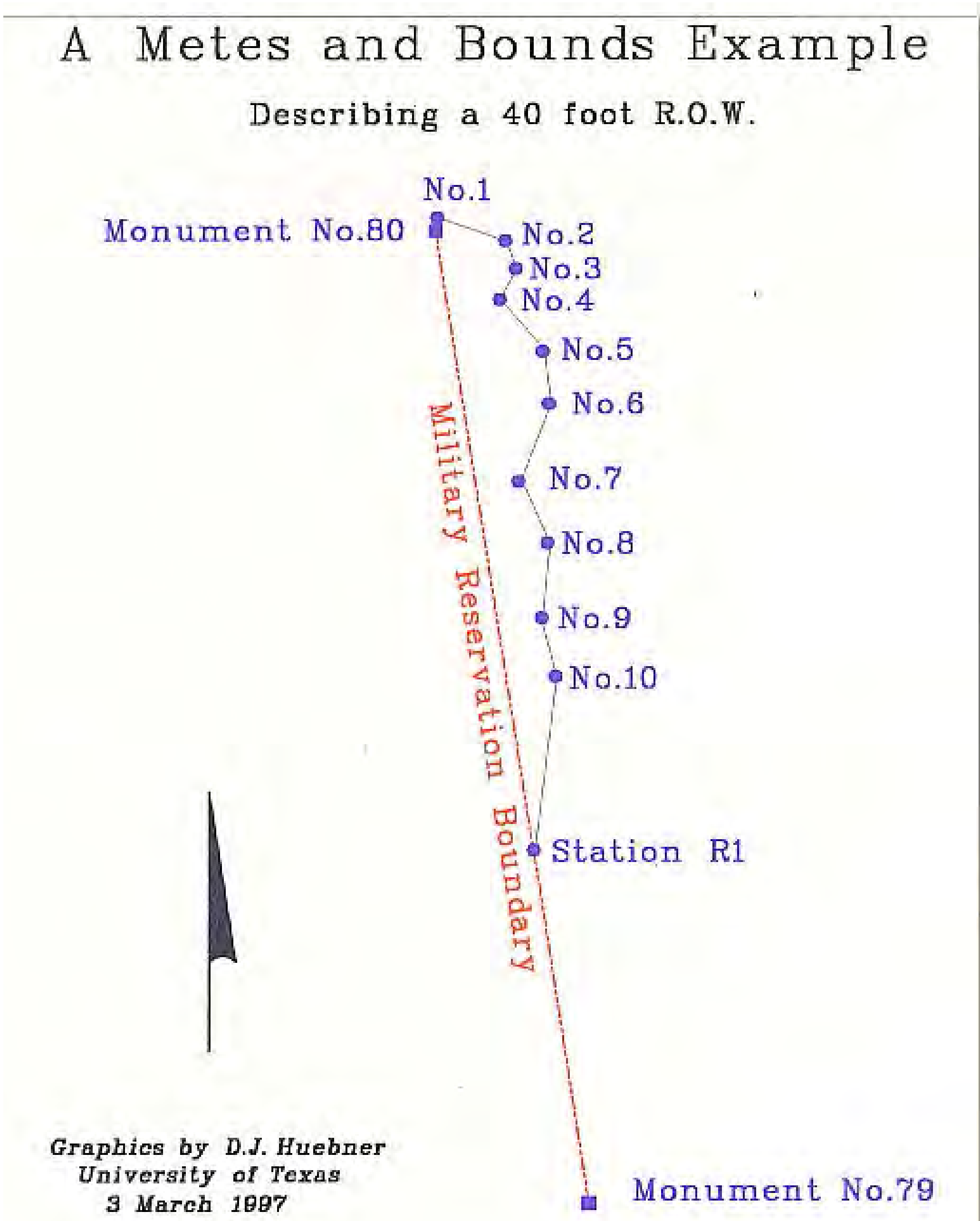


Figure 28a. Metes and Bounds graphic

Figure 29. The Texas Capitol Building

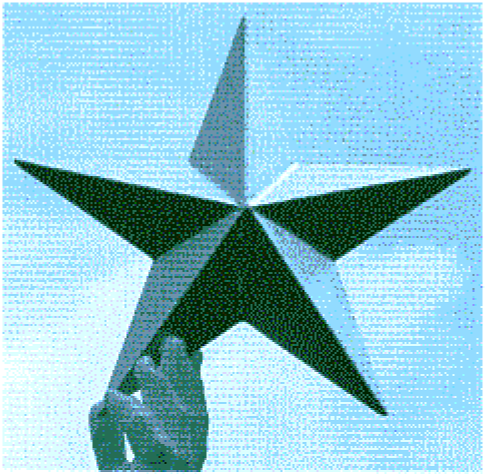


Figure 30. The Star in the Hand of The Goddess of Liberty

Position Descriptions in Selected Coordinate Systems

Star in the Hand of the Statue of the Goddess of Liberty atop

the Dome of the State Capitol Building

Austin, Texas, USA

Description System	System
Capitol Building, Congress Avenue, Austin, TX 78705	Postal Address, No., Street, City, State, ZIP Code
Austin Capitol Dome, Star in Hand of Liberty	National Geodetic Survey Station Name
30° 16' 28.82343" North 097° 44' 25.19350" West 221.1 m	NAD 83 Geodetic Coordinates: Latitude, Longitude, Height above Geoid
30° 16' 28.069" North 097° 44' 24.180" West 259.1 m	NAD 27 Geodetic Coordinates: Latitude, Longitude, Height above Geoid
30° 16' 28.82343" North 097° 44' 25.19350" West 194.4 m	WGS 84 Geodetic Coordinates: Latitude, Longitude, Height above Ellipsoid
949465.059 m 3070309.475 m Texas Central 4203	NAD 83 State Plane Coordinates: Easting, Northing , Zone, Zone No.
2818560.55 ft 230591.76 ft Texas Central 4203	NAD 27 State Plane Coordinates: X, Y, Zone, Zone No.
721201.977 m 4271229.432 m TX South Central 4204	NAD 83 State Plane Coordinates: Easting, Northing , Zone, Zone No.
889749.98 ft 2397741.25 ft TX South Central 4204	NAD 27 State Plane Coordinates: X, Y, Zone, Zone No.
-742529.80 m -5462904.79 m 3196804.62 m	WGS 84 Earth Centered, Earth Fixed: X, Y, Z
14RPJC21194049689	NAD 27 Military Grid Reference System
14RPU021161049894	WGS 84 Military Grid Reference System
FJHA1516	World Geographic Reference System
621190.779 m 3349689.51 m 14	NAD 27 Universal Transverse Mercator Coordinates: Easting, Northing , Zone No.
621160.976 m 3349893.53 m 14	NAD 83 Universal Transverse Mercator Coordinates: Easting, Northing, Zone No.
230.46° 2.271 nmi 114.6 Ch. 93 AUS	VOR-DME (magnetic bearing, distance, VOR ID
7980 10998.86, 24794.96, 47040.75, 63902.28 microseconds	Loran-C Time Differences, GRI, X, Y, Z

Table 12. One Location Described by a Variety of Systems

Unit 014 - Latitude and Longitude

by Anthony P. Kirvan, Department of Geography, University of Texas at Austin, USA

This section was edited by Kenneth Foote, Department of Geography, University of Texas Austin.

Advanced Organizer

Topics covered in this unit

- This unit provides an overview of latitude and longitude, including:
  - Earth rotation, the North and South Poles, and the Equator
  - Parallels of latitude and meridians of longitude
  - Determination of north or south position with latitude
  - The use of longitude to determine east or west position
  - The measurement of latitude and longitude with degrees, minutes, and seconds

Learning Outcomes

- After learning the material covered in this unit, students should gain an appreciation for:
  - The relationship between plane and earth coordinate geometries
  - The importance of the earth's rotation and poles to measurement and point location
  - The use of latitude and longitude to determine locations on the earth's surface
  - The differences and relationships between latitude and longitude
  - Using latitude and longitude to measure distances

Full Table of Contents

Metadata and Revision History

Unit 014 - Latitude and Longitude

1. Frames of Reference

- Throughout history, many methods of keeping track of locations have been developed.

- *Plane coordinate geometry* was developed as an abstract frame of reference for flat surfaces.

- Once the earth's round, three-dimensional shape was accepted, a spherical coordinate system was created to determine locations around the world.

1.1. Plane Coordinate Geometry

- René Descartes' contributions to mathematics were developed into *cartesian coordinate geometry*.

  - This is the familiar system of equally-spaced intersecting perpendicular lines in a single plane.
  - The two principal axes are the horizontal (x) and the vertical (y) .
  - Any point's position can be described with respect to its corresponding x and y values (x,y).
  - Figure 1. The position (5,3) is a unique location easily plotted on the cartesian plane.
  - The position of one point relative to another can also be shown with the cartesian coordinate system.

---

2. Earth Coordinate Geometry

- The earth's spherical shape is more difficult to describe than a plane surface.

- Concepts from cartesian coordinate geometry have been incorporated into the earth's coordinate system.

2.1. Rotation of the Earth

- The spinning of the earth on its imaginary axis is called *rotation*.

- Aside from the cultural influences of rotation, this spinning also has a physical influence.
  - The spinning has led to the creation of a system to determine points and directions on the sphere.
  - The North and South poles represent the axis of spin and are fixed reference points.

        - If the North Pole was extended, it would point to a fixed star, the North Star (Polaris).
    - Any point on the earth's surface moves with the rotation and traces an imaginary curved line:
        - *Parallel of Latitude*

2.2. The Equator

- If a plane bisected the earth midway between the axis of rotation and perpendicular to it, the intersection with the surface would form a circle.
    - This unique circle is the *equator*.
    - The equator is a fundamental reference line for measuring the position of points around the globe.

- Figure 2. The equator and the poles are the most important parts of the earth's coordinate system.

2.3. The Geographic Grid

- The spherical coordinate system with latitudes and longtitudes used for determining the locations of surface features.
    - Parallels: east-west lines parallel to the equator.
    - Meridians: north-south lines connecting the poles.
    - Figure 3. The Geographic Grid

- Parallels are constantly parallel, and meridians converge at the poles.

- Meridians and parallels always intersect at right angles.

2.3.1. Parallels of Latitude

- *Parallels of latitude* are all small circles, except for the equator.

    - True east-west lines
    - Always parallel
    - Any two are always equal distances apart
    - An infinite number can be created
    - Parallels are related to the horizontal x-axes of the cartesian coordinate system.
    - Figure 4. Parallels of Latitude

2.3.2. Meridians of Longitude

- *Meridians of longitude* are halves of great circles, connecting one pole to the other.
    - All run in a true north-south direction
    - Spaced farthest apart at the equator and converge to a point at the poles
    - An infinite number can be created on a globe
    - Meridians are similar to the vertical y-axes of the cartesian coordinate system.

Meridians of Longitude - Figure 4.

2.3.3. Degrees, Minutes, and Seconds

- Angular measurement must be used in addition to simple plane geometry to specify location on the earth's surface.
  - This is based on a *sexagesimal scale:*
  - A circle has 360 degrees, 60 minutes per degree, and 60 seconds per minute.
  - There are 3,600 seconds per degree.
  - Example: 45° 33' 22" (45 degrees, 33 minutes, 22 seconds).

- It is often necessary to convert this conventional angular measurement into decimal degrees.
  - To convert 45° 33' 22", first multiply 33 minutes by 60, which equals 1,980 seconds.
  - Next add 22 seconds to 1,980: 2,002 total seconds.
  - Now compute the ratio: 2,002/3,600 = 0.55.
  - Adding this to 45 degrees, the answer is 45.55°.

- The earth rotates on its axis once every 24 hours, therefore:
  - Any point moves through 360° a day, or 15° per hour.

2.3.4. Great and Small Circles

- A *great circle* is a circle formed by passing a plane though the exact center of a sphere.
  - The largest circle that can be drawn on a sphere's surface.
  - An infinite number of great circles can be drawn on a sphere.
  - Great circles are used in the calculation of distance between two points on a sphere.

- A *small circle* is produced by passing a plane through any part of the sphere other than the center.

- Figure 5 - Great and Small Circles

2.3.5. Loxodromes

- Arcs of great circles are very important to navigation since they represent the shortest route between two points.
  - A loxodrome, or rhumb line, intersects each meridian at the same angle (constant compass bearing).
  - Unfortunately, this route traced by a loxodrome is not the shortest distance.
    - Maintaining a constant heading or azimuth traces a sprial on the globe called a loxodromic curve.
  - To approximate the path of a great circle, which constantly changes azimuth, navigators plot courses along a series of loxodromes.

- The Mercator projection was developed especially for navigators, and presents straight

lines as loxodromes.
  - Because of the great distortion of parallels and meridians on this projection, great circles appear as deformed curves.
  - Figure 6 - Loxodrome and Great Circle Comparison on Mercator Projection

---

3. Using Latitude and Longitude for Location

3.1. Latitude

- **Authalic Latitude** is based on a spherical earth:
  - Measures the position of a point on the earth's surface in terms of the angular distance between the equator and the poles.
  - Indicates how far north or south of the equator a particular point is situated.
  - *North latitude*: all points north of the equator in the northern hemisphere
  - *South latitude*: all points south of the equator in the southern hemisphere

- Latitude is measured in angular degrees from 0° at the equator to 90° at either of the poles.
  - A point in the northern hemisphere 40 degrees north of the equator is labeled Lat. 40° N.
  - Forty degrees south of the equator, the label changes to Lat. 40° S.

- The north or south measurement of latitude is actually measured along the meridian which passes through that location
  - It is known as an *arc* of the meridian.

- **Geodetic Latitude** is based on an ellipsoidal earth:
  - The ellipsoid is a more accurate representation of the earth than a sphere since it accounts for polar flattening.
  - Refer to the Shape of the Earth (Unit 015) for more information.
  - Modern large-scale mapping, GIS, and GPS technology all require the higher accuracy of an ellipsoidal reference surface.
  - Refer to the Coordinate Systems Overview (Unit 013) for more information.

- When the earth's shape is based on the WGS 84 Ellipsoid:
  - The length of 1° of latitude is not the same everywhere as it is on the sphere.
  - At the equator, 1° of latitude is 110.57 kilometers (68.7 miles).
  - At the poles, 1° of latitude is 111.69 kilometers (69.4 miles).
  - Table 1 - Length of a Degree of Geodetic Latitude

3.1.1. Latitude and Distance

- Parallels of latitude decrease in length with increasing latitude.
  - *Mathematical expression*: length of parallel at latitude x = (cosine of x) * (length of equator)
  - The length of each degree is obtained by dividing the length of that parallel by

360.
    - Example: the cosine of 60° is 0.5, so the length of the parallel at that latitude is one half the length of the equator.

- Since the variation in lengths of degrees of latitude varies by only 1.13 kilometers (0.7 mile), the standard figure of 111.325 kilometers (69.172 miles) can be used.
    - For example, anywhere on the earth, the length represented by 3° of latitude is (3 * 111.325) 333.975 kilometers.

3.2. Longitude

- Longitude measures the position of a point on the earth's surface east or west from a specific meridian, the *prime meridian*.
    - The longitude of a place is the arc, measured in degrees along a parallel of latitude from the prime meridian.
    - The most widely accepted prime meridian is based on the *Bureau International de l'Heure (BIH) Zero Meridian*:
        - Defined by the longitudes of many BIH stations around the world..
        - Passes through the old Royal Observatory in Greenwich, England.
        - The prime meridian has the angular designation of 0° longitude.
        - All other points are measured with respect to their position east or west of this meridian.
        - Longitude ranges from 0° to 180°, either east or west.
    - Since the placement of a prime meridian is arbitrary, other countries have often used their own.
        - For the purposes of measurement, no one prime meridian is better than another
        - Having a widely accepted meridian allows comparison between maps published in different areas.

- The distance represented by a degree of longitude varies upon where it is measured.
    - The length of a degree of longitude along a meridian is not constant because of polar flattening.
    - At the equator, the approximate length is determined by dividing the earth's circumference (24,900 miles) by 360 degrees: 111.05 kilometers (69 miles).
    - The meridians converge at the poles, and the distance represented by one degree decreases.
    - At 60° N latitude, one degree of longitude is equal to about 55.52 kilometers (34.5 miles).

3.2.1. Longitude and Distance

- Because the earth is not a perfect sphere, the equatorial circumfererence does not equal that of the meridians.

- On a perfect sphere, each meridian of longitude equals one-half the circumference of the sphere.
    - The length of each degree is equal to the circumference divided by 360.

  - Each degree is equal to every other degree.

- Measurement along meridians of longitude accounts for the earth's polar flattening:.
  - Degree lengths along meridians are not constant:
    - 111.325 kilometers (69.172 miles) per degree at the equator
    - 16.85 kilometers (10.47 miles) per degree at 80° North 0
    - kilometers at the poles

- The distance between meridians of longitude on a sphere is a function of latitude:
  - *Mathematical expression*: Length of a degree of longitude = cos (latitude) * 111.325 kilometers
  - Example: 1° of longitude at 40° N = cos (40°) * 111.325
  - Since the cosine of 40° is 0.7660, the length of one degree is 85.28 kilometers.

- Table 2 - Length of a Degree of Geodetic Longitude
  - These lengths are based on an ellipsoid and are similar to the lengths computed with the spherical formula.

3.3. Calculating Distances in Latitude and Longitude

- Calculating distance on a sphere based on latitude and longitude is a complicated task.
  - The calulation of the distance between two points on a plane surface is a relatively simple task and has promoted the use of two-dimensional maps throughout history.
  - When calculating distances over large areas, the authalic sphere can be used as a reference surface.
    - The shortest distance between two points on a sphere is the arc on the surface directly above the true straight line.
    - The arc is based on a great circle.
    - Table 3 - Great Circle Distance Calculation
    - See the Web References section for online examples.
  - The difference betwen the sphere and ellipsoid is important when working with large areas.
    - At a scale of 1:40,000,000, a 23 kilometer error in distance would equal a pen line (0.5 mm) on paper.
  - Complex geodetic models based on ellipsoids are necessary for precise meaurement.
    - Long range radio navigation requires precise distances.
    - Loran-C requires range computations with better than 10 meter accuracy over 2,000 kilometers.
    - Geodetic measurements using satellites requires very accurate range computations.
    - Table 4 - Ellipsoidal Distance Calculation

---

4. Review and Study Questions

4.1. Essay and Short Answer Questions

- Describe the relationship between the cartesian coordinate system and the geographic grid.
- Convert 35.40° into degrees, minutes, and seconds.
- Explain why the length of a degree of longitude decreases as one approaches the poles.

4.2. Multiple-Choice Questions

- The equator can also be called a:
    1. Prime Meridian
    2. Parallel of Latitude
    3. Great Circle
    4. Both 1 and 2
    5. Both 2 and 3
- Which of the following is **not** true of parallels of latitude?
    1. They are true east-west lines
    2. Any two are always equal distances apart
    3. Always meet at the poles
    4. Related to the x-axis of the cartesian coordinate system
- Which of the following is **not** true of meridians of longitude?
    1. They always meet at the poles
    2. True north-south lines
    3. Each is equal to half the length of a great circle
    4. Always begin with the Prime Meridian through Greenwich, England

---

5. Reference Materials

5.1. Print References

- Dent, Borden D. *Cartography: Thematic Map Design*, William C. Brown Publishers, 1990.
- Muehrcke, Phillip C., and Juliana O. Muehrcke. *Map Use: Reading-Analysis-Interpretation,* 4th ed. Madison, WI: J.P. Publications, 1998.
- Robinson, Arthur H., et al. *Elements of Cartography*, New York: John Wiley & Sons, 1995.
- Strahler, Arthur N., and Alan H. Strahler. *Elements of Physical Geography: Fouth Edition*, New York: John Wiley & Sons, 1989.

- Strahler, Arthur N., and Alan H. Strahler. *Modern Physical Geography: Third Edition*, New York: John Wiley & Sons, 1987.

5.2. Web References

- Bali Online: How far is it? - This service calculates the distance between two places.
- Geographic Names Information System (GNIS) - This database can be used to locate the longitude and latitude of over 1,233,933 features in the U.S.
- GeoSystems Information on Latitude and Longitude
- Bureau of the Census Gazetteer - Search for latitude and longitude data by entering a zip code or town and state information.

Citation

To reference this material use the appropriate variation of the following format:

Kirvan, Anthony P. (1997) Latitude/Longitude, *NCGIA Core Curriculum in GIScience*, http://www.ncgia.ucsb.edu/giscc/units/u014/u014.html, posted (today).

Created: October 29, 1997. Last revised: July 7, 2000.

Unit 014 - Latitude and Longitude

Table of Contents

Advanced Organizer
- Unit Topics
- Intended Learning Outcomes
- Metadata and Revision History

Body of Unit
1. Frames of Reference
    1. Plane Coordinate Geometry
2. Earth Coordinate Geometry
    1. Rotation of the Earth
    2. The Equator
    3. The Geographic Grid
    4. Parallels of Latitude
    5. Meridians of Longitude
    6. Degrees, Minutes, and Seconds
    7. Great and Small Circles
    8. Loxodromes
3. Using Latitude and Longitude for Location
    1. Latitude
        1. Latitude and Distance
    2. Longitude
        1. Longitude and Distance
    3. Calculating Distances in Latitude and Longitude
4. Review and Study Questions
    1. Essay and Short Anwer Questions
        1. Multiple-Choice Questions
5. Reference Materials
    1. Print References
    2. Web References

Citation

Back to the Unit

Unit 014 - Latitude and Longitude

Metadata and Revision History

1. About the main contributors

- author: Anthony P. Kirvan, Department of Geography,
  University of Texas at Austin, Austin, TX, USA, 78712-1098
- editor: Kenneth E. Foote, Department of Geography,
  University of Texas at Austin, Austin, TX, USA, 78712-1098

2. Details about the file

- unit title:
  - Latitude and Longitude
- unit key number:
  - 014

3. Key words

- Coordinate Systems
- Latitude and Longitude

4. Index words

- Parallels of Latitude
- Meridians of Longitude
- Great and Small Circles
- Prime Meridian
- Equator and Poles

5. Prerequisite units

- 008 - Representing the Earth

6. Subsequent units

- 013 - Overview of Coordinate Systems
- 015 - The Shape of the Earth
- 018 - Mapping the Earth

7. Revision history

- 29 October 1997. First revision of unit published.
- 4 October 1997. First set of graphics added to module.
- 09 November 1997. Unit converted into NCGIA format, frame, short table of contents, metadata, and tables created.
- 13 November 1997. Review and study questions added to module.
- 19 November 1997. Revisions to section 3 on geodetic latitude and longitude, great circle calculation added.
- 12 June 1998. Additional revisions based on reviewer comments.
- July 1, 1998. Minor revisions.
- June 19, 2000. Tables revised.
- July 7, 2000. External links updated.

- Back to the Unit

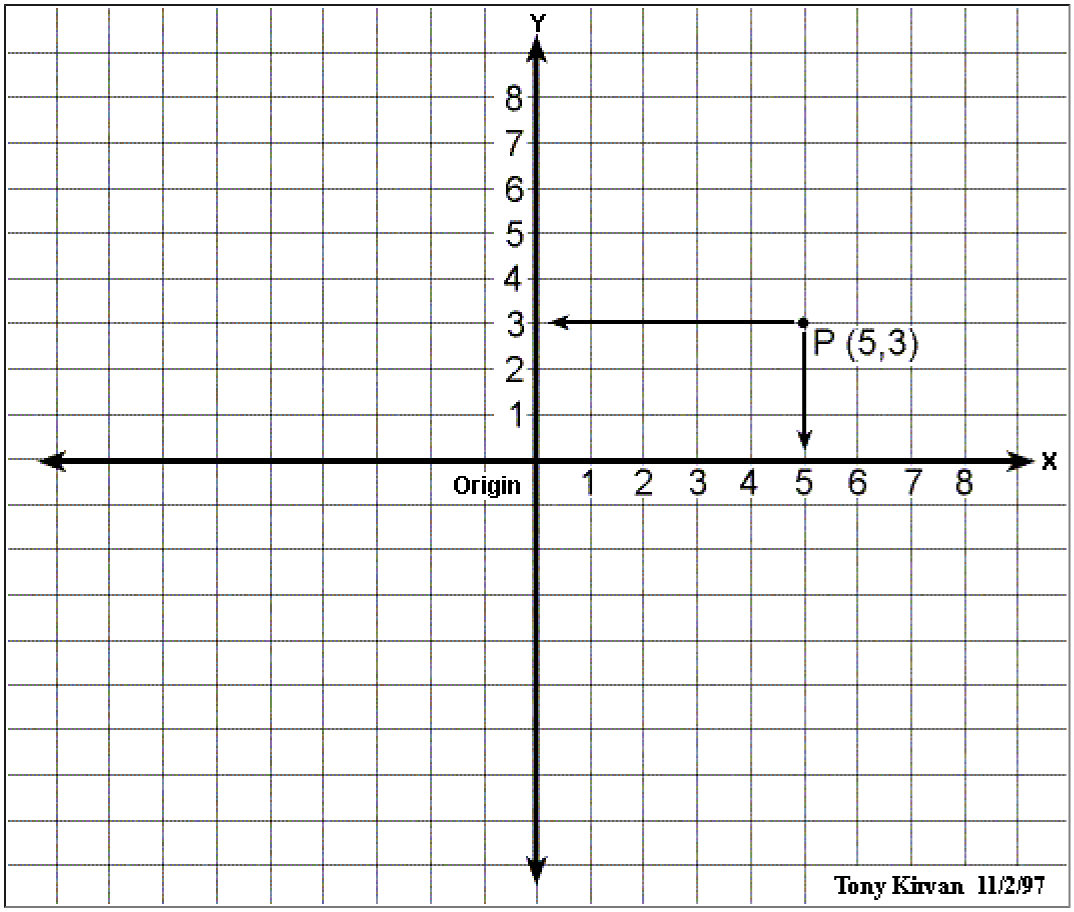


Figure 1. The Cartesian Coordinate System

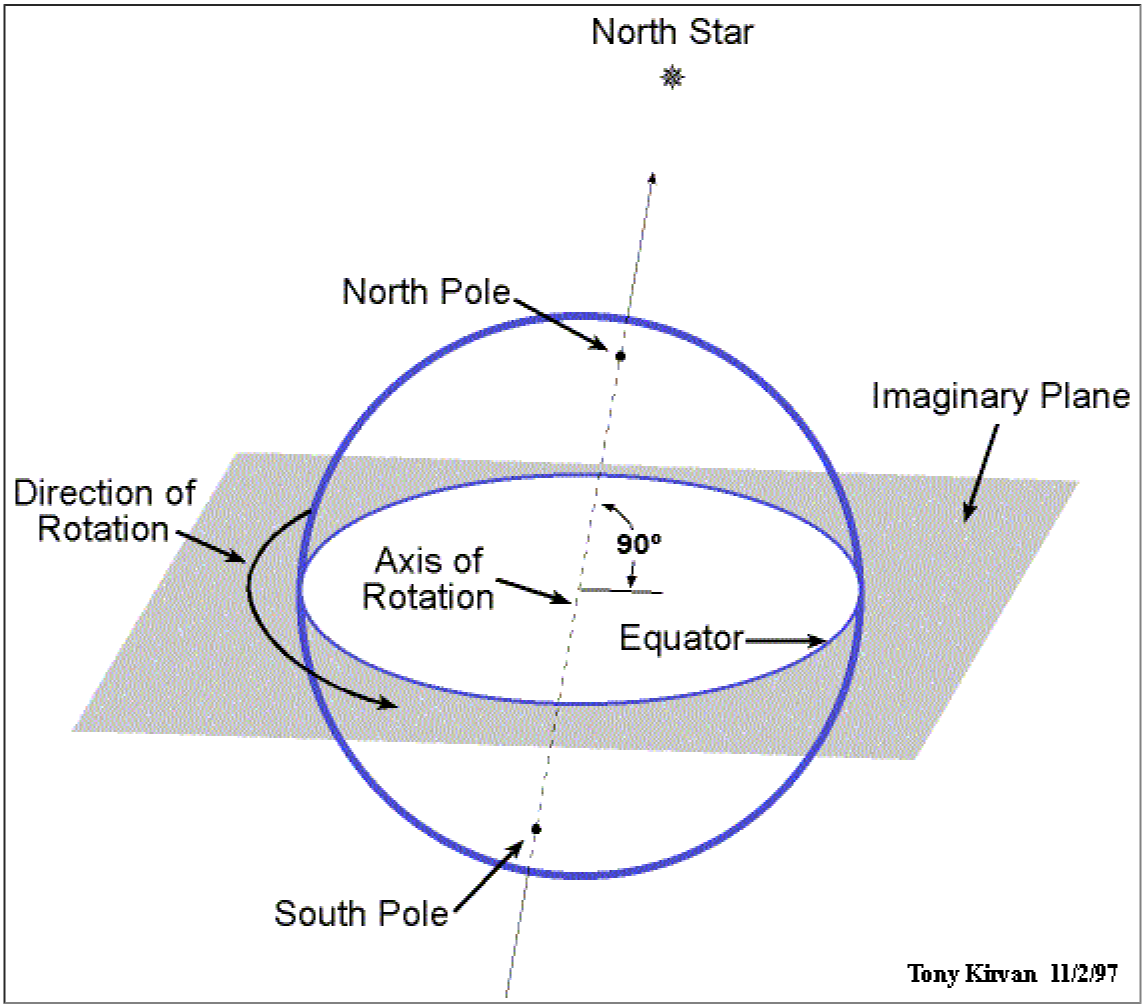


Figure 2. Location of the Equator, North & South Poles, and the Imaginary Axis of Rotation.

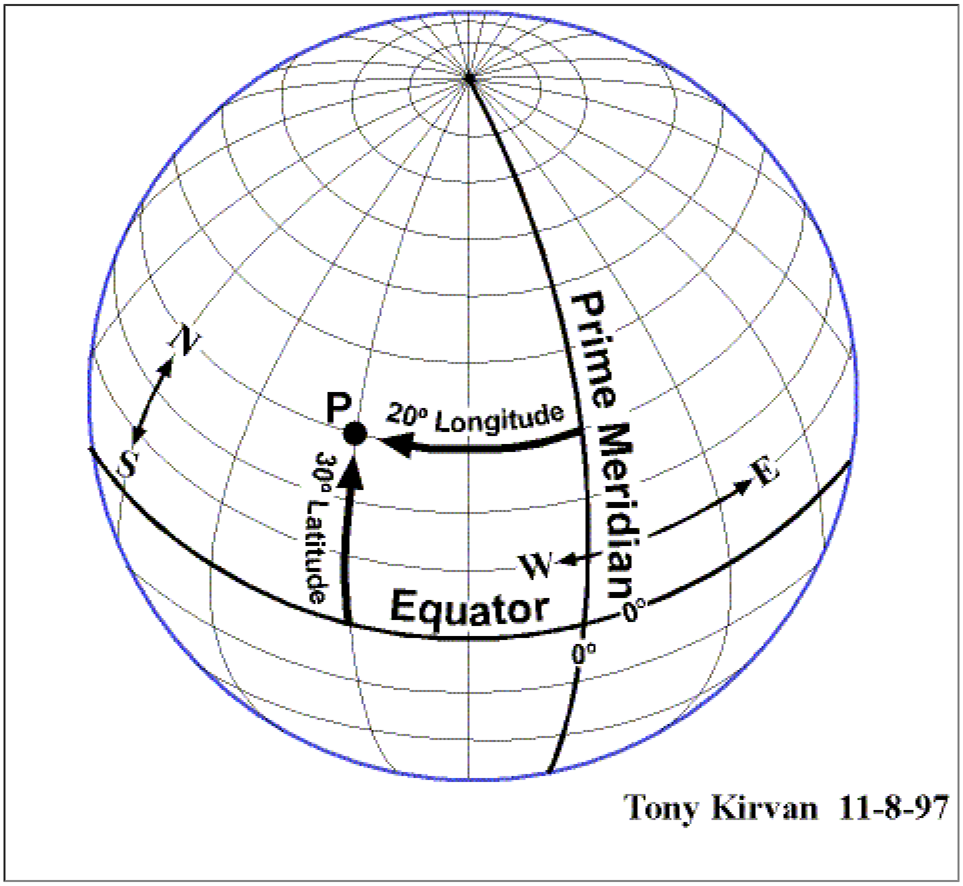


Figure 3. The Geographic Grid. The Point P has alatitude of 30 degrees North and a longitude of 20 degrees West.

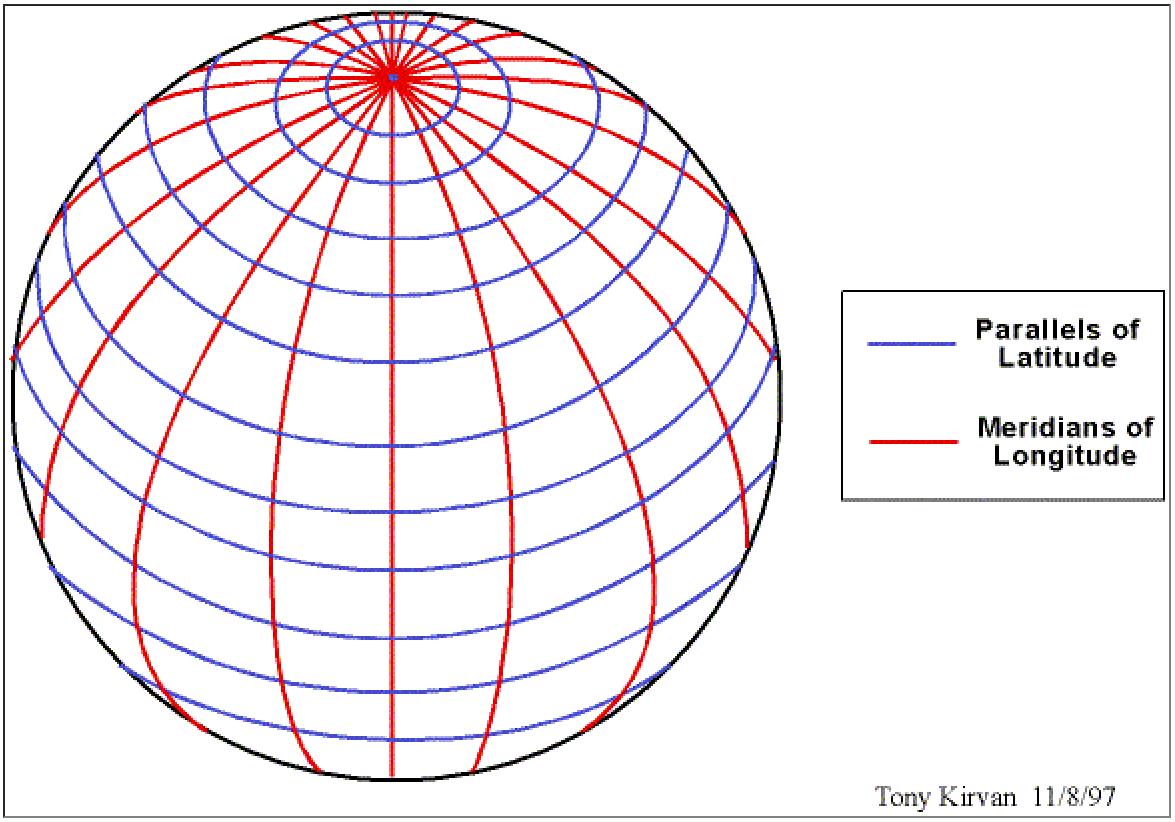


Figure 4. Parallels of Latitude and Meridians of Longitude.

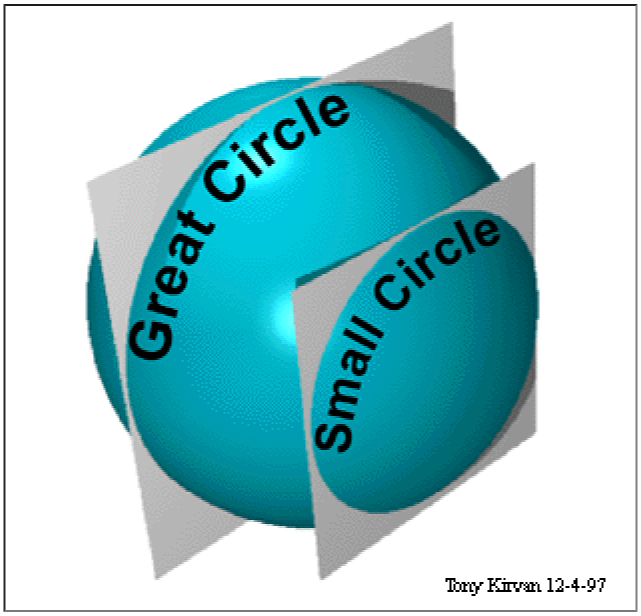


Figure 5. Great and Small Circles. The plane forming the great circle must pass through the exact center of the sphere. The plane forming the small circle can be anywhere else.

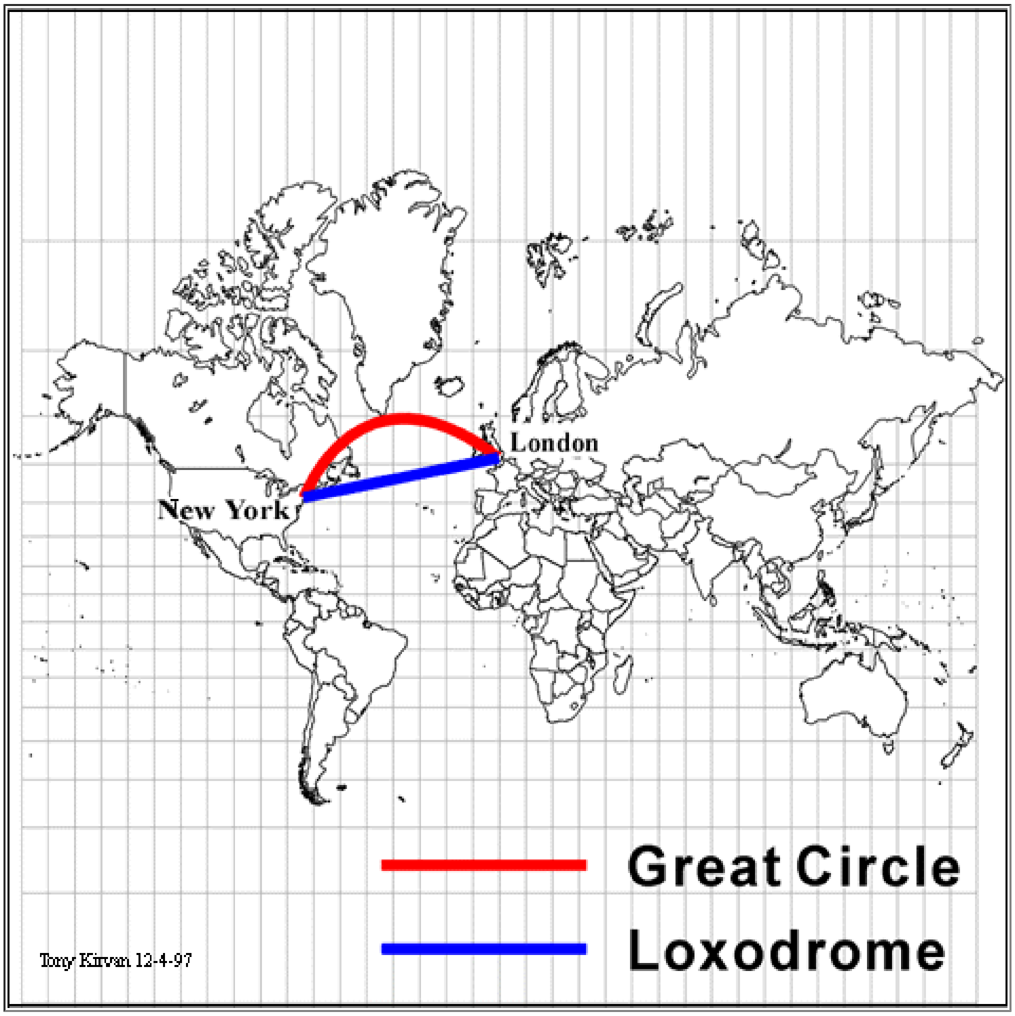


Figure 6. Comparison of Great Circle Route and Loxodrome on the Mercator Projection. The loxodrome is a line of constant heading, and the great circle, although appearing longer than the loxodrome, is actually the shortest route between New York and London.

Table 1 - Length of a Degree of Geodetic Latitude

Latitude (º)	Miles	Kilometers
0	68.71	110.57
10	68.73	110.61
20	68.79	110.70
30	68.88	110.85
40	68.99	111.04
50	69.12	111.23
60	69.23	111.41
70	69.32	111.56
80	69.38	111.66
90	69.40	111.69

Table 2 - Length of a Degree of Geodetic Longitude

Latitude (º)	Miles	Kilometers
0	69.17	111.32
10	68.13	109.64
20	65.03	104.65
30	59.95	96.49
40	53.06	85.39
50	44.55	71.70
60	34.67	55.80
70	23.73	38.19
80	12.05	19.39
90	0.00	0.00

Table 3 - Calculating the Great Circle Distance Between Two Cities

The great circle distance (D) between any two points P and A on the sphere is calculated with the following formula:

cos D = (sin *p* sin *a*) + (cos *p* cos *a* cos |dl|)

- ***p*** and ***a*** are the latitudes of P and A
- |dl| is the absolute value of the difference in longitude between P and A

Calculate the great circle distance between Paris (P) and Austin (A):
Paris, France (48° 52' N, 02° 20' E)
Austin, Texas (30° 16' 09" N, 97° 44' 37" W)

1. Convert to decimal degrees:

- Paris: 48.87° N, 02.33° E
- Austin: 30.27° N, 97.74° W

2. cos D = [sin(48.87) * sin(30.27)] + [cos(48.87) * cos(30.27) * cos(|-97.74 - 2.33|)]

3. cos D = [0.753 * 0.504] + [0.658 * 0.864 * -0.174] = 0.281

4. D = $\cos^{-1}$ (0.281) = 73.68°
5. D = 73.68° * 111.23 kilometers/degree = **8,195.44 kilometers (5,092.03 miles)**

SodanInv.mcd

MathCad implimentation of Sodano' s Appendix C
Inverse Geodesic

PH Dana 12/09/99

E. M. Sodano, Genral Non-Iterative Solution of the Inverse and Direct Geodetic Problems
Bulletin Geodesique 75 1965. 69-89.

WGS-84 defining parameters

$a_0 := 6378137.0$ semi-major axis

$f := \frac{1}{298.257223563}$ flattening

Derived ellipsoid parameters

$es := (2 - f) \cdot f$ first eccentricity squared

$b_0 := \sqrt{a_0^2 \cdot ((1 - es))}$ semi-minor axis

$eps := \frac{a_0^2 - b_0^2}{b_0^2}$ second eccentricity squared

$n := \frac{a_0 - b_0}{a_0 + b_0}$ $n = 0.001679220386384$

$B_1 := \left(30 + \frac{16}{60} + \frac{09}{3600}\right) \cdot deg$ $B_2 := \left(48 + \frac{52}{60} + \frac{00}{3600}\right) \cdot deg$

$L_1 := -\left(97 + \frac{44}{60} + \frac{37}{3600}\right) \cdot deg$ $L_2 := \left(02 + \frac{20}{60} + \frac{00}{3600}\right) \cdot deg$

From and To Positions

$$L := L_2 - L_1$$

$$L := \text{if}(|L| > \pi, L \cdot -1, L)$$

$$\beta_1 := \text{atan}\left[(1-f)\cdot\tan(B_1)\right] \quad \beta_2 := \text{atan}\left[(1-f)\cdot\tan(B_2)\right]$$ Parametric latitude

$$a := \sin(\beta_1)\cdot\sin(\beta_2)$$

$$b := \cos(\beta_1)\cdot\cos(\beta_2)$$

$$\cos\phi := a + b\cdot\cos(L)$$

$$b2mb1 := (B_2 - B_1) + 2\cdot(\sin(B_2 - B_1))\cdot\left[(n+n^2+n^3)\cdot a - (n-n^2+n^3)\cdot b\right]$$

$$\sin\phi := \sqrt{(\sin(L)\cdot\cos(\beta_2))^2 + \left(\sin(b2mb1) + 2\cdot\cos(\beta_2)\cdot\sin(\beta_1)\cdot\sin\left(\frac{L}{2}\right)^2\right)^2}$$

$$\phi := \text{atan2}(\cos\phi, \sin\phi)$$

$$c := \frac{(b\cdot\sin(L))}{\sin\phi}$$

$$m := 1 - c^2$$

$$\begin{aligned}
Sdb := & \left[(1+f+f^2)\cdot\phi\right] \ldots \\
& + a\cdot\left[(f+f^2)\cdot\sin\phi - \left(\frac{f^2}{2}\right)\cdot\phi^2\cdot\csc(\phi)\right] \ldots \\
& + m\cdot\left[-\left(\frac{f+f^2}{2}\right)\cdot\phi - \left(\frac{f+f^2}{2}\right)\cdot\sin\phi\cdot\cos\phi + \frac{f^2}{2}\cdot\phi^2\cdot\cot(\phi)\right] \ldots \\
& + a^2\cdot\left(\frac{-f^2}{2}\cdot\sin\phi\cdot\cos\phi\right) \ldots \\
& + m^2\cdot\left[\left(\frac{f^2}{16}\right)\cdot\phi + \frac{f^2}{16}\cdot\sin\phi\cdot\cos\phi - \frac{f^2}{2}\cdot\phi^2\cdot\cot(\phi) - \frac{f^2}{8}\cdot\sin\phi\cdot\cos\phi^3\right] .. \\
& + a\cdot m\cdot\left(\frac{f^2}{2}\cdot\phi^2\cdot\csc(\phi) + \frac{f^2}{2}\cdot\sin\phi\cdot\cos\phi^2\right)
\end{aligned}$$

$$S := Sdb\cdot b_0$$

$S = 8215651.30627337$ geodetic range in meters

$\frac{S}{1609.344} = 5104.9690471853$ geodetic range in statue miles

Unit 015 - The Shape of the Earth

by Peter H. Dana, Department of Geography, University of Texas at Austin, USA

This section was edited by Kenneth Foote, Department of Geography, University of Texas Austin.

Advanced Organizer

Topics covered in this unit

- This unit provides an overview of concepts related to the shape of the earth, including:
  - Geodetic Datums
  - Geometric Earth Models
  - Reference Ellipsoids
  - Earth Surfaces

Learning Outcomes

- After learning the material covered in this unit, students should gain an appreciation for:
  - The various methods of describing the size and shape of the earth
  - The evolution of a flat earth model into an accurate spherical representation

Full Table of Contents

Metadata and Revision History

Unit 015 - The Shape of the Earth

1. Introduction to Geodetic Datums

- Geodetic datums define the reference systems that describe the size and shape of the earth, and the origin and orientation of the coordinate systems used to map the earth.
  - Hundreds of different datums have been used to frame position descriptions since the first estimates of the earth's size were made by Aristotle.
  - Datums have evolved from those describing a spherical earth to ellipsoidal models derived from years of satellite measurements.
- Modern geodetic datums range from flat-earth models used for plane surveying to complex models used for international applications which completely describe the size, shape, orientation, gravity field, and angular velocity of the earth.
- While cartography, surveying, navigation, and astronomy all make use of geodetic datums, the science of geodesy is the central discipline for the topic.
- Referencing geodetic coordinates to the wrong datum can result in position errors of hundreds of meters.
- Different nations and agencies use different datums as the basis for coordinate systems used to identify positions in geographic information systems, precise positioning systems, and navigation systems.
- The diversity of datums in use today and the technological advancements that have made possible global positioning measurements with sub-meter accuracies requires careful datum selection and careful conversion between coordinates in different datums.

---

2. The Figure of the Earth

- Geodetic datums and the coordinate reference systems based on them were developed to describe geographic positions for surveying, mapping, and navigation.
- Through a long history, the "figure of the earth" was refined from flat-earth models to spherical models of sufficient accuracy to allow global exploration, navigation and mapping.
- True geodetic datums were employed only after the late 1700s when measurements showed that the earth was ellipsoidal in shape.

2.1. Geometric Earth Models

- Early ideas of the figure of the earth resulted in descriptions of the earth as an oyster (The Babylonians before 3000 B.C.), a rectangular box, a circular disk, a cylindrical column, a spherical ball, and a very round pear (Columbus in the last years of his life).
- Flat earth models are still used for plane surveying, over distances short enough so that earth curvature is insignificant (less than 10 kms).

- Spherical earth models represent the shape of the earth with a sphere of a specified radius.
  - Spherical earth models are often used for short range navigation (VOR-DME) and for global distance approximations.
  - Spherical models fail to model the actual shape of the earth.
  - The slight flattening of the earth at the poles results in about a twenty kilometer difference at the poles between an average spherical radius and the measured polar radius of the earth.

- Ellipsoidal earth models are required for accurate range and bearing calculations over long distances.
  - Loran-C, and GPS navigation receivers use ellipsoidal earth models to compute position and waypoint information.
  - Ellipsoidal models define an ellipsoid with an equatorial radius and a polar radius.
  - The best of these models can represent the shape of the earth over the smoothed, averaged sea-surface to within about one-hundred meters.

2.2. Reference Ellipsoids

- Reference ellipsoids are usually defined by semi-major (equatorial radius) and flattening (the relationship between equatorial and polar radii).

- Other reference ellipsoid parameters such as semi-minor axis (polar radius) and eccentricity can computed from these terms.
  - Figure 1 - Reference Ellipsoid Parameters

- Many reference ellipsoids are in use by different nations and agencies.
  - Figure 2 - Selected Reference Ellipsoids
  - Table 1 - A More Complete List of Reference Ellipsoids

- Some geodetic datums are based on ellipsoids that touch the surface of the earth at a defined point. North American Datum 1927 (NAD27) is tangent to the mean sea level surface at Meades Ranch in Kansas. NAD27 is not a global datum. Others are "topocentric" datums with a reference ellipsoid that has its center at the center of mass of the earth. Word Geodetic System 1984 (WGS-84) is an example of a global datum. These global datums can be better fits to the gravity surface for the entire earth but can be less accurate in specific areas.

2.3. Earth Surfaces

- The earth has a highly irregular and constantly changing surface.

- Models of the surface of the earth are used in navigation, surveying, and mapping.

- Topographic and sea-level models attempt to model the physical variations of the surface, while gravity models and geoids are used to represent local variations in gravity that change the local definition of a level surface.
  - Figure 3 - Earth Surfaces

- The topographical surface of the earth is the actual surface of the land and sea at some moment in time. Aircraft navigators have a special interest in maintaining a positive height vector above this surface.
- Sea level is the average (methods and temporal spans vary) surface of the oceans. Tidal forces and gravity differences from location to location cause even this smoothed surface to vary over the globe by hundreds of meters.
- Gravity models attempt to describe in detail the variations in the gravity field. The importance of this effort is related to the idea of leveling. Plane and geodetic surveying uses the idea of a plane perpendicular to the gravity surface of the earth, the direction perpendicular to a plumb bob pointing toward the center of mass of the earth. Local variations in gravity, caused by variations in the earth's core and surface materials, cause this gravity surface to be irregular.
  - National Geodetic Survey Geoid-96
- Geoid models attempt to represent the surface of the entire earth over both land and ocean as though the surface resulted from gravity alone. Bomford described this surface as the surface that would exist if the sea was admitted under the land portion of the earth by small frictionless channels.
- The WGS-84 Geoid defines geoid heights for the entire earth.
- The U. S. Defense Mapping Agency publishes a ten by ten degree grid of geoid heights for the WGS-84 geoid.
  - By using a four point linear interpolation algorithm at the four closest grid points, the geoid height for any location can be determined.
  - Table 2 - A Ten by Ten Degree WGS-84 Geoid Height Model.
  - The same grid can be used to produce a contour map of geoid heights for the globe.
  - Figure 4 - WGS-84 Geoid Heights
  - The National Imagery and Mapping Agency (formerly the Defense Mapping Agency) publishes a 0.25 degree model of the WGS-84 Geoid (1441 by 721 grid points).
  - Figure 5 - Shaded Relief of NIMA 0.25° WGS-84 Geoid Height Model

---

3. Geodetic Datums

3.1. Datum Types

- Horizontal
  - Datums that define the relationship between the physical earth and horizontal coordinates such as latitude and longitude. Examples include the North American Datum of 1927 (NAD27) and the European Datum 1950 (ED50)..
- Vertical
  - Datums that define level surfaces. Examples include the National Geodetic Vertical Datum of 1929 (NGVD29) and the North American Vertical Datum of 1988 (NAVD88). Some are based on sea-level measurements and leveling networks (NGVD29), others on gravity measurements (NAVD88).

- Complete
    - Datums that describe both vertical and horizontal systems. Some, such as World Geodetic System 1984 (WGS-84), also describe other parameters such as the rotation rate of the earth and various physical constants such as the angular velocity of the earth and the earth's gravitational constant.

3.2. Datums in Use

- Hundreds of geodetic datums are in use around the world.

- North American Datum of 1983 is used for United States marine, aviation, and topographic maps (based in the past on NAD 1927).

- The Global Positioning system is based on the World Geodetic System 1984 (WGS-84).

- Parameters for simple XYZ conversion between many datums and WGS-84 are published by the Defense mapping Agency.
    - Figure 7 - Selected Geodetic Datums and Three Parameter Conversion Constants
    - Table 3 - A More Complete List of Geodetic Datums

3.3. Datum Shifts

- Coordinate values resulting from interpreting latitude, longitude, and height values using the wrong datum can cause position errors in three dimensions of up to one kilometer.
    - Figure 8 - Horizontal Position Shifts from Datum Differences

3.4. Datum Conversions

- Datum conversions are accomplished by various methods.

- Complete datum conversion is based on seven parameter transformations that include three translation parameters, three rotation parameters and a scale parameter. These conversions are only accurate in the region for which the parameters were computed. These can result in local accuracies of less than one meter.

- Multiple regression formulas can be used with parameters that represent fits to large contiguous land areas. Multiple regression equations can model datum shifts with accuracies of two meters over large (continental) areas. When coupled with tables of locally measured shifts these can provide better than one meter accuracies.

- Simple three parameter conversion between latitude, longitude, and height in different datums can be accomplished by conversion through Earth-Centered, Earth Fixed XYZ Cartesian coordinates in one reference datum and three origin offsets that approximate differences in rotation, translation and scale. These conversions can have accuracies ranging from two to twenty-five meters.
    - Figure 9 - Conversion from ECEF XYZ to Latitude, Longitude, and Height

  - Figure 10 - Conversion from Latitude, Longitude, and Height to ECEF XYZ.
  - Figure 11 - XYZ Three Parameter Datum Conversion

- The Standard Molodensky formulas can be used to convert latitude, longitude, and ellipsoid height in one datum to another datum if the Delta XYZ constants for that conversion are available and ECEF XYZ coordinates are not required.
  - Figure 12 - Standard Molodensky Datum Conversion

---

4. Review and Study Questions

4.1. Essay and Short Answer Questions

- Essay Questions
  - In what ways does the existence of hundreds of local and regional geodeitc datums limit the possibility of for international cooperation in GIS projects?
  - To what extent is the problem of georeferencing a major obstacle to the creation of global GIS?

- Short Answer
  - Why is it important to know the datum used for a given map?
  - Which datum are you most likely to encounter for maps used in the US?
  - Why is the use of the correct map datum important in determining location?

4.2. Multiple-Choice Questions

Choose the best or most appropriate answer(s) to the question.

- What is a geodetic datum?
  - The latitude and longitude of Meades Ranch, Kansas, the NAD 27 origin.
  - The data point that defines the location of Greenwich, England.
  - A theoretical map project designed to provide accurate scale over the entire surface of an oblate spheroid.
  - The set of parameters that define the size and shape of the earth and the origin of coordinate systems that describe positions on the earth.
- Which of the following datums can be used anywhere in the world for accurate mapping?
  - WGS 1983 and NAD 1927
  - WGS 1972 and NAD 1984
  - NAD 1927 and NAD 1983
  - There are no global datums
  - None of the above
- Which of the following datums is the *best* representation of the shape (or gravity field) of the entire earth?
  - NAD 27
  - NAD 83
  - WGS 84

- WGS 27
- None of the above

---

5. Reference Materials

5.1. Print References

- Bomford, G. 1980. Geodesy. Oxford: Clarendon Press.
- Burkard, Richard K. 1983. Geodesy for the Layman. Washington, DC: NOAA.
- National Imagery and Mapping Agency. 1997. Department of Defense World Geodetic System 1984: Its Definition and Relationships with Local Geodetic Systems. NIMA TR8350.2 Third Edition 4 July 1997. Bethesda, MD: National Imagery and Mapping Agency.
- National Oceanic and Atmospheric Administration. 1986. Geodetic Glossary. Rockville, MD: National Geodetic Information Center.
- Schwarz, Charles R. 1989. North American Datum of 1983. Rockville, MD: National Geodetic Survey.
- Torge, Wolfgang. 1991 Geodesy, 2nd Edition, New York: deGruyter.

5.2. Web References

- National Imagery and Mapping Agency
- National Geodetic Survey Geoid-96 Page

5.3. Glossary

Citation

To reference this material use the appropriate variation of the following format:

Dana, Peter H. (1997) The Shape of the Earth, *NCGIA Core Curriculum in GIScience*, http://www.ncgia.ucsb.edu/giscc/units/u015/u015.html, posted (today).

Last revised: July 15, 1998.

The Shape of the Earth

Table of Contents

Advanced Organizer
- Unit Topics
- Intened Learning Outcomes
- Metadata and Revision History

Body of Unit
- 1. Introduction to Geodetic Datums
- 2. The Figure of the Earth
  - 2.1 Geometric Earth Models
  - 2.2 Reference Ellipsoids
  - 2.3 Earth Surfaces
- 3. Geodetic Datums
  - 3.1 Datum Types
  - 3.2 Datums in Use
  - 3.3 Datum Shifts
  - 3.4 Datum Conversions
- 4. Review and Study Questions
  - 4.1 Essay and Short Answer Questions
  - 4.2 Multiple Choice Questions
- 5. References
  - 5.1 Print References
  - 5.2 Web References
  - 5.3 Glossary
- Citation

Back to the Unit

Unit 015 - The Shape of the Earth

Metadata and Revision History

1. About the main contributors

- author: Peter H. Dana, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098

- editor: Kenneth E. Foote, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098 and Anthony Kirvan, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098.

2. Details about the file

- unit title:
  - The Shape of the Earth
- unit key number:
  - 015

3. Key words

- Geodetic Datums
- Reference Ellipsoids

4. Index words

- geodetic datum ("geodetic datum")
- reference ellipsoid ("reference ellipsoid")
- Spherical Earth Models
- Ellipsoidal Earth Models

5. Prerequisite units

- 008 - Representing the Earth
- 014 - Latitude and Longitude

6. Subsequent units

- 018 - Mapping the Earth
- 096 - Handling Uncertainty

- 136 - Making it Work

7. Revision history

- 07 November 1997. Converted from Geographer's Craft Geodetic Datums Overview
- 14 November 1997. Metadata and table of contents created.
- 30 June 1998. Revisions in response to reviews.
- June 15, 1998 Last revision date

Back to the Unit:

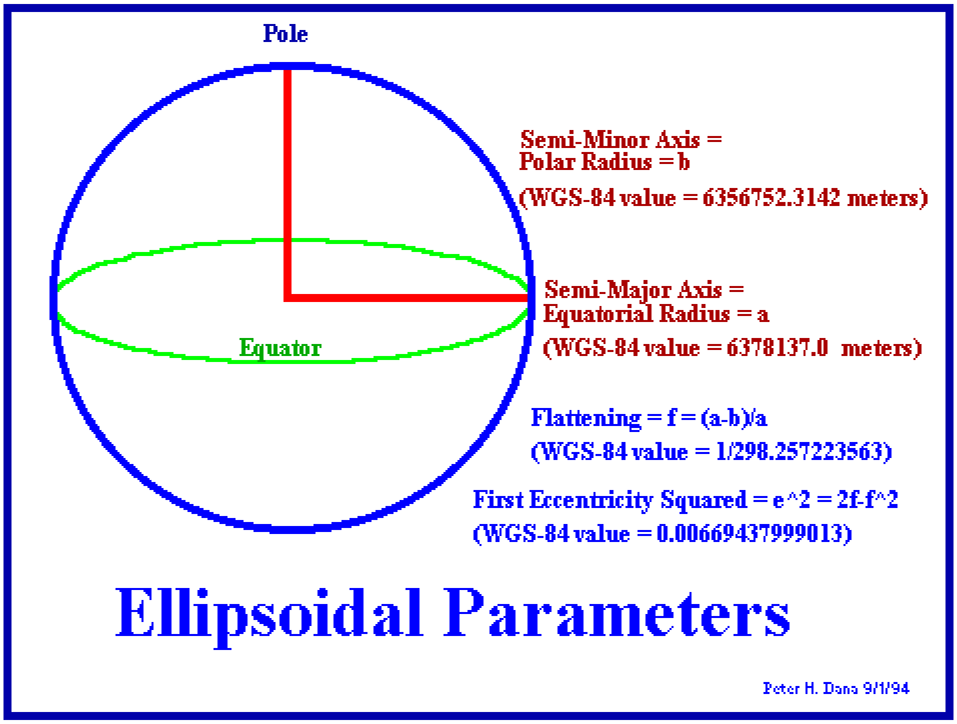


Figure 1 - Reference Ellipsoid Parameters

Selected Reference Ellipsoids

Ellipse	Semi-Major Axis (meters)	1/Flattening
Airy 1830	6377563.396	299.3249646
Bessel 1841	6377397.155	299.1528128
Clarke 1866	6378206.4	294.9786982
Clarke 1880	6378249.145	293.465
Everest 1830	6377276.345	300.8017
Fischer 1960 (Mercury)	6378166.0	298.3
Fischer 1968	6378150.0	298.3
G R S 1967	6378160.0	298.247167427
G R S 1975	6378140.0	298.257
G R S 1980	6378137.0	298.257222101
Hough 1956	6378270.0	297.0
International	6378388.0	297.0
Krassovsky 1940	6378245.0	298.3
South American 1969	6378160.0	298.25
WGS 60	6378165.0	298.3
WGS 66	6378145.0	298.25
WGS 72	6378135.0	298.26
WGS 84	6378137.0	298.257223563

Peter H. Dana 9/1/94

Figure 2 - Selected Reference Ellipsoids

Reference Ellipsoid List

- Reference Ellipsoid, Equatorial Radius (a), Reciprocal Flattening (1/f), Delta a, Delta f (*10^4).
- Delta parameters are with respect to WGS-84 Parameters for conversion from WGS-84 to the specified datum.
- Parameter Delta a is the WGS-84 Equatorial radius minus the specified datum Equatorial radius in meters.
- Parameter Delta f is the WGS-84 flattening minus the specified datum flattening multiplied by 10^4.
  - WGS-84 Equatorial Radius (a) = 6378137.0
  - WGS-84 Flattening (f) = 1/298.257223563

Source:
Defense Mapping Agency. 1987b. DMA Technical Report: Supplement to Department of Defense World Geodetic System 1984 Technical Report. Part I and II. Washington, DC: Defense Mapping Agency.

Airy, 6377563.396, 299.3249646, 573.604, 0.11960023
Australian National, 6378160.0, 298.25, -23.0, -0.00081204
Bessel 1841, 6377397.155, 299.1528128, 739.845, 0.10037483
Bessel 1841 (Nambia), 6377483.865, 299.1528128, 653.135, 0.10037483
Clarke 1866, 6378206.4, 294.9786982, -69.4, -0.37264639
Clarke 1880, 6378249.145, 293.465, -112.145, -0.54750714
Everest, 6377276.345, 300.8017, 860.655, 0.28361368
Fischer 1960 (Mercury), 6378166.0, 298.3, -29.0, 0.00480795
Fischer 1968, 6378150.0, 298.3, -13..0, 0.00480795
GRS 1967, 6378160.0, 298.247167427, -23.0, -0.00113048
GRS 1980, 6378137, 298.257222101, 0.0, -0.00000016
Helmert 1906, 6378200.0, 298.3, -63.0, 0.00480795
Hough, 6378270.0, 297.0, -133.0, -0.14192702
International, 6378388.0, 297.0, -251.0.0, -0.14192702

Krassovsky, 6378245.0, 298.3, -108.0, 0.00480795
Modified Airy, 6377340.189, 299.3249646, 796.811, 0.11960023
Modified Everest, 6377304.063, 300.8017, 832.937, 0.28361368
Modified Fischer 1960, 6378155.0, 298.3, -18.0, 0.00480795
South American 1969, 6378160.0, 298.25, -23.0, -0.00081204
WGS 60, 6378165.0, 298.3, -28.0, 0.00480795
WGS 66, 6378145.0, 298.25, -8.0, -0.00081204
WGS-72, 6378135.0, 298.26, 2.0, 0.0003121057
WGS-84, 6378137.0, 298.257223563, 0.0, 0.0

Table 1 - A More Complete List of Reference Ellipsoids

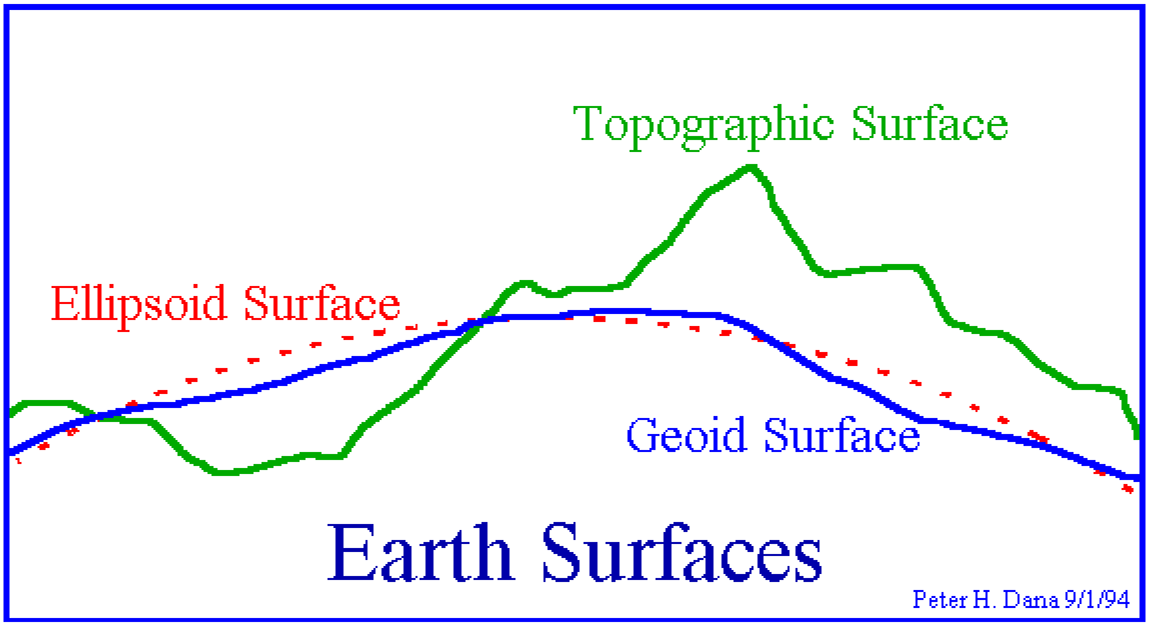


Figure 3 - Earth Surfaces

WGS-84 Geoid Heights

- Ten by Ten Degree WGS-84 Geoid Heights from -180 to +170 Degrees of Longitude
- Geoid height approximations in meters

Source:
Defense Mapping Agency. 12 Jan 1987. GPS UE Relevant WGS-84 Data Base Package. Washington, DC: Defense Mapping Agency.

---

90 Degrees N: 13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13
80 Degrees N: 3,1,-2,-3,-3,-3,-1,3,1,5,9,11,19,27,31,34,33,34,33,34,28,23,17,13,9,4,4,1,-2,-2,0,2,3,2,1,1
70 Degrees N: 2,2,1,-1,-3,-7,-14,-24,-27,-25,-19,3,24,37,47,60,61,58,51,43,29,20,12,5,-2,-10,-14,-12,-10,-14,-12,-6,-2,3,6,4
60 Degrees N: 2,9,17,10,13,1,-14,-30,-39,-46,-42,-21,6,29,49,65,60,57,47,41,21,18,14,7,-3,-22,-29,-32,-32,-26,-15,-2,13,17,19,6
50 Degrees N: -8,8,8,1,-11,-19,-16,-18,-22,-35,-40,-26,-12,24,45,63,62,59,47,48,42,28,12,-10,-19,-33,-43,-42,-43,-29,-2,17,23,22,6,2
40 Degrees N: -12,-10,-13,-20,-31,-34,-21,-16,-26,-34,-33,-35,-26,2,33,59,52,51,52,48,35,40,33,-9,-28,-39,-48,-59,-50,-28,3,23,37,18,-1,-11
30 Degrees N: -7,-5,-8,-15,-28,-40,-42,-29,-22,-26,-32,-51,-40,-17,17,31,34,44,36,28,29,17,12,-20,-15,-40,-33,-34,-34,-28,7,29,43,20,4,-6
20 Degrees N:

5,10,7,-7,-23,-39,-47,-34,-9,-10,-20,-45,-48,-32,-9,17,25,31,31,26,15,6,1,-29,-44,-61,-67,-59,-36,-11,21,39,49,39,22,10
10 Degrees N: 13,12,11,2,-11,-28,-38,-29,-10,3,1,-11,-41,-42,-16,3,17,33,22,23,2,-3,-7,-36,-59,-90,-95,-63,-24,12,53,60,58,46,36,26
0 Degrees: 22,16,17,13,1,-12,-23,-20,-14,-3,14,10,-15,-27,-18,3,12,20,18,12,-13,-9,-28,-49,-62,-89,-102,-63,-9,33,58,73,74,63,50,32
10 Degrees S: 36,22,11,6,-1,-8,-10,-8,-11,-9,1,32,4,-18,-13,-9,4,14,12,13,-2,-14,-25,-32,-38,-60,-75,-63,-26,0,35,52,68,76,64,52
20 Degrees S: 51,27,10,0,-9,-11,-5,-2,-3,-1,9,35,20,-5,-6,-5,0,13,17,23,21,8,-9,-10,-11,-20,-40,-47,-45,-25,5,23,45,58,57,63
30 Degrees S: 46,22,5,-2,-8,-13,-10,-7,-4,1,9,32,16,4,-8,4,12,15,22,27,34,29,14,15,15,7,-9,-25,-37,-39,-23,-14,15,33,34,45
40 Degrees S: 21,6,1,-7,-12,-12,-12,-10,-7,-1,8,23,15,-2,-6,6,21,24,18,26,31,33,39,41,30,24,13,-2,-20,-32,-33,-27,-14,-2,5,20
50 Degrees S: -15,-18,-18,-16,-17,-15,-10,-10,-8,-2,6,14,13,3,3,10,20,27,25,26,34,39,45,45,38,39,28,13,-1,-15,-22,-22,-18,-15,-14,-10
60 Degrees S: -45,-43,-37,-32,-30,-26,-23,-22,-16,-10,-2,10,20,20,21,24,22,17,16,19,25,30,35,35,33,30,27,10,-2,-14,-23,-30,-33,-29,-35,-43
70 Degrees S: -61,-60,-61,-55,-49,-44,-38,-31,-25,-16,-6,1,4,5,4,2,6,12,16,16,17,21,20,26,26,22,16,10,-1,-16,-29,-36,-46,-55,-54,-59
80 Degrees S: -53,-54,-55,-52,-48,-42,-38,-38,-29,-26,-26,-24,-23,-21,-19,-16,-12,-8,-4,-1,1,4,4,6,5,4,2,-6,-15,-24,-33,-40,-48,-50,-53,-52
90 Degrees S: -30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30,-30

Table 2 - A Ten by Ten Degree WGS-84 Geoid Height Model.

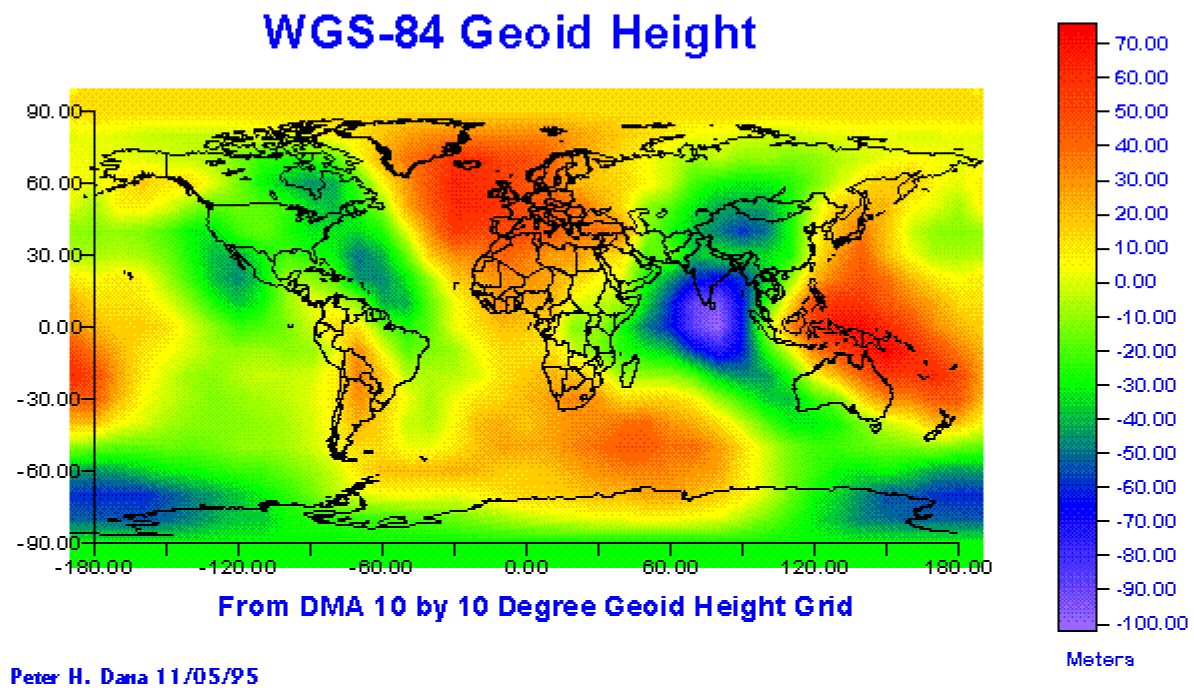


Figure 4 - WGS-84 Geoid Heights

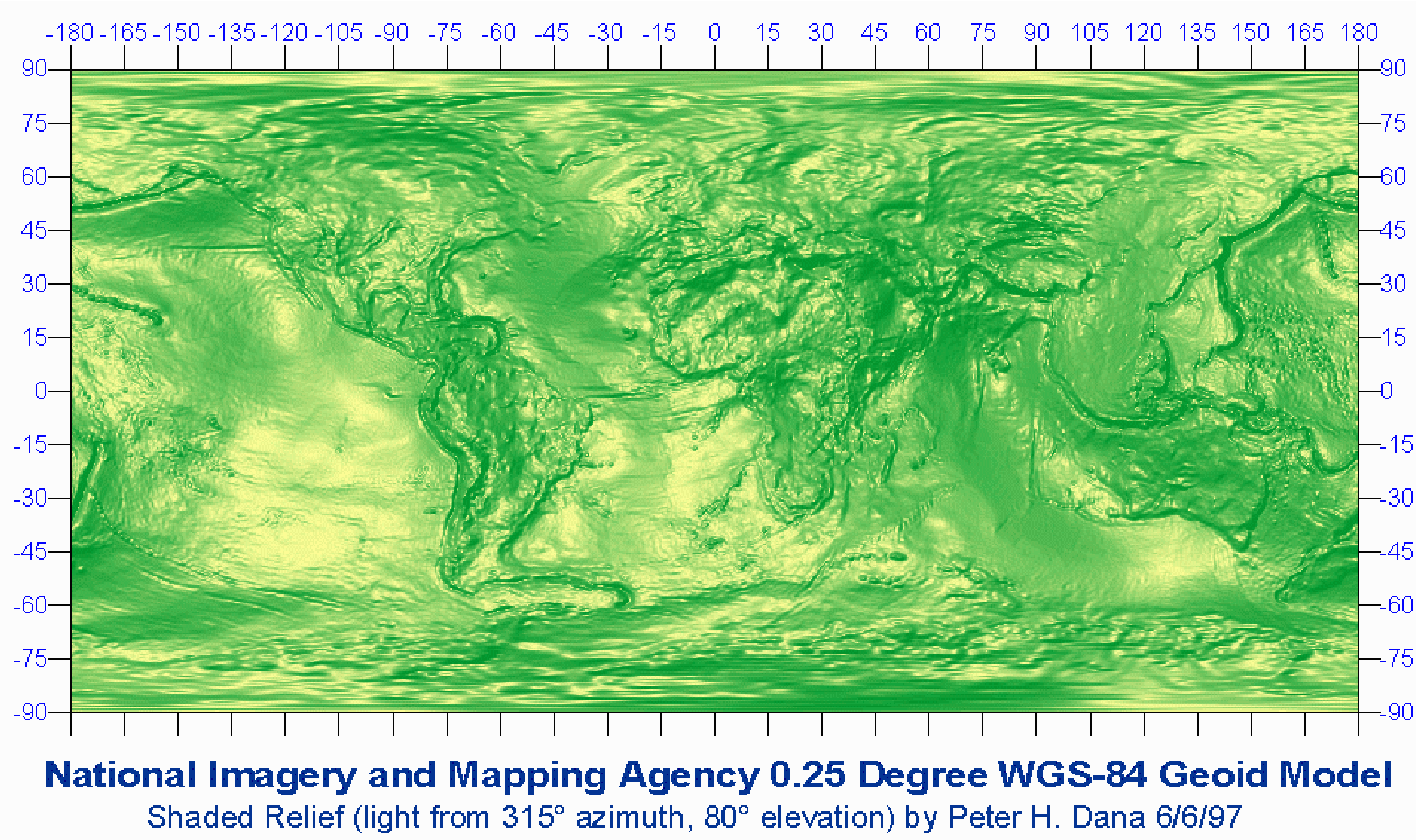


Figure 5 - Shaded Relief of NIMA 0.25° WGS-84 Geoid Height Model

Selected Geodetic Datums and WGS-84 Shift Parameters

Datum	Ellipsoid	DX	DY	DZ
Adindan	Clarke 1880	-162	-12	206
Arc1950	Clarke 1880	-143	-90	-294
Arc1960	Clarke 1880	-160	-8	-300
Australian Geodetic 1966	Australian National	-133	-48	148
Australian Geodetic 1984	Australian National	-134	-48	149
Camp Area Astro	International	-104	-129	239
Cape	Clarke 1880	-136	-108	-292
European Datum 1950	International	-87	-98	-121
European Datum 1979	International	-86	-98	-119
Geodetic Datum 1949	International	84	-22	209
Hong Kong 1963	International	-156	-271	-189
Hu-Tzu-Shan	International	-634	-549	-201
Indian	Everest	289	734	257
North American Datum 1927	Clarke1 866	-8	160	176
North American Datum 1983	GRS 80	0	0	0
Oman	Clarke 1880	-346	-1	224
Ordnance Survey 1936	Airy	375	-111	431
Pulkovo 1942	Krassovsky 1942	27	-135	-89
Provisional S American 1956	International	-288	175	-376
South American 1969	S American 1969	-57	1	-41
Tokyo	Bessel 1841	-128	481	664
World Geodetic System 1972	WGS 72	0	0	-4.5
World Geodetic System 1984	WGS 84	0	0	0

Peter H. Dana 11/8/96

Figure 7 - Selected Geodetic Datums and Three Parameter Conversion Constants

Geodetic Datum List

- Datum, Ellipsoid, Delta a, Delta f (* 10^4), Delta X, Delta Y, Delta Z.
- Delta parameters are with respect to WGS-84 parameters for conversion from the specified datum to WGS-84.
- Parameter Delta a is the WGS-84 Equatorial radius minus the specified datum Equatorial radius in meters.
- Parameter Delta f is the WGS-84 flattening minus the specified datum flattening multiplied by 10^4.
- Delta X, Y, Z parameters are WGS-84 X, Y, Z parameters minus the specified datum X, Y, Z in meters.
- The Delta X, Y, and Z parameters are added to the specified datum X, Y, Z to convert to WGS-84.
- The source for most of these parameters is Defense Mapping Agency Technical Report, Department of Defense World Geodetic System 1984, DMA TR 8350.2 Second Edition, 1 September 1991.
  - WGS-84 Equatorial Radius (a) = 6378137.0
  - WGS-84 Flattening (f) = 1/298.257223563

Adindan, Clarke_1880, -112.145, -0.54750714, -166, -15, +204
Afgooye, Krassovsky, -108.0, 0.00480795, -43, -163, +45
Ain_El_Abd_1970, International, -251.0, -0.14192702, -150, -251, -2
Alaska_(NAD-27), Clarke_1866, -69.4, -0.37264639, -5, +135, +172
Alaska/Canada_NAD-27, Clarke_1866, -69.4, -0.37264639, -9, +151, +185
Anna_1_Astro_1965, Australian_National, -23.0, -0.00081204, -491, -22, +435
ARC-1950_mean, Clarke_1880, -112.145, -0.54750714, -143, -90, -294
ARC-1960_mean, Clarke_1880, -112.145, -0.54750714, -160, -8, -300
Ascension_Island_'58, International, -251.0, -0.14192702, -207, +107, +52
Astro_B4_Sor.Atoll, International, -251.0, -0.14192702, +114, -116, -333
Astro_Beacon_"E", International, -251.0, -0.14192702, +145, +75, -272
Astro_Pos_71/4, International, -251.0, -0.14192702,

-320, +550, -494
Astronomic_Stn._'52, International, -251.0, -0.14192702, +124, -234, -25
Australian_Geodetic_1984, Australian_National, -23.0, -0.00081204, -134, -48, +149
Bahamas_(NAD-27), Clarke_1866, -69.4, -0.37264639, -4, +154, +178
Bellevue_(IGN), International, -251.0, -0.14192702, -127, -769, +472
Bermuda_1957, Clarke_1866, -69.4, -0.37264639, -73, +213, +296
Bogota_Observatory, International, -251.0, -0.14192702, +307, +304, -318
Bukit_Rimpah, Bessel_1841, 739.845, 0.10037483, -384, +664, -48
Camp_Area_Astro, International, -251.0, -0.14192702, -104, -129, +239
Campo_Inchauspe, International, -251.0, -0.14192702, -148, +136, +90
Canada_Mean_(NAD27), Clarke_1866, -69.4, -0.37264639, -10, +158, +187
Canal_Zone_(NAD27), Clarke_1866, -69.4, -0.37264639, 0, +125, +201
Canton_Island_1966, International, -251.0, -0.14192702, +298, -304, -375
Cape, Clarke_1880, -112.145, -0.54750714, -136, -108, -292
Cape_Canaveral_mean, Clarke_1866, -69.4, -0.37264639, -2, +150, +181
Carribean_(NAD27), Clarke_1866, -69.4, -0.37264639, -7, +152, +178
Carthage, Clarke_1880, -112.145, -0.54750714, -263, +6, +431
Central_America_(NAD27), Clarke_1866, -69.4, -0.37264639, 0, +125, +194
Chatham_1971, International, -251.0, -0.14192702, +175, -38, +113
Chua_Astro, International, -251.0, -0.14192702, -134, +229, -29
Corrego_Alegre, International, -251.0, -0.14192702, -206, +172, -6

Corrego_Alegre_(Provisional), International, -251.0, -0.14192702, -206, +172, -6
Cuba_(NAD27), Clarke_1866, -69.4, -0.37264639, -9, +152, +178
Cyprus, International, -251.0, -0.14192702, -104, -101, -140
Djakarta(Batavia), Bessel_1841, 739.845, 0.10037483, -377, 681, -50
DOS_1968, International, -251.0, -0.14192702, +230, -199, -752
Easter_lsland_1967, International, -251.0, -0.14192702, +211, +147, +111
Egypt, International, -251.0, -0.14192702, -130, -117, -151
European_1950, International, -251.0, -0.14192702, -87, -96, -120
European_1950_mean, International, -251.0, -0.14192702, -87, -98, -121
European_1979_mean, International, -251.0, -0.14192702, -86, -98, -119
Finnish_Nautical_Chart, International, -251.0, -0.14192702, -78, -231, -97
Gandajika_Base, International, -251.0, -0.14192702, -133, -321, +50
Geodetic_Datum_'49, International, -251.0, -0.14192702, +84, -22, +209
Ghana, WGS-84, 0.0, 0.0, 0, 0, 0
Greenland_(NAD27), Clarke_1866, -69.4, -0.37264639, +11, +114, +195
Guam_1963, Clarke_1866, -69.4, -0.37264639, -100, -248, +259
Gunung_Segara, Bessel_1841, 739.845, 0.10037483, -403, +684, +41
Gunung_Serindung_1962, WGS-84, 0.0, 0.0, 0, 0, 0
GUX_1_Astro, International, -251.0, -0.14192702, +252, -209, -751
Herat_North, International, -251.0, -0.14192702, -333, -222, +114
Hjorsey_1955, International, -251.0, -0.14192702, -73, +46, -86
Hong_Kong_1963, International, -251.0, -0.14192702,

-156, -271, -189
Hu-Tzu-Shan, International, -251.0, -0.14192702, -634, -549, -201
Indian, Everest, 860.655, 0.28361368, +289, +734, +257
Iran, International, -251.0, -0.14192702, -117, -132, -164
Ireland_1965, Modified_Airy, 796.811, 0.11960023, +506, -122, +611
ISTS_073_Astro_'69, International, -251.0, -0.14192702, +208, -435, -229
Johnston_Island_'61, International, -251.0, -0.14192702, +191, -77, -204
Kandawala, Everest, 860.655, 0.28361368, -97, +787, +86
Kerguelen_Island, International, -251.0, -0.14192702, +145, -187, +103
Kertau_'48, Modified_Everest, 832.937, 0.28361368, -11, +851, +5
L.C._5_Astro, Clarke_1866, -69.4, -0.37264639, +42, +124, +147
La_Reunion, International, -251.0, -0.14192702, +94, -948, -1262
Liberia_1964, Clarke_1880, -112.145, -0.54750714, -90, +40, +88
Luzon, Clarke_1866, -69.4, -0.37264639, -133, -77, -51
Mahe_1971, Clarke_1880, -112.145, -0.54750714, +41, -220, -134
Marco_Astro, International, -251.0, -0.14192702, -289, -124, +60
Masirah_Is._(Nahrwan), Clarke_1880, -112.145, -0.54750714, -247, -148, +369
Massawa, Bessel_1841, 739.845, 0.10037483, +639, +405, +60
Merchich, Clarke_1880, -112.145, -0.54750714, +31, +146, +47
Mexico_(NAD27), Clarke_1866, -69.4, -0.37264639, -12, +130, +190
Midway_Astro_'61, International, -251.0, -0.14192702, +912, -58, +1227

Mindanao, Clarke_1866, -69.4, -0.37264639, -133, -79, -72
Minna, Clarke_1880, -112.145, -0.54750714, -92, -93, +122
Montjong_Lowe, WGS-84, 0.0, 0.0, 0, 0, 0
Nahrwan, Clarke_1880, -112.145, -0.54750714, -231, -196, +482
Naparima_BWI, International, -251.0, -0.14192702, -2, +374, +172
North_America_'83, GRS_80, 0.0, -0.00000016, 0, 0, 0
North_America_1927_mean, Clarke_1866, -69.4, -0.37264639, -8, +160, +176
Observatorio_1966, International, -251.0, -0.14192702, -425, -169, +81
Old_Egyptian, Helmert_1906, -63.0, 0.00480795, -130, +110, -13
Old_Hawaiian_mean, Clarke_1866, -69.4, -0.37264639, +89, -279, -183
Old_Hawaiian_Kauai, Clarke_1866, -69.4, -0.37264639, +45, -290, -172
Old_Hawaiian_Maui, Clarke_1866, -69.4, -0.37264639, +65, -290, -190
Old_Hawaiian_Oahu, Clarke_1866, -69.4, -0.37264639, +56, -284, -181
Oman, Clarke_1880, -112.145, -0.54750714, -346, -1, +224
Ordnance_Survey_of_Great_Britain_'36, Airy, 573.604, 0.11960023, +375, -111, +431
Pico_De_Las_Nieves, International, -251.0, -0.14192702, -307, -92, +127
Pitcairn_Astro_'67, International, -251.0, -0.14192702, +185, +165, +42
Potsdam_Rauenberg_DHDN, Bessel_1841, 739.845, 0.10037483, +606, +23, +413
Provisional_South_American_1956_mean, International, -251.0, -0.14192702, -288, +175, -376
Provisional_South_Chilean_1963, International, -251.0, -0.14192702, +16, +196, +93
Puerto_Rico, Clarke_1866, -69.4, -0.37264639, +11, +72, -101

Pulkovo_1942, Krassovsky, -108,0.00480795, +28, -130, -95
Qornoq, International, -251.0, -0.14192702, +164, +138, -189
Quatar_National, International, -251.0, -0.14192702, -128, -283, +22
Rome_1940, International, -251.0, -0.14192702, -225, -65, +9
S_42, Krassovsky, -108,0.00480795, +28, -121, -77

S.E.Asia_(Indian), Everest, 860.655, 0.28361368, +173, +750, +264
SAD-69/Brazil, South_American_1969, -23.0, -0.00081204, -60, -2, -41
Santa_Braz, International, -251.0, -0.14192702, -203, +141, +53
Santo_(DOS), International, -251.0, -0.14192702, +170, +42, +84
Sapper_Hill_'43, International, -251.0, -0.14192702, -355, +16, +74
Schwarzeck, Bessel_1841_(Namibia), 653.135, 0.10037483, +616, +97, -251
Sicily, International, -251.0, -0.14192702, -97, -88, -135
Sierra_Leone_1960, WGS-84, 0.0, 0.0, 0, 0, 0
South_American_1969_mean, South_American_1969, -23.0, -0.00081204, -57, +1, -41
South_American_1969_mean, South_American_1969, -23.0, -0.00081204, -57, +1, -41
South_Asia, Modified_Fischer_1960, -18.0, 0.00480795, +7, -10, -26
Southeast_Base, International, -251.0, -0.14192702, -499, -249, +314
Southwest_Base, International, -251.0, -0.14192702, -104, +167, -38
Tananarive_Observatory_'25, International, -251.0, -0.14192702, -189, -242, -91
Thai/Viet_(Indian), Everest, 860.655, 0.28361368, +214, +836, +303
Timbalai_1948, Everest, 860.655, 0.28361368, -689, +691, -45

Tokyo_mean, Bessel_1841, 739.845, 0.10037483, -128, +481, +664
Tristan_Astro_1968, International, -251.0, -0.14192702, -632, +438, -609
Unites_Arab_Emirates_(Nahrwan), Clarke_1880, -112.145, -0.54750714, -249, -156, +381
Viti_Levu_1916, Clarke_1880, -112.145, -0.54750714, +51, +391, -36
Wake-Eniwetok_'60, Hough, -133.0, -0.14192702, +101, +52, -39
WGS-72, WGS-72, 2.0, 0.0003121057, 0, 0, +5
WGS-84, WGS-84, 0.0, 0.0, 0, 0, 0
Yacare, International, -251.0, -0.14192702, -155, +171, +37
Zanderij, International, -251.0, -0.14192702, -265, +120, -358

Table 3 - A More Complete List of Geodetic Datums

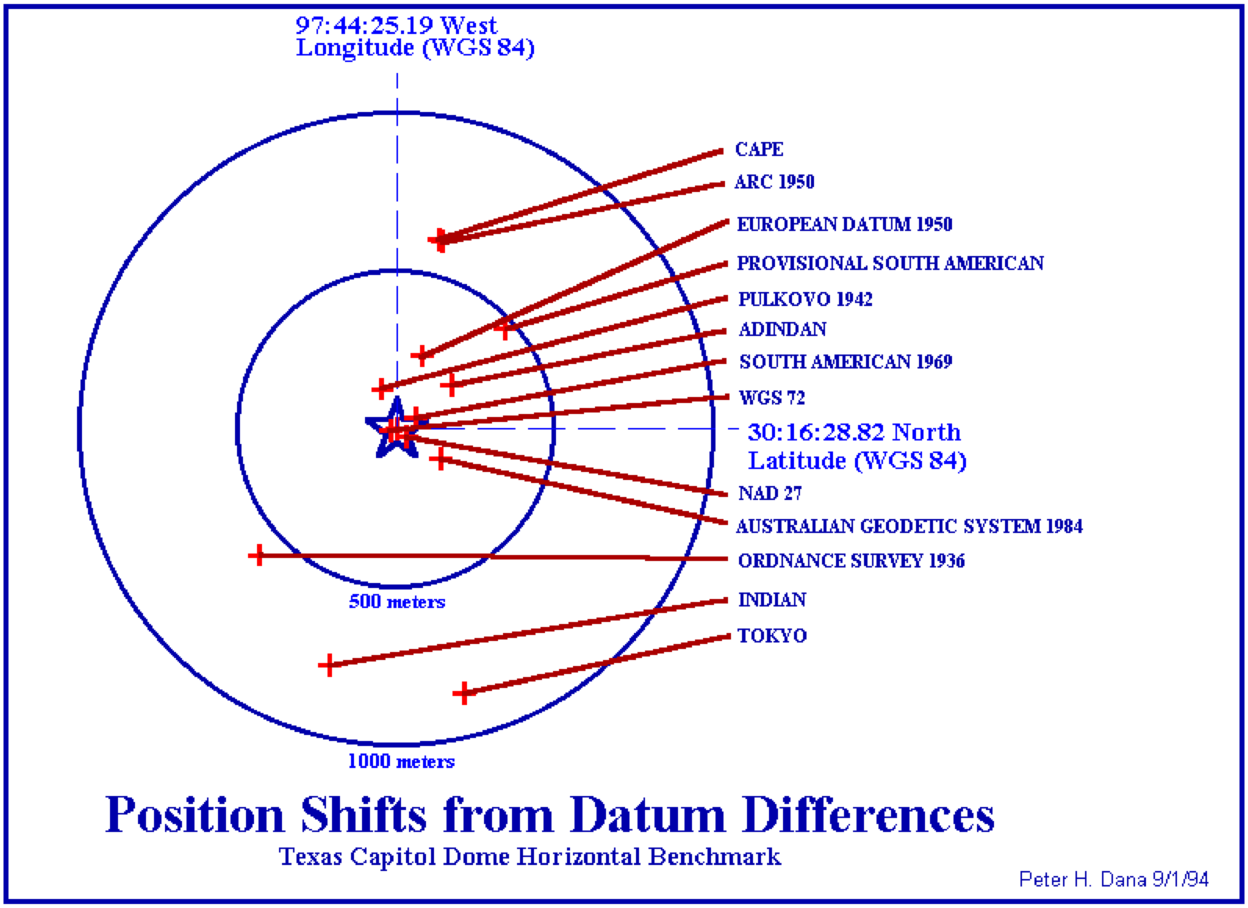


Figure 8 - Horizontal Position Shifts from Datum Differences

Coordinate Conversion: Cartesian (ECEF X, Y, Z) and Geodetic (Latitude, Longitude, and Height)

Direct Solution for Latitude, Longitude, and Height from X, Y, Z

$$\phi = \operatorname{atan}\left(\frac{Z + e'^2 b \sin^3 \theta}{p - e^2 a \cos^3 \theta}\right)$$

$$\lambda = \operatorname{atan2}(Y, X)$$

$$h = \frac{p}{\cos(\phi)} - N(\phi)$$

where:

ϕ, λ, h = geodetic latitude, longitude, and height above ellipsoid

X, Y, Z = Earth Centered Earth Fixed Cartesian coordinates

and:

$$p = \sqrt{X^2 + Y^2} \qquad \theta = \operatorname{atan}\left(\frac{Za}{pb}\right) \qquad e'^2 = \frac{a^2 - b^2}{b^2}$$

$N(\phi) = a / \sqrt{1 - e^2 \sin^2 \phi}$ = radius of curvature in prime vertical

a = semi - major earth axis (ellipsoid equatorial radius)

b = semi - minor earth axis (ellipsoid polar radius)

$f = \frac{a - b}{a}$ = flattening

$e^2 = 2f - f^2$ = eccentricity squared

Peter H. Dana 2/10/97

Figure 9 - Conversion from ECEF XYZ to Latitude, Longitude, and Height

Coordinate Conversion
Geodetic Latitude, Longitude, and Height to ECEF, X, Y, Z

$$X = (N + h)\cos\phi\cos\lambda$$

$$Y = (N + h)\cos\phi\sin\lambda$$

$$Z = [N(1 - e^2) + h]\sin\phi$$

where:

$\phi, \lambda, h =$ geodetic latitude, longitude, and height above ellipsoid

$X, Y, Z =$ Earth Centered Earth Fixed Cartesian Coordinates

and:

$N(\phi) = a / \sqrt{1 - e^2 \sin^2 \phi} =$ radius of curvature in prime vertical

$a =$ semi-major earth axis (ellipsoid equatorial radius)

$b =$ semi-minor earth axis (ellipsoid polar radius)

$$f = \frac{a - b}{a} = \text{flattening}$$

$e^2 = 2f - f^2 =$ eccentricity squared

Peter H. Dana 8/3/96

Figure 10 - Conversion from Latitude, Longitude, and Height to ECEF XYZ.

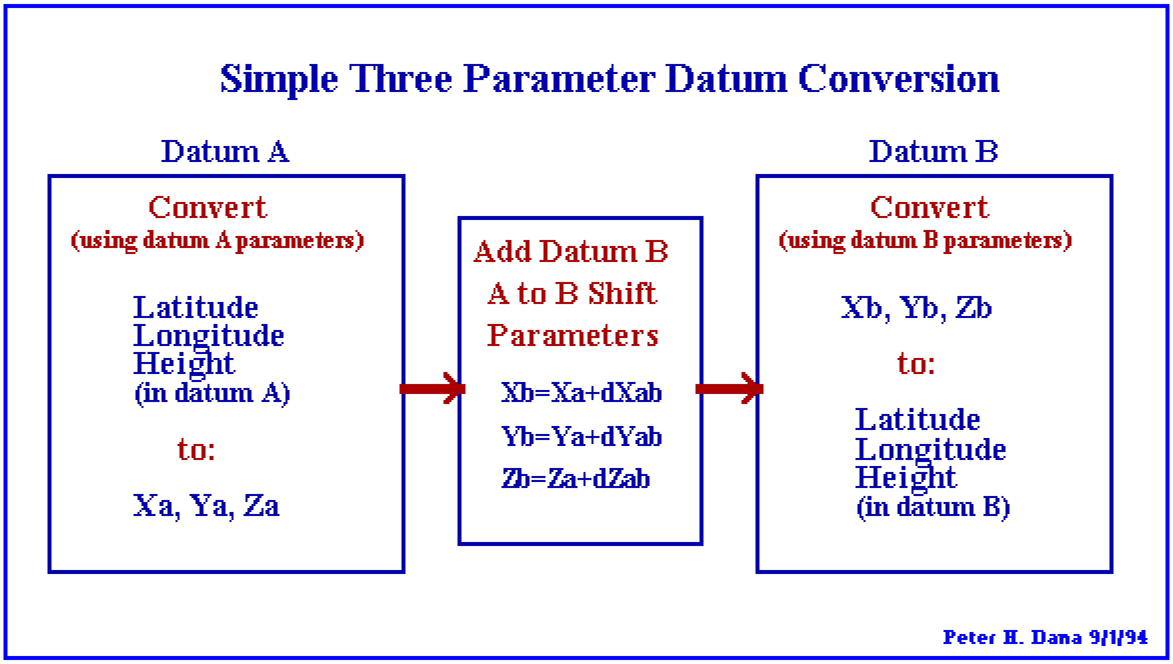


Figure 11 - XYZ Three Parameter Datum Conversion

Standard Molodensky Datum Transformation: Local System to WGS 84
(DMA TR 8350.2 Part II Table 7.8 page 7-40 (modified for radians) Peter H. Dana 04/15/98

Sample local position (NAD27) in degrees converted to radians and height in meters:

$from\_\phi := 30 \cdot deg \qquad from\_\lambda := -100 \cdot deg \qquad from\_h := 232$

Datum constants for FROM datum (NAD 27 CONUS)

a=equatorial radius f=flattening es=second eccentricity squared:

$from\_a := 6378206.4 \qquad from\_f := \frac{1}{294.9786982} \qquad from\_es := 2 \cdot from\_f - from\_f \cdot from\_f$

Datum constants for TO datum (WGS 84)): $to\_a := 6378137.0 \qquad to\_f := \frac{1}{298.257223563}$

NAD27 to WGS 84 datum shift parameters: $\delta X := -8$ Delta X $\delta Y := 160$ Delta Y $\delta Z := 176$ Delta Z

Compute geodetic position shifts: $bda := 1 - from\_f$ Polar radius divided by equatorial radius

$\delta a := to\_a - from\_a$ Delta equatorial radius $\delta f := to\_f - from\_f$ Delta flattening

$s\phi := \sin(from\_\phi) \quad c\phi := \cos(from\_\phi) \quad s\lambda := \sin(from\_\lambda) \quad c\lambda := \cos(from\_\lambda)$ Sin, cos terms

$$Rn := \frac{from\_a}{\sqrt{1.0 - from\_es \cdot \sin(from\_\phi)^2}}$$ Radius of curvature in prime vertical

$$Rm := from\_a \cdot \frac{1 - from\_es}{\left(1 - from\_es \cdot \sin(from\_\phi)^2\right)^{\left(\frac{3}{2}\right)}}$$ Radius of curvature in prime meridian

Delta latitude, longitude, height above the reference ellipsoid:

$$\delta\phi := \frac{\left[\left(\left(-\delta X \cdot s\phi \cdot c\lambda - \delta Y \cdot s\phi \cdot s\lambda\right) + \delta Z \cdot c\phi\right) + \delta a \cdot \frac{Rn \cdot from\_es \cdot s\phi \cdot c\phi}{from\_a}\right] + \delta f \cdot \left(\frac{Rm}{bda} + Rn \cdot bda\right) \cdot s\phi \cdot c\phi}{Rm + from\_h}$$

$$\delta\lambda := \frac{-\delta X \cdot s\lambda + \delta Y \cdot c\lambda}{(Rn + from\_h) \cdot c\phi} \qquad \delta h := \delta X \cdot c\phi \cdot c\lambda + \delta Y \cdot c\phi \cdot s\lambda + \delta Z \cdot s\phi - \delta a \cdot \frac{from\_a}{Rn} + \delta f \cdot bda \cdot Rn \cdot s\phi \cdot s\phi$$

Compute TO position: $to\_\phi := from\_\phi + \delta\phi \quad to\_\lambda := from\_\lambda + \delta\lambda \quad to\_h := from\_h + \delta h$

$$\frac{to\_\phi}{deg} = 30.0002239 \qquad \frac{to\_\lambda}{deg} = -100.0003696 \qquad to\_h = 194.816$$

Figure 12 - Standard Molodensky Datum Conversion

Unit 016 - Discrete Georeferencing

by David J. Cowen, Department of Geography, University of South Carolina, Columbia, USA

This section was edited by Kenneth Foote, Department of Geography, University of Texas Austin.

Advanced Organizer

Topics covered in this unit

- This unit provides an overview of discrete georeferencing, including:
  - Description of how Georeferencing is used to create GIS databases
  - Applications that rely on georeferencing
  - The level of geographic resolution possible for various alternatives of georeferencing
  - Sources of base maps for georeferencing
  - Software for georeferencing address files
  - Problems associated with handling addresses
  - Internet resources for georeferencing

Learning Outcomes

- After learning the material covered in this unit, students should gain an appreciation for:
  - The importance of georeferencing as a way to create GIS databases
  - The limitations of the approach and the benefits of certain alternatives
  - The mechanics of how to use GIS software to perform georeferencing tasks
  - Sources of software and data for performing geocoding operations

Full Table of Contents

Instructors' Notes

Metadata and Revision History

Unit 016 - Discrete Georeferencing

1. Georeferencing (or Geocoding)

- The process of assigning a geographic location (e.g. latitude and longitude) to a geographic feature on the basis of its address.
- This is beneficial because existing addresses can be automatically converted into a GIS database.
- The digital record for the feature must have a field which can be linked to a geographic base file with known geographic coordinates.
  - This can simply be a relational data base join in which the geographic coordinates of the basemap are linked to the address records and made *spatial*.
  - In most cases, a spatial search is required to determine the best geographic representation for each address.
- Georeferencing is an important tool for emergency response, package delivery and marketing applications
- Georeferencing software and the creation and maintenance of base maps has become a significant business.

1.1. Example of Georeferencing

- In order to understand how geocoding works, it is necessary to examine the content of a mailing address.
- Although this may differ from country to country, generally a mailing address consists of a hierarchy of geographic identifiers that become more specific as you proceed from the bottom to the top of the address.
  - Mail is progressively sorted in that order until its gets placed in the specific order that the postal carrier delivers it
  - Geocoding systems use information in an address to assign it to various geographic features.
- The following table breaks down a typical mailing address in reverse order, from least specific to most specific:

The Palmetto Seafood Company

2200 Gervais Street

Columbia, SC 29204-1808 USA

Address Feature	Description	Figures
USA	Country	Figure 1.
29204-1808		
292	Three digit ZIP-Code Area	Figure 2.
29204	Five digit ZIP-Code Area	Figure 3.
29204-18	ZIP Plus 2 Area	Figure 4.
29204-1808	ZIP Plus 4 Point	Figure 5.
SC	State	Figure 6.
Columbia	City	Figure 7.
The postal definition of Columbia	Group of ZIP Areas	Figure 8.
2200 Gervais Street	Street Address	Figure 9.
The UTM Coordinates	X, Y Coordinate pairs	Figure 10.
The Palmetto Seafood Company	Name of Business	Figure 11.

1.2. Georeferencing Applications

- Addresses represent the location of geographic features.
- Georeferencing provides the link to place these addresses into a GIS database.
- Some applications of georeferencing:
  - Emergency response (911)
  - Real estate
  - Crime analysis
  - Package delivery
  - Market analysis
  - Distribution of clients, customers, membership, etc.
  - Trade area assessment
  - Mass mailing
  - Simple navigation

---

2. Georeferencing Methods

- The goal is to build a GIS data base from a set of addresses.
- The ability to do this is based on the reference or base maps that are available for your local area.

2.1. Direct Survey and property boundaries

- Determine the coordinates of an address by actually visiting the site.
  - Calculate the location of a property through conventional surveying methods including use of *Global Positioning Systems* (GPS).

- Determine the location of an address from a digital version of the boundary of property.
    - These files are usually called tax parcels because they are generally created by local governments for tax assessment.
    - Accurate parcel level files are created from the legal descriptions of the property on deeds using special software that uses coordinate geometry to convert meets and bounds information into geographical coordinates.
    - It is impossible to visually determine the legal boundaries of a property.
    - This parcel level information is often adjusted to digital orthophotographs to provide visual content and planimetric accuracy.
    - It should be done rigorously to create an accurate Multi Purpose Cadastre often at scales of 1" = 100' (1:1200).
    - Parcel centroids or label points can be automatically generated from the polygon boundaries to create a point level file for geocoding purposes - In the UK the Ordinance Survey has such a point level file for all property.

2.2. Simple Database Queries

- The essence of georeferencing is to link an address record to a geographic location
- When an existing GIS database includes any geocodes from the mailing address, the records of the address file can be *joined* to the base map file.
- A simple data base management system can usually join the tables.
    - For example, in Columbia, SC, there is a parcel centroid file that includes:
        - Street Name
        - Address
        - Nine-Digit ZIP Code
    - The attributes or information about the address (e.g. real estate, crime reports, utility information etc.) can be directly made into a GIS data base by virtually joining the records on the basis of the address - which forms the unique identification key
- Any set of addresses can be accurately georeferenced by joining to this file on the basis of common fields.
    - Many GIS software applications support direct queries of the spatial database.
    - One may also determine the coordinate of a single address with a direct query of the GIS database by entering the address in a dialog box.
    - Once the particular address is located on a map then the coordinates can usually be read directly from the screen.
    - Depending in the level of detail required and the number of addresses this method can work fine.:
- Figure 12. Simple *Locate Address* Function

2.3. Specialized Georeferencing Options

- Many firms have developed specialized software applications that perform geocoding.
    - These products are designed to process and edit large address files.
    - They are typically purchased by organizations that need to create geographic databases for marketing applications.
    - Specialized georeferencing systems often constitute the front end to applications

for package delivery, emergency response, etc.
    - Many firms will geocode a set of addresses as a service.
        - The **U.S. Census Bureau** has a large list of firms online.

- Several general purpose GIS packages now incorporate Geocoding functions.
    - This is particularly true of several desktop mapping and GIS systems that take advantage of the available GIS databases generated from public domain sources such as the **Census TIGER** files.
    - A geocoding system provides the user with a series of georeferencing options.
    - The choice will be based on the type of base map that is available.
    - The following list is the typical set of options:

2.3.1. Single Field

- This method is based on establishing a one-to-one match of an address with a look-up table of points or polygons such as a tax parcel or centroid.
- A tax map or multi-purpose cadastre file maintained by a local government such as a county tax assessor is usually required.
    - Figure 13. Address Matching Inputs and Results
- In the UK, the **Ordinance Survey** licenses a very accurate *Address Point file* with over 25,000,000 addresses.

2.3.2. Zip Code Address Style

- This method matches an address to a record in the base map file on the basis of its postal zone information.
- The actual street address is not utilized - only the postal codes.
- It can be used in countries with geographic base files of postal zones.
    - Figure 14. *Zip+4* Address Matching Inputs and Results
- In the US, the *Zone Improvement Plan (ZIP)* is administered by the **US Postal Service**.
    - Look up the 9-digit zip code for any US address: (http://www.usps.gov).
- A *Zip Code* is really just an extension of the single address process.
- Although the Postal Service assigns the new ZIP + 4 numbers to geographical features the ZIP code geographical base files are produced as commercial products

- The code becomes more precise with each additional digit:
    - 3 digits: least precise - point or polygon representation
    - 5 digit: point or polygon representation
    - Zip + 2: point or polygon representation - based on a cluster of zip+ 4 points
    - Zip + 4: point representation - most precise - typically block face, increments of 100 addresses, a building, or even the floor of a building if it receives enough mail; Generally the base file is a set of points that are located along a TIGER street segment to correspond with the midpoint of the address range

2.3.3. US Streets Address Style

- This method interpolates the location of an address on the basis of address ranges and side of street.
- It relies on a street centerline geographic base file with address ranges.
- Figure 15. U.S. Streets address matching inputs and results
- Figure 16. Census Bureau **TIGER** (*Topologically Integrated Geographic Encoding and Reference*) line files represent the most commonly used files for this purpose.

    - The Streets segments are stored as directed links with from and to nodes.
    - Address ranges are associated with the sides of the streets.
    - Linear interpolation is performed for each address on the basis of the proportion of the theoretical range of addresses along a street segment.
        - Figure 17. Assumes even distribution of addresses along the link
        - Figure 18. Uses theoretical range rather than actual address along a street
        - Figure 19. The process often results in clustered points. (This is a set of all business addresses in downtown Columbia, SC.)
        - The user can typically select off-set distance from street centerline. (This is helpful for putting the address into the correct polygon such as a census block, block group or tract.)

2.3.4. Single Range

- This method is a modification of the US Street Style except that interpolation of addresses is performed along street centerline without regard to side of street.
    - This method is used when address ranges cannot be determined for different sides of the street.
    - It can be used to create addresses for rural routes and box numbers.

---

3. Problems With Address Records

- Every set of addresses will have some problems that make it difficult to obtain a 100% match rate.
- These problems can be grouped into the following categories:
    - Lack of street names - PO Boxes, Rural Routes
    - Human errors in address records - Typos, spelling errors
    - Inconsistency of address records - Multiple spellings (Green & Greene)
        - Figure 20. See actual addresses for 2200 block of Gervais St.
        - Note: in this example of the block that contains the Palmetto Seafood Company there are multiple lots with the same address, front and rear addresses, lots with no address, and buildings that have numbers out of sequence.

3.1. Handling Address Errors

- Once a set of addresses is initially processed, the user typically has to determine how to handle the non-matched records.
- This process is often referred to as *reject processing*.
- Most georeferencing software allows the user to control the processing of a set of address records:
  - If there are a large number of addresses, a set of rules can be established at the beginning of the process to handle the rejects in a batch mode.
  - For a smaller number of records, or in cases when the user wants to be involved in the process, they can be handled interactively.

3.2. ArcView Example

- Figure 21. Because reject processing functions differ by vendor the following examples are based on the georeferencing functions of **ArcView 3.0** which is produced by Environmental Systems Research Institute (ESRI) (http://www.esri.com).
- Figure 22. With this system, addresses are matched to specific records in the base map file on the basis of a scoring system.
  - A perfect match yields a score of 100.
  - A match score between 75 and 100 can generally be considered a good match.
  - The batch match process will not match the address if it yields a match score below the minimum match score.

3.2.1. Spelling Sensitivity

- The user can specify the level of spelling sensitivity to determine how exact the spelling must be for a record in the base map file to be a candidate for the matching process.
- This also includes road type suffixes and directional prefixes.

3.2.2. Minimum Match Score

- The minimum match score controls how well addresses have to match their most likely candidate in the reference theme, in order to be considered matched.
- The batch match process will not match the address if it yields a match score below the minimum match score.
  - A perfect match yields a score of 100
  - A match score between 75 and 100 can generally be considered a good match.
  - The default is 60.

3.2.3. Minimum Score to be Considered a Candidate

- This establishes a threshold to determine to whether a potential candidate should be considered.
- Candidates that yield a match score lower than this threshold will not be considered.
  - The ArcView default is 30.

3.3. Examples

3.3.1. Example 1

- With the US Street georeferencing option, assume that the **TIGER** record for 2200 to 2298 Gervais St is the appropriate record for matching.
- Then the following addresses yield Score:

Address	**Score**
2200 Gervais St	100
Figure 23. 2200 Gervaiss St	91
2200 Gervais Dr	75
2200 Gerv St	72
2200 N. Gervais St	52

- If the minimum match score was set at 80, then only the first two records would have matched.
- If the spelling sensitivity is reduced to 50, then three candidate street records are found for 2200 Gerv St.:

Address	**Score**
Gervais	100
Gregg	57
Green	57

- In an interactive mode, the user would be able select the best alternative for matching
- Figure 24. If the spelling sensitivity is set too low, inappropriate matches will be made.

3.3.2. Example 2

- In this example of matching against a single field, a non existent address (2201 Gervais St) generated the following scores:

Address	**Score**
2210 Gervais St	85
2221 Gervais St	70
2200 Gervais St	70
2010 Gervais St	70

2100 Gervais St	53
2229 Gervais St	40

- Therefore, in a batch processing mode, 2201 Gervais St would be matched to 2210 - which is actually across the street!

3.4. Limitations of Georeferencing

- Poor match rates result in incomplete databases - Raises questions about the integrity of the addresses used in research projects or the omission of important records simply because they could not be located.
- New subdivisions are not included in geocoding data bases - This can be a particularly critical problem for applications that require such information for planning and emergency response - i.e. school districts. Also accidents that occur on building sites cannot be accurately reported.
- Mixed levels of geographic resolution for features in a layer based on the level of georeferencing accuracy
    - For example - a large data base that includes both rural and urban areas will often be geocoded on the basis of a three step hierarchy: attempt to find a street address match, assign address to the zip+ 4 point and finally assign the address to the centroid of the five digit zip code area.
    - As a result the positional accuracy of the data can easily range from a few hundred feet to several miles.
- Mail address often not at the location of the feature - This is particularly true of post office box numbers which are located at the post office
- Rural addresses (route and box numbers) do not have conventional street names and numbers which cannot be handled with geocoding software.
- The best solution is a perfect look-up table with a one-to-one match to a specific file that contains a unique representation for each address.

---

4. Sources of Basemaps for Georeferencing

4.1. Bureau of the Census

- **TIGER** is by far the leading source for a geocoding base map.
    - Advantages
        - Nationwide coverage
        - Public domain
    - Limitations
        - Relatively poor positional accuracy - 1:100,000
        - Completeness of street names and address ranges
        - Currency of the data

4.2. Other Suppliers

- Several companies provide their own versions of street centerline data and ZIP + 4 files.
- A comprehensive list of these vendors can be found at (http://www.census.gov/cgi-bin/geo/vendors).
- Two well known sources:
  - Geographic Data Technology (GDT) (http://www.geographic.com/technol.html).
  - ETAK (http://www.etak.com/)

---

5. Sources of Address Data

5.1. Digital Yellow Pages

- Most georeferencing involves individual user-defined lists of addresses.
- Digital yellow pages provide convenient directories of businesses.

5.1.1. Web Based

- The number of firms offering web based sources of addresses and address locating systems is constantly changing

- **Bigbook** provides on line business listings and interactive mapping capabilities.
  - (http://www.bigbook.com)
- Figure 25. A series of five maps of the location of the *Palmetto Seafood Company* generated by **Bigbook**
- MapsOnUs provides an extremely fast interactive address locating system (http://www.MapsOnUS.com).

5.1.2. CD-ROM Based

- Several companies now offer digital telephone directories which include addresses, telephone numbers, Standard Industrial Classifications (SIC), and even latitude and longitude.
  - **Select Street** is one example of such a product from **Pro-Cd**

5.2. Demographic and Marketing firms

- Other companies offer a full range of demographic and marketing services based on address information.
  - **Equifax** (http://www.equifax.com/)

- Several other companies are involved in *Commercial Address Matching Services.*
  - (http://www.usps.gov/ncsc/vendors/cassmass.html)
  - These companies provide services for target marketing, bulk mailing, etc.

---

6. Review and Study Questions

- These questions refer primarily to the US postal code system
- (If outside the US, then use the address of the *Palmetto Seafood Company* or search any of the yellow page listings to obtain US addresses.)
  - Go to the **Postal Service** Web Site (http://www.usps.gov)and request the nine digit ZIP code for your address and an address across the street - Are they different?
  - Use one of the yellow page directories with mapping functions (such as http://www.bigbook.com) to obtain a distribution of addresses for two categories of businesses in your hometown - How do they differ?
  - Look in your local phone book for postal ZIP code maps.
    - Can you determine the boundaries for your five digit zip code?
    - How far is your house from the center of that zip code area?
  - Examine the actual addresses along your street versus the potential addresses.
    - Are most of the numbers less than half the potential range?
    - For example, if the start of the next block is 200, what is the largest address on the 100 block?

---

7. Reference Materials

7.1. Print References

Berry, Joseph K. 1996. "Spatial Objects--Parse and Parcel of a GIS?," *GIS World*. October: Vol.9, No.10, p. 28.

Cooke, Donald F. 1993. "TIGER 1992 Version Scheduled to Arrive," *GIS World*. May, Vol.6, No.5. p. 61.

Cooke, Donald, 1997. "Understanding Geodemographics," *Business Geograpics*, Vol.5, No.1, p. 32.

Halls, Joanne. 1994. "Address-Matching Using U.S. Postal Service Zip+4", *Proceedings*. ESRI Users Conference.

Lange, Art. 1996. "Georeferencing Basics Lead to Accurate GIS Data" *GIS World*, December, Vol. 9, No.12, p. 106.

Raper, J., D. Rhind, and J. Sheperd. *1992 Postcodes: The New Geography*, Essex: Longman Scientific.

Marx. 1990. *The TIGER system: Yesterday*, *Today and Tomorrow*, *Cartography and GIS* Vol. 17, No.1, pp. 89-97. (This volume of CAGIS was dedicated to TIGER)

Thrall, Grant, J. del Valle, and S. Elshaw-Thrall. 1995. "Business GIS Data Part 6: When is Zip+2 Geocoding Good Enough?,"*Geo Info Systems*, Vol.5, No.11, p. 40.

Thrall, Grant, J. del Valle, and S. Elshaw-Thrall. 1994 "Shop Talk: Business GIS Data, Part Three Zip plus 4 Geocoding," *Geo Info Systems*, Vol. 4, p. 57.

Van Demark, Peter. 1993. "City Tailors GIS to Address Information Needs," December: Vol.6, No.12, p. 50.

Van Demark, Peter. 1993. "TIGER Massage Expands TIGER FILE FUNCTIONALITY," *GIS World*, August: Vol. 6, No.8, p. 62.

7.2. Web References

- **Census Bureau**-LANDVIEW II
  - Enables one to find a street and list address ranges.
- Commercial Vendors
  - The **Census Bureau** maintains a list of vendors that provide georeferencing software and services.

7.3. Glossary

- (Glossary)

Citation

To reference this material use the appropriate variation of the following format:

Cowen, David J. (1997) Discrete Georeferencing, *NCGIA Core Curriculum in GIScience*, http://www.ncgia.ucsb.edu/giscc/units/u016/u016.html, posted February 11, 1997.

Created: February 11, 1997. Last revised: December 18, 1997.

Unit 016 - Discrete Georeferencing

Table of Contents

- Advanced Organizer
  - Topics Covered in this Unit
  - Learning Outcomes
  - Instructors' Notes
  - Metadata and Revision History
- Body of Unit
  - 1. Georeferencing
    - 1.1 Example of Georeferencing
    - 1.2 Georeferencing Applications
  - 2. Methods
    - 2.1 Direct Survey
    - 2.2 Simple Database Queries
    - 2.3 Specialized Georeferencing Options
      - 2.3.1 Single Field
      - 2.3.2 Zip Code Address Style
      - 2.3.3 US Streets Address Style
      - 2.3.4 Single Range
  - 3. Problems with Address Records
    - 3.1 Handling Address Errors
    - 3.2 ArcView Example
      - 3.2.1 Spelling sensitivity
      - 3.2.2 Minimum Match Score
      - 3.2.3 Minimum Score to be Considered a Candidate
    - 3.3 Examples
      - 3.3.1 Example 1
      - 3.3.2 Example 2
    - 3.4 Limitations of Georeferencing
  - 4. Sources of Basemaps for Geocoding
    - 4.1 Bureau of the Census
    - 4.2 Other Suppliers
  - 5. Sources of Address Data
    - 5.1 Digital Yellow Pages
      - 5.1.1 Web-based
      - 5.1.2 CD-ROM
    - 5.2 Demographic and Marketing Firms
  - 6. Review and Study Questions
  - 7. Reference Materials
    - 7.1 Print References
    - 7.2 Web References
    - 7.3 Glossary

- Citation

Discrete Georeferencing (016)

Instructor's Notes

The lesson on discrete georeferencing was developed largely from the perspective US postal code system and the Bureau of the Census TIGER files. However, some of the examples do use the city of Columbia parcel level file. The parcel level geocoding or single address method can be used anywhere in the world - all that is required is that you have a set of addresses associated with a set of X, Y locations. Therefore, the concepts should be rather universal. From a web browser you can do a lot of the examples using the Palmetto Seafood company as an example. But you could just as easily find another address in an other city. Maybe a book publisher or 1600 Pennsylvania Av, Washington DC

There are several ways that you could use the materials. If you have geocoding software you should be able to set up the TIGER data for your area and develop a set of exercises or examples. I like to emphasize that most geocoding is based on interpolation. The Census works on the basis of potential address range - i.e. the 100 block goes from 101 - 199, and 100 - 198 even though the actual addresses on a street rarely exceed 50% of that range. Therefore the interpolation process can only get you so close and it is easily to demonstrate. It is also important to note that if you end up locating an address on the basis of the center of its five digit zip code you can be very far (several miles) from the actual location.

If you have access to a GPS system you could build a point level geocoding base and geocode using a single address procedure.

If you do not have geocoding software then you can do the entire lesson with a web browser. Except that you will not create the actual GIS data base. I particularly like http://MapsOnUS.com for locating a single address. The students could select a number of addresses along the same street and see how the interpolation system works. The postal service zip+4 locator is also informative.

http://bigbook.com is a good way to select and locate a series of businesses in a city. It is a useful way to teach some economic geography by comparing automobile dealerships that tend to cluster versus grocery stores that are more dispersed.

Back to the Unit

Unit 016 - Discrete Georeferencing

Metadata and Revision History

---

1. About the main contributors

- David J. Cowen, Department of Geography, University of South Carolina, Columbia, SC, USA.
- Edited by Jacquelyn Cunningham, Information Systems Manager, Liberal Arts Computing Lab, University of South Carolina, Columbia, SC, USA.
- Additional contributions by John Steward, graduate student, Department of Geography, University of South Carolina, USA
- Lynn Shirley, GIS Manager, Liberal Arts Computing Lab, University of South Carolina, USA.

section editors:

- Kenneth E. Foote, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098
- Tony Kirvan, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098

2. Details about the file

- unit title:
  - Discrete Georeferencing
- unit key number:
  - 016

3. Key words

- Address matching
- Georeferencing
- Postal codes
- Postal codes

4. Index words

- Zone improvement Plan
- Zip+4
- spelling sensitivity

- reject processing
- street center lines
- Military Grid Reference System ("MGRS")
- parcels

5. Prerequisite units

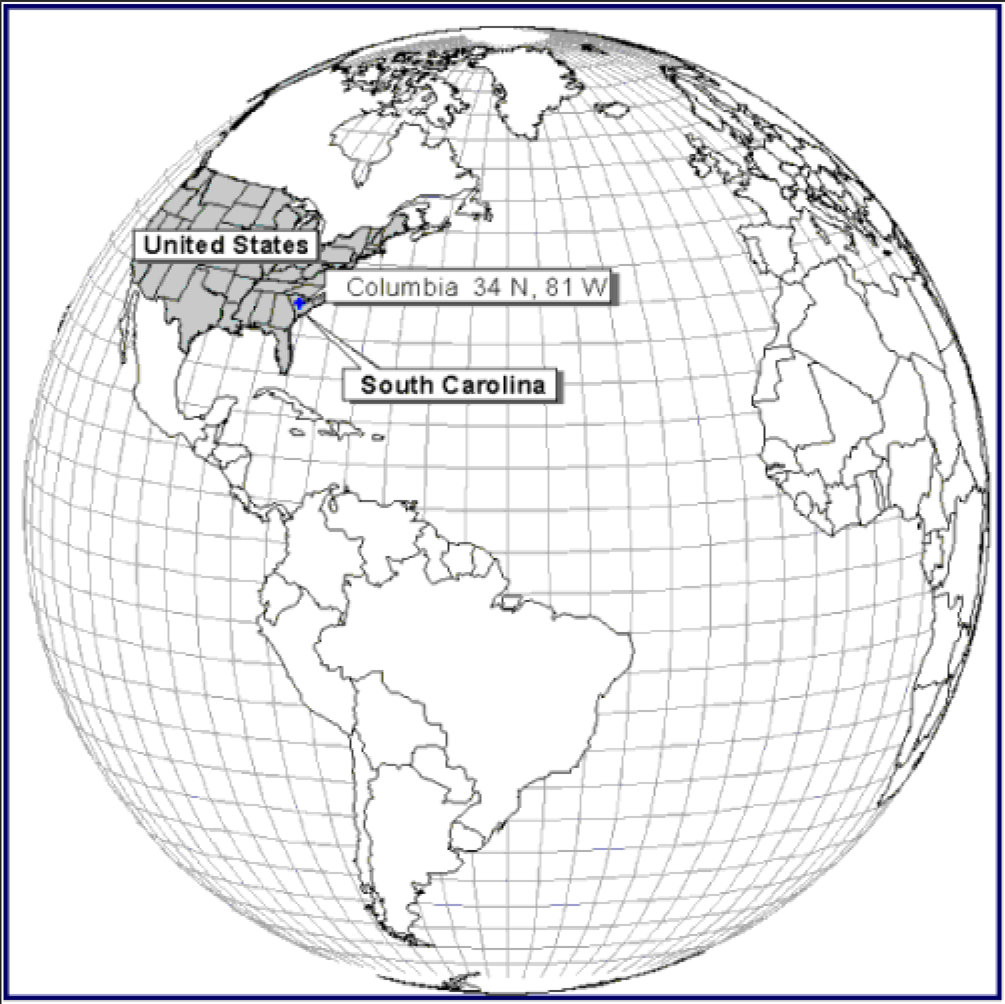
- Unit 13: Coordinate systems overview

6. Subsequent units

7. Revision history

- 17 September 1997. Major format revision. Bold and italics added for definitions and technical terms. Frame version, table of contents, and short table of contents created.
- 18 December 1997. Minor revisions.
- 7 July 2000. External links updated.

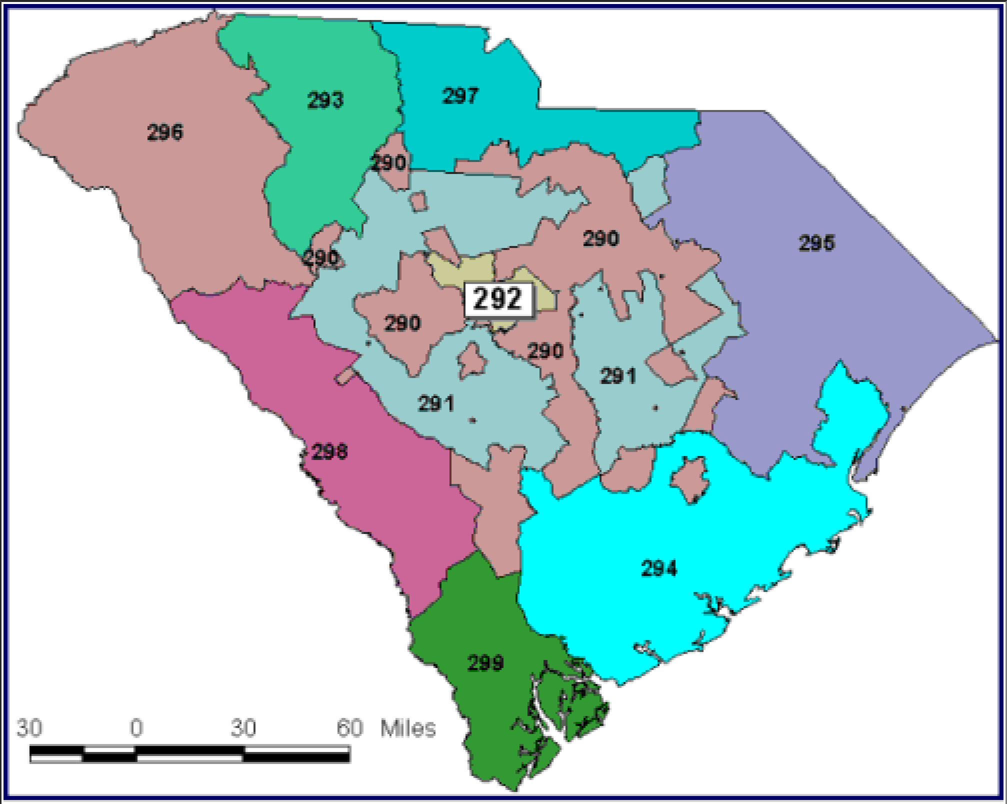
- Back to the Unit



Where in the World is South Carolina?

- Knowing that the address is in the USA provides an initial sort for international mail.

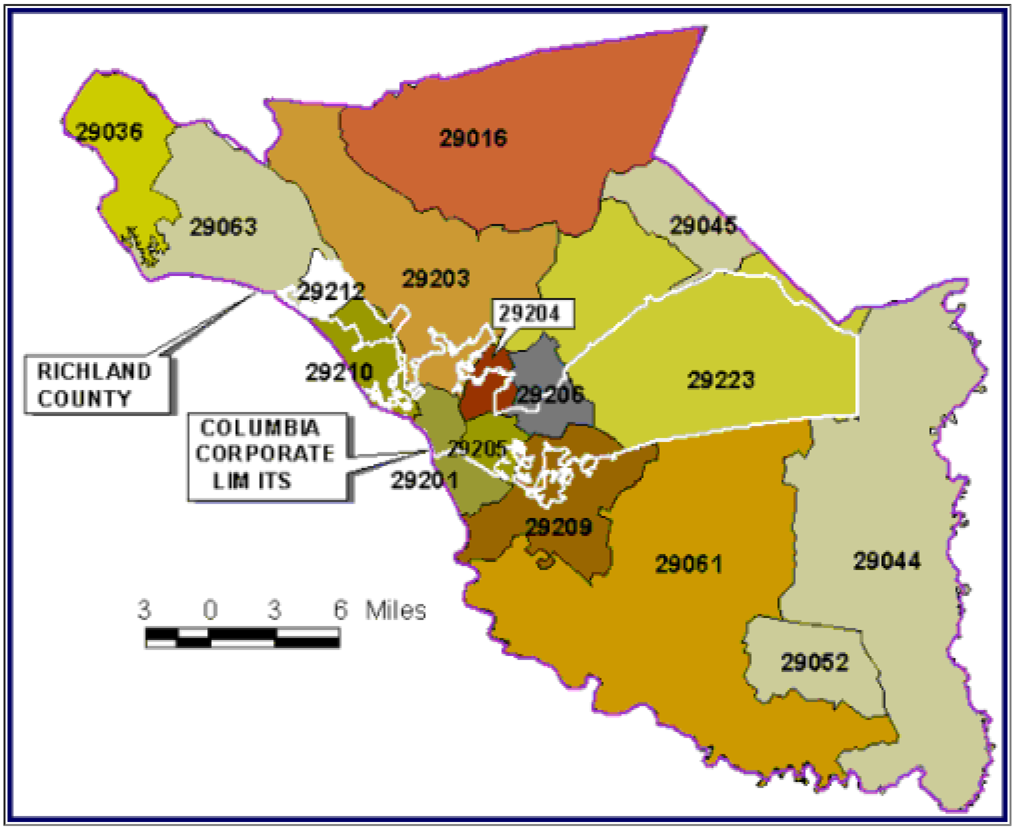
Figure 1.



Where in South Carolina is 292?

- South Carolina is divided into ten 3-digit zip code areas 290-299.
- These areas can consist of multiple non-contiguous polygons.
  - 292 is a single polygon in the center of the state.
- The 3-digit polygons can be extracted from the Census TIGER files.
- They are also available as sample data sets with several GIS programs.

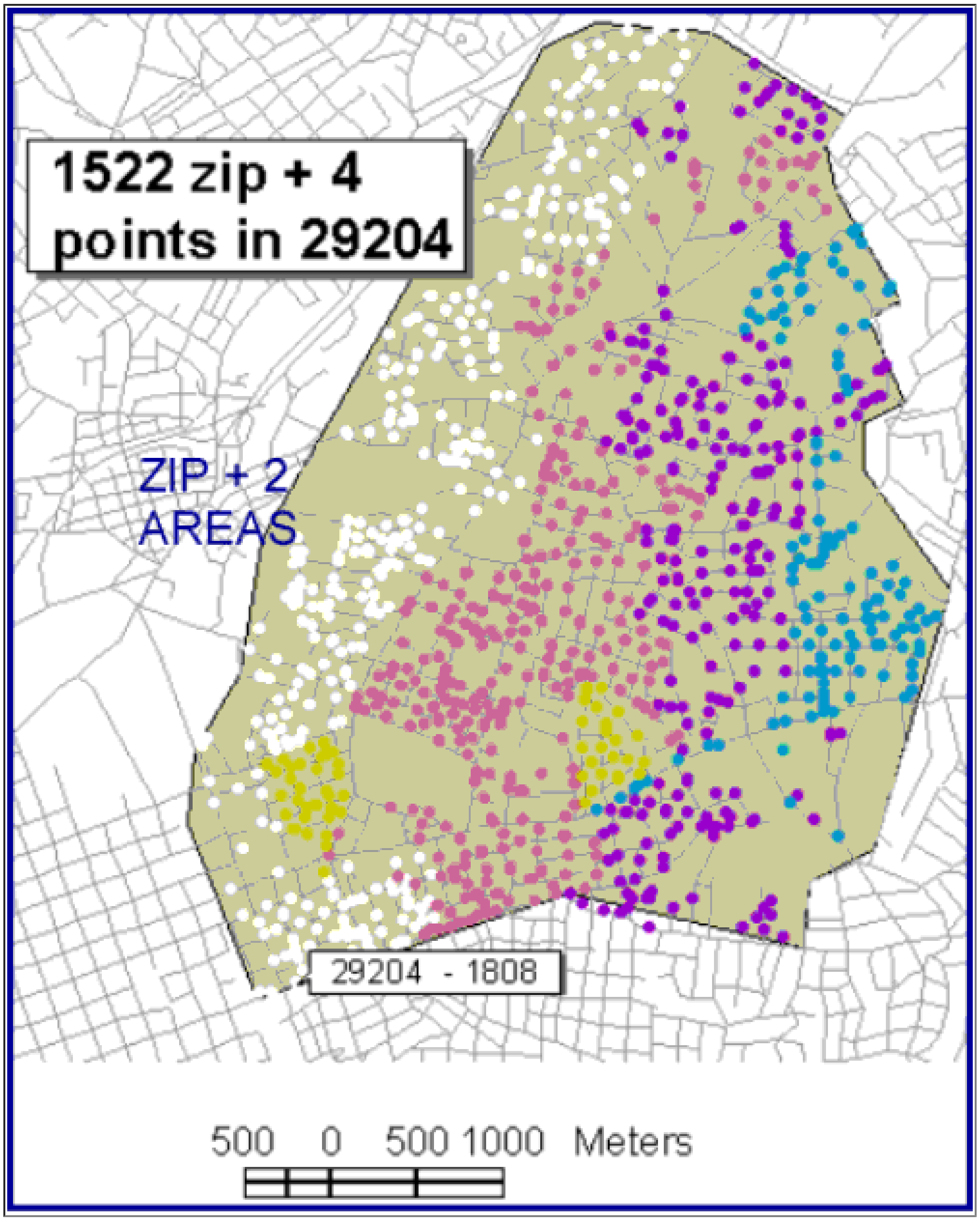
Figure 2.



Where in Richland County is 29204?

- Zipcode 29204 is one of 15 five digit zip codes in Richland County, SC.
- At a national level, the five digit zip codes are often represented as a centroid.
- The five digit zip code polygon boundaries can be extracted for any area from the Census TIGER files.

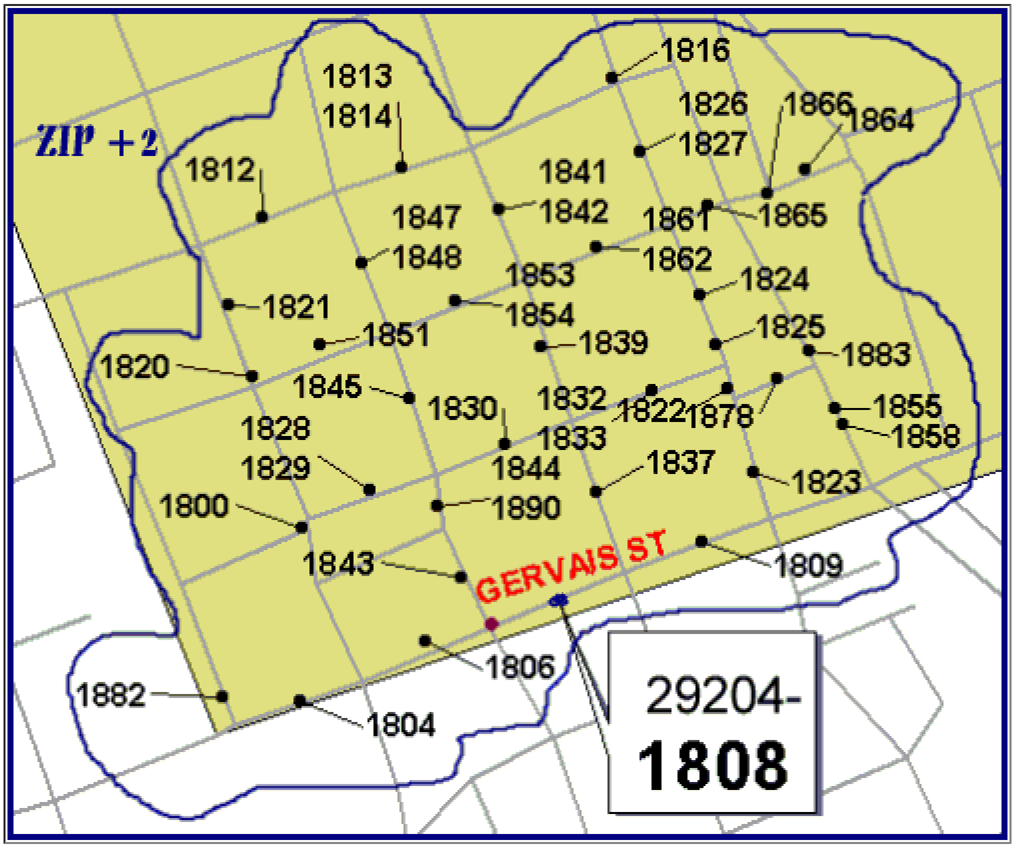
Figure 3.



Where is 29204-18?

- Zip + 2 areas are really logical clusters of the nine digit zipcode points and correspond to specific mail carrier routes.
- These clusters are often represented by a centroid.
- Point files that consist of the coordinates of these points can be purchased or leased from several vendors.

Figure 4.



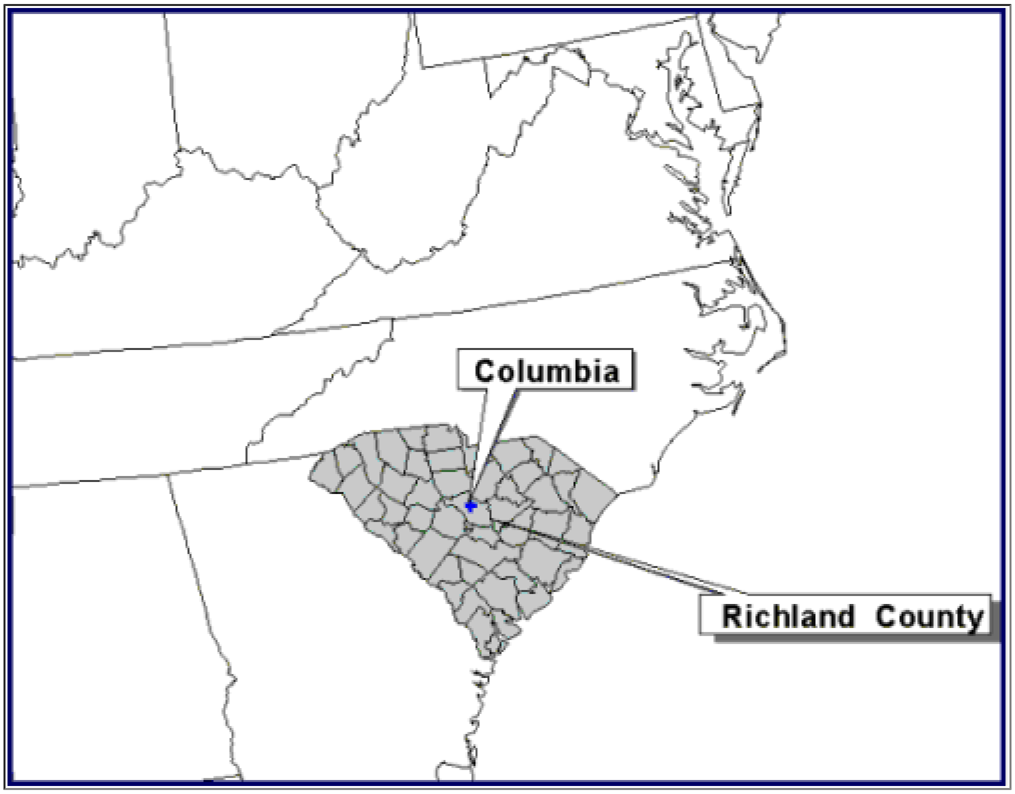
Where is 29204-1808?

- A nine digit or ZIP + 4 code is represented as a point.
- Generally there are two points assigned for every 100 addresses:
    - One for the odd, and one for the even side of the street
- These points are usually mathematically calculated to be located at the midpoint of the TIGER street centerline for that address range.
- As a result, even though there are different points for each side of the street, the coordinates are often exactly the same.
- Unique ZIP + 4 numbers can also be assigned by the Postal Service to any business or organization that receives a large volume of mail.
    - A large office building can actually be represented by several 9 digit zip codes with the same coordinate points.
    - Separate divisions within the same business that receive large volumes of mail can even have their own ZIP + 4.

Note that in 29204 there are 1,522 ZIP + 4 points.

- If there is a 9 digit zip code in the address then it is generally possible to geographically reference that address to the proper side of the street within a block.

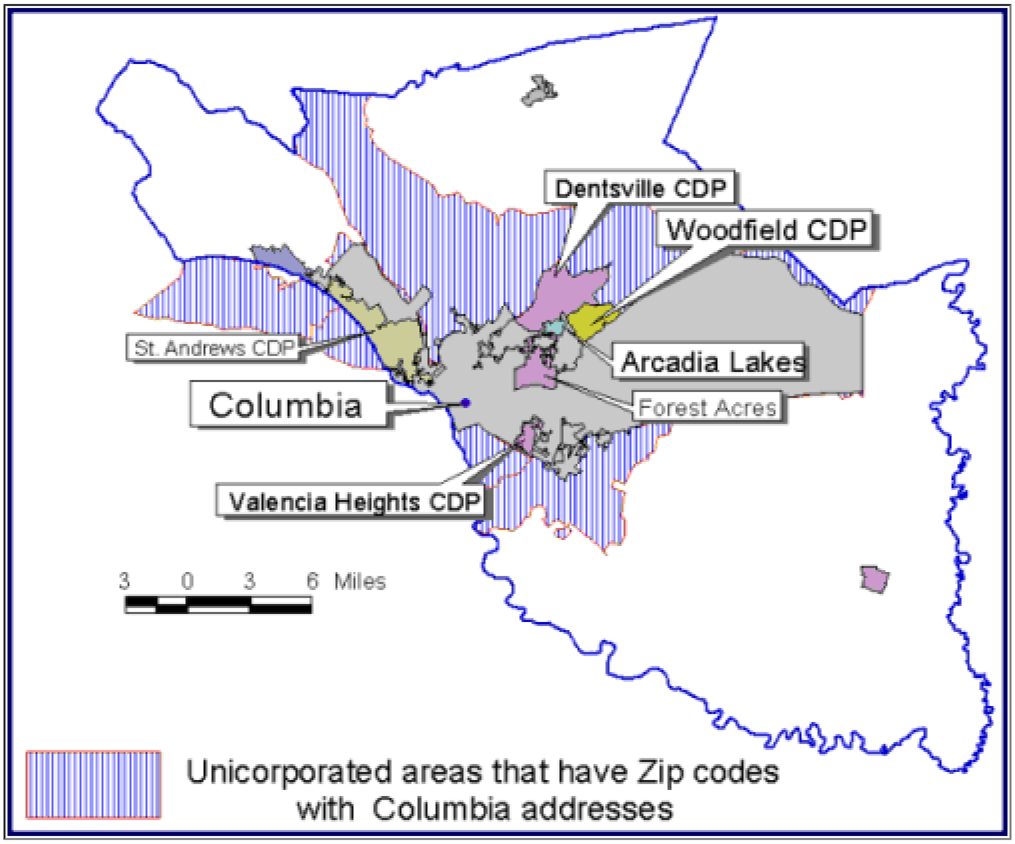
Figure 5.



Where in the U.S. is South Carolina?

- South Carolina is one of fifty states.
- All SC addresses could be directly joined to a GIS polygon representing the state.

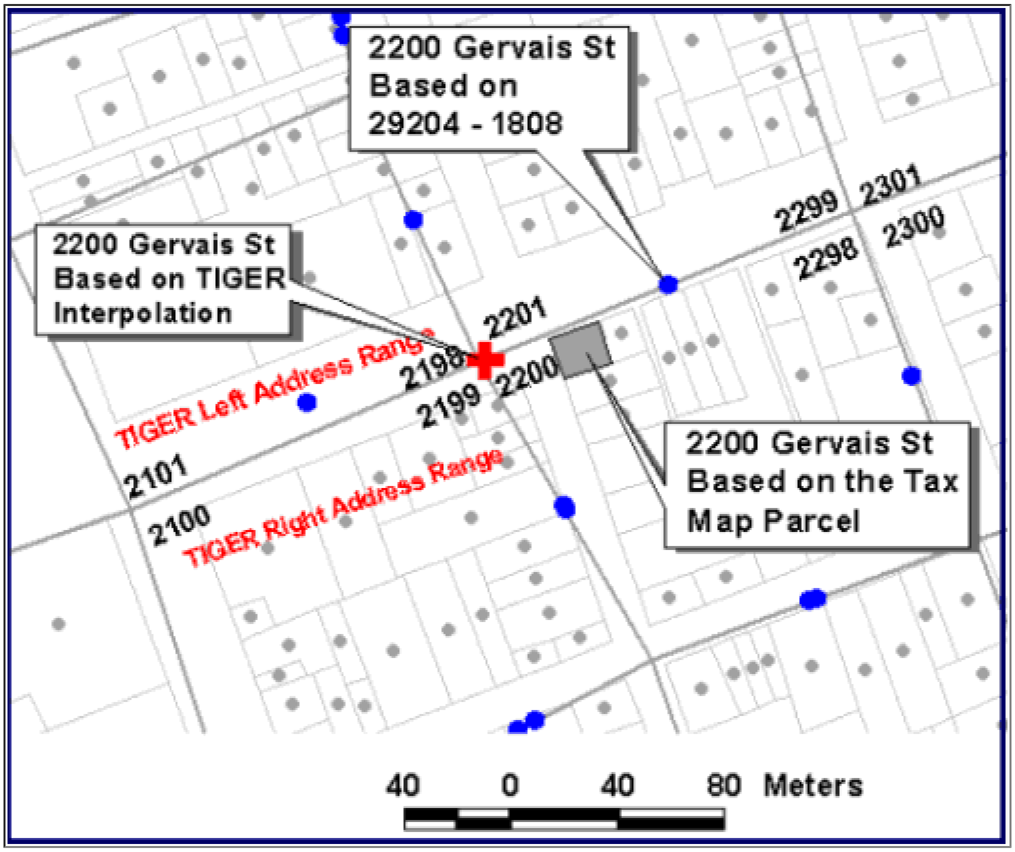
Figure 6.



What areas have Columbia mailing addresses?

- Most addresses use the name of the largest city in the region, even though the specific address may not be within the corporate limits of that city.
    - In fact, it may not even be in the same county.
- In this example, several different five digit zip code areas are called Columbia.
- Therefore, a geocode of Columbia can be very ambiguous.
- This is one of the reasons the ***Zone Improvement Plan*** was developed.

Figure 7/8.

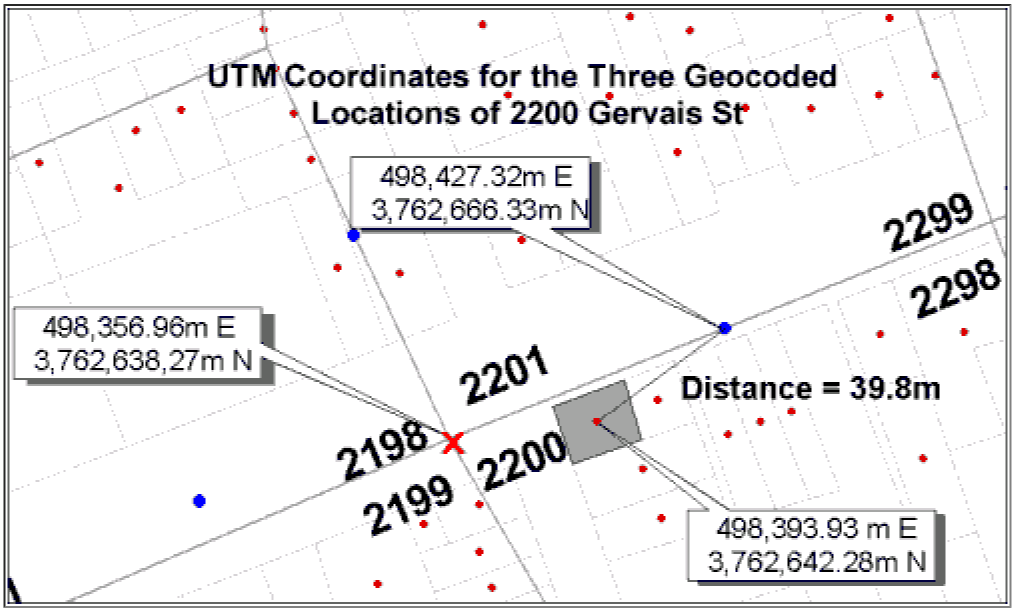


Where is 2200 Gervais Street?

- With the street name and number it is possible to more precisely assign an X Y coordinate to the address.
- The level of precision is a function of the type of basemap that is available:
  - If there is a digital version of the tax maps or another representation of the property boundaries then the address can be accurately assigned to either the parcel polygon or centroid.
  - If a parcel level GIS file does not exist then the best alternative is to interpolate along a street segment.
- This is the major approach to Geocoding in the United States and represents the basic approach developed by the Bureau of Census in the original **DIME (Dual Independent Map Encoding)** system implemented in the 1970 Census.
  - It relies on a topologically structured file with from and to nodes and addresses ranges for both sides of the street.

Addresses are assigned coordinates by interpolation from the nodes on the basis of the proportion of the address range the address represents

Figure 9.



What are the geographical coordinates of 2200 Gervais St?

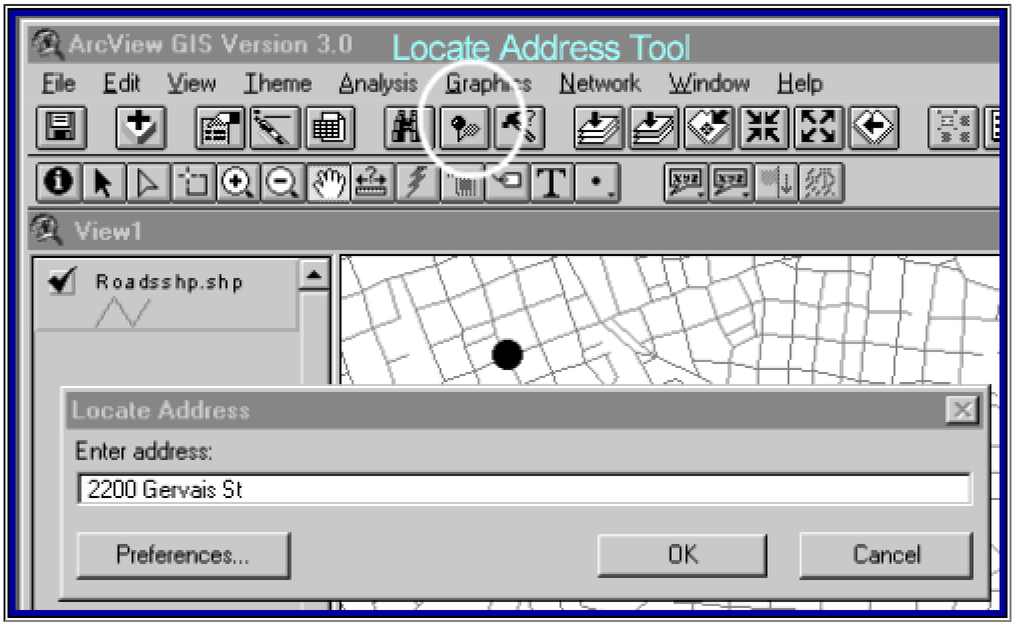
- The geocoding process creates a GIS point theme.
- In this case the coordinate system is Universal Transverse Mercator (UTM):
  - UTM X coordinates are in meters relative to a false easting of 500,000 at the center of the zone. The center of zone 17 is 81 degrees west longitude which is only about 1500 meters east of this location.
  - The UTM Y coordinates are in meters north of the equator.
- Most GIS software does not actually include the X,Y coordinates as attributes of the record. However, it is also usually a simple process to add them to records that you may wish to export and use on another system.
- Note the difference in location of the address based on the different approaches taken to locate the address.

Figure 10.

The Palmetto Seafood Company

Columbia, South Carolina

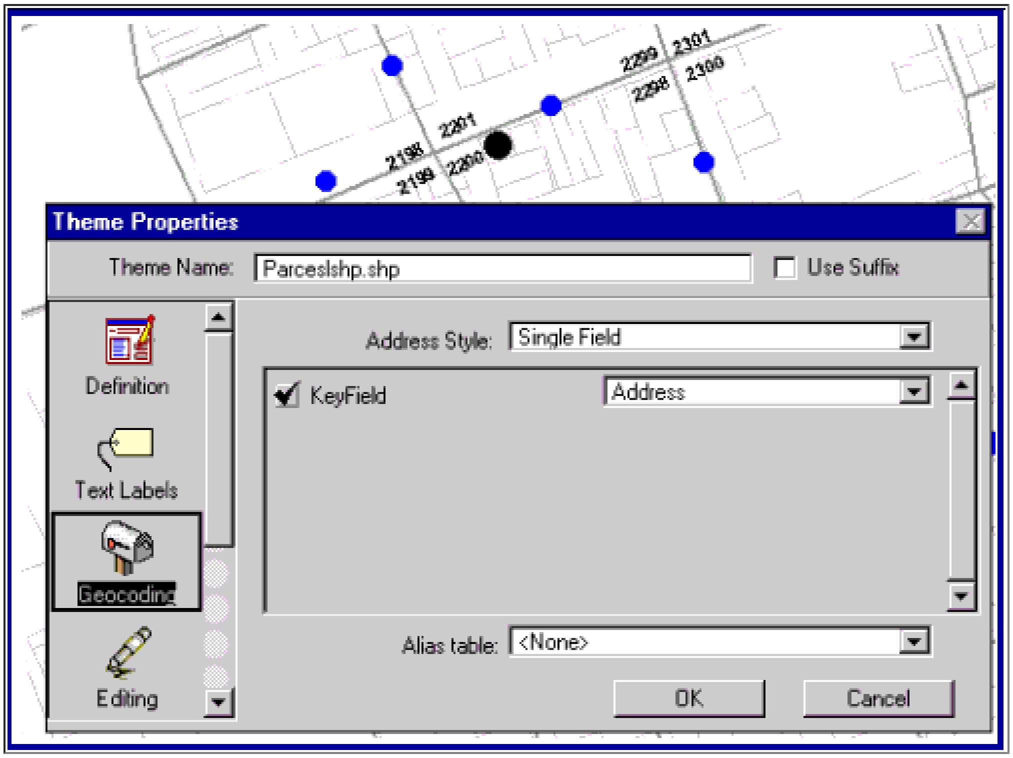
Figure 11.



Simple *Locate Address* Function

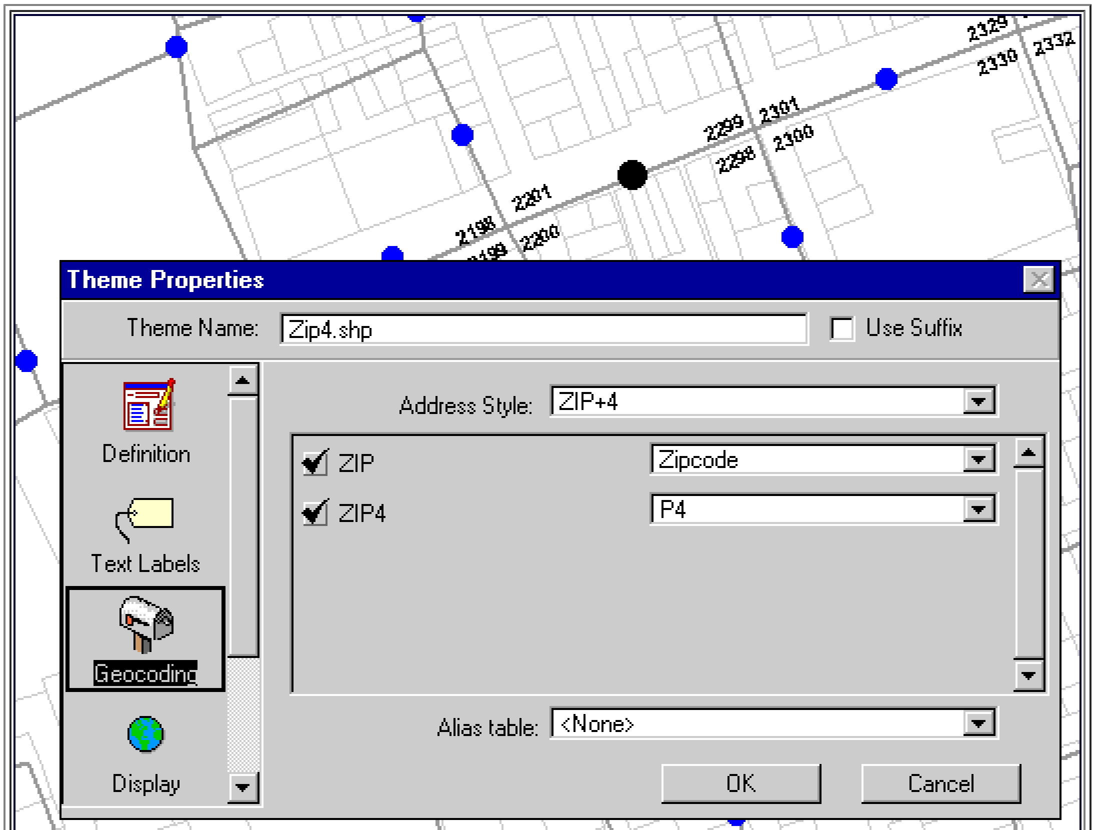
- Creates a graphic at the address, "Gervais Street?"

Figure 12. Simple Locate Address Function



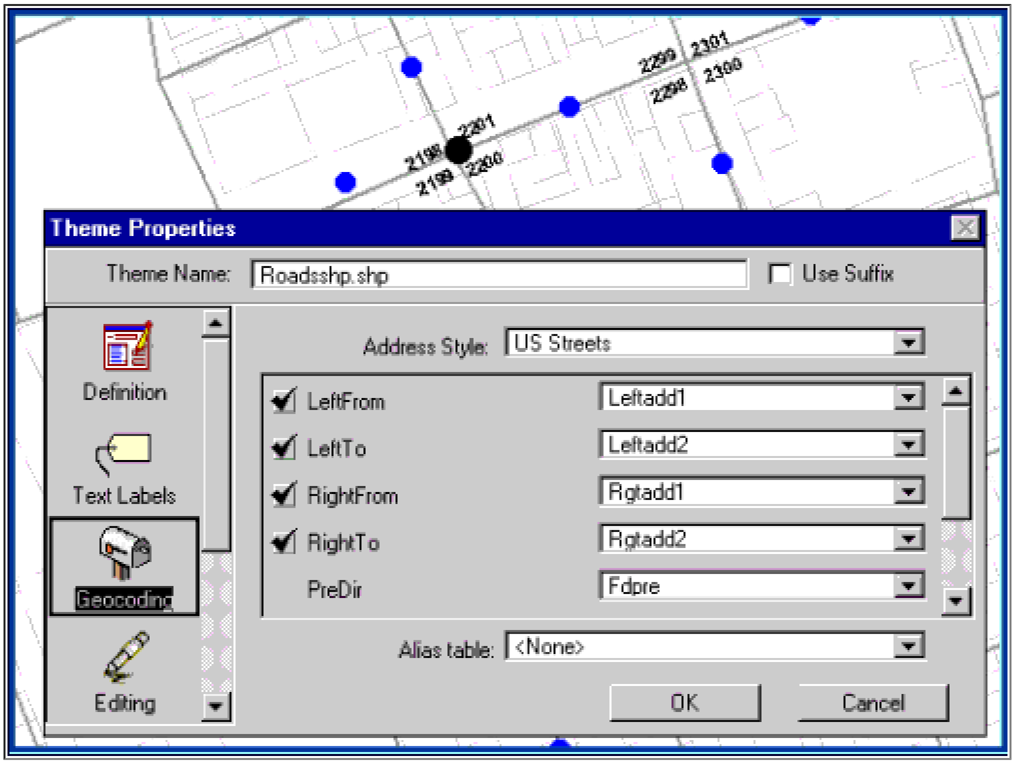
Single field address matching inputs and results, matches to the parcel centroid

Figure 13. Address Matching Inputs and Results



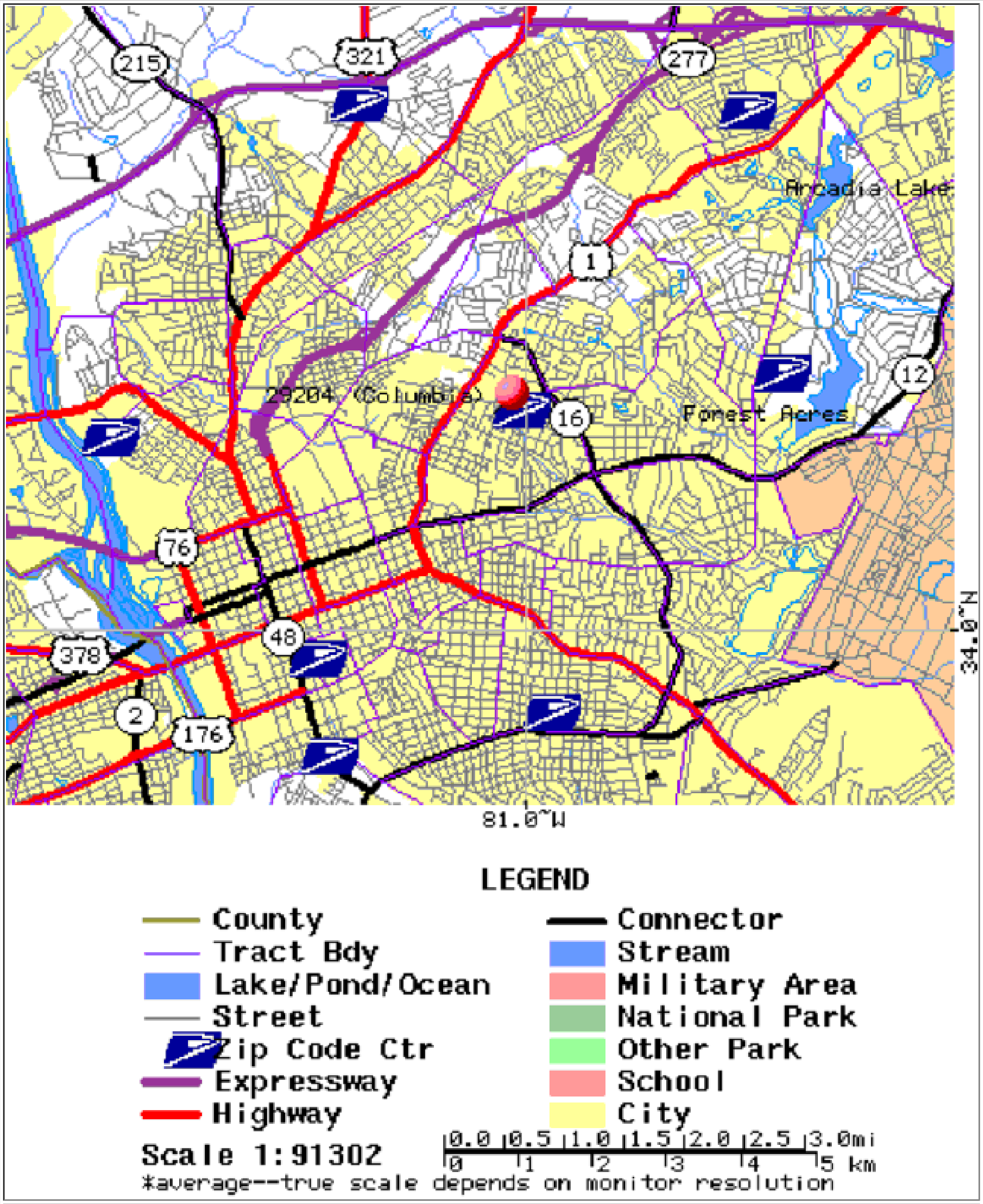
Zip+4 Address Matching Inputs and Results

Figure 14. Zip+4 Address Matching Inputs and Results



US Streets address matching inputs and results, requires left and right side address ranges, linear interpolation of the address

Figure 15. U.S. Streets address matching inputs and results



Web Map of Columbia SC

- TIGER features and location of post offices
-

Figure 16. Census Bureau TIGER (Topologically Integrated Geographic Encoding and Reference) line files represent the most commonly used files for this purpose

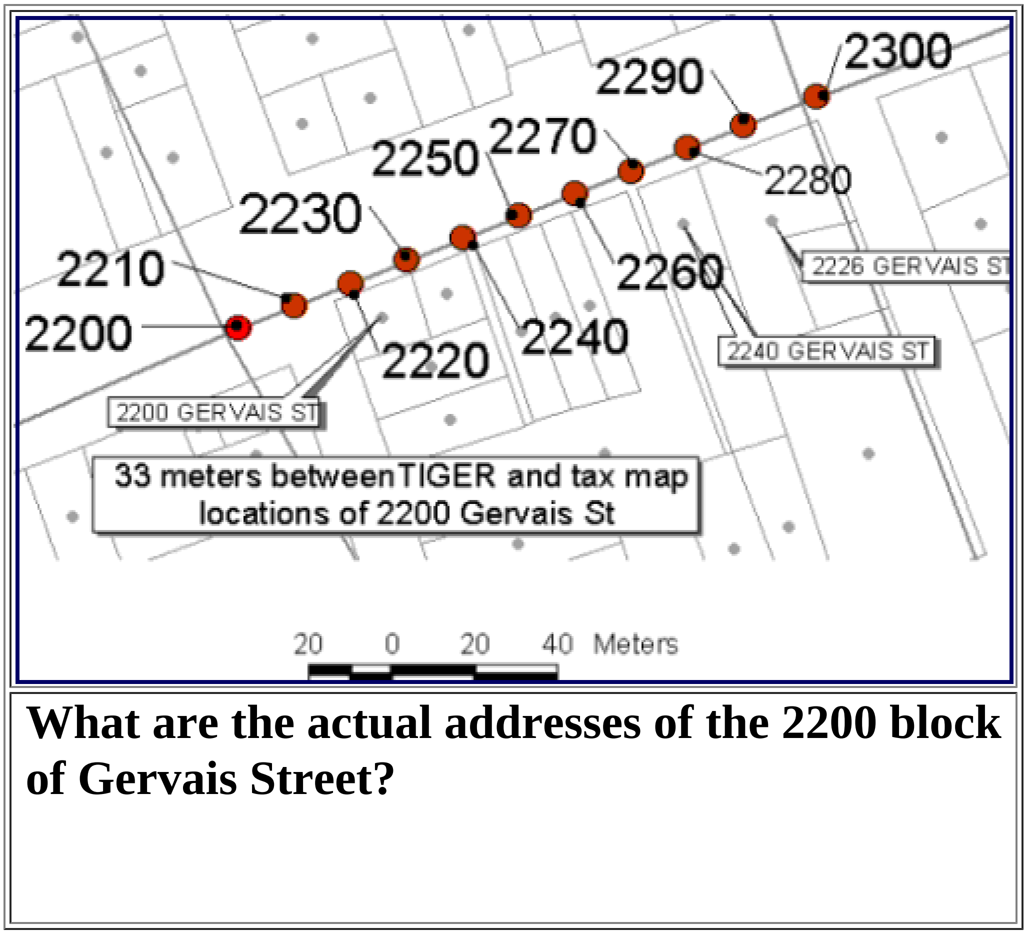
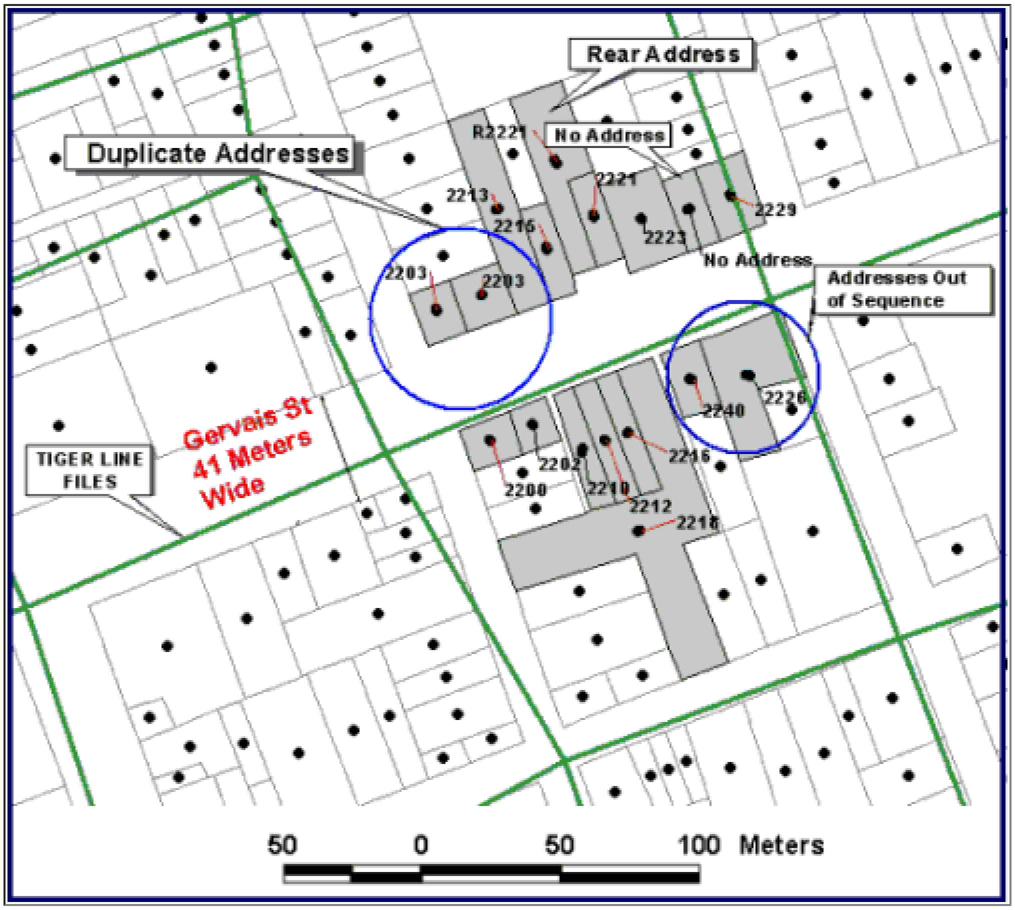
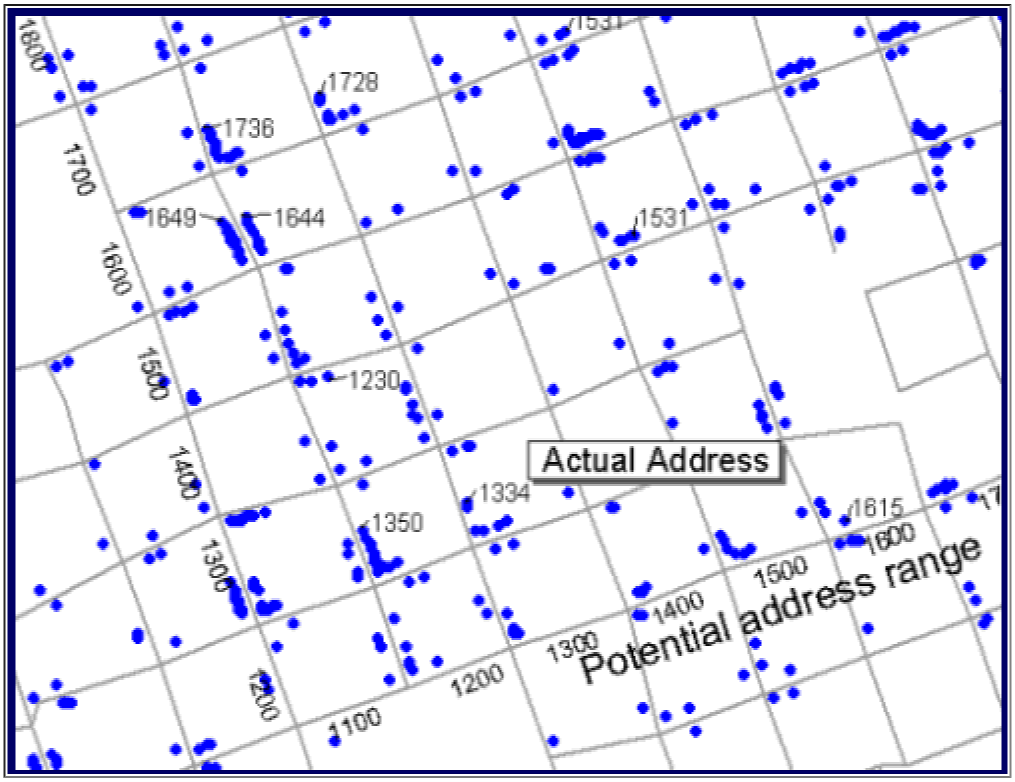


Figure 17. Assumes even distribution of addresses along the link



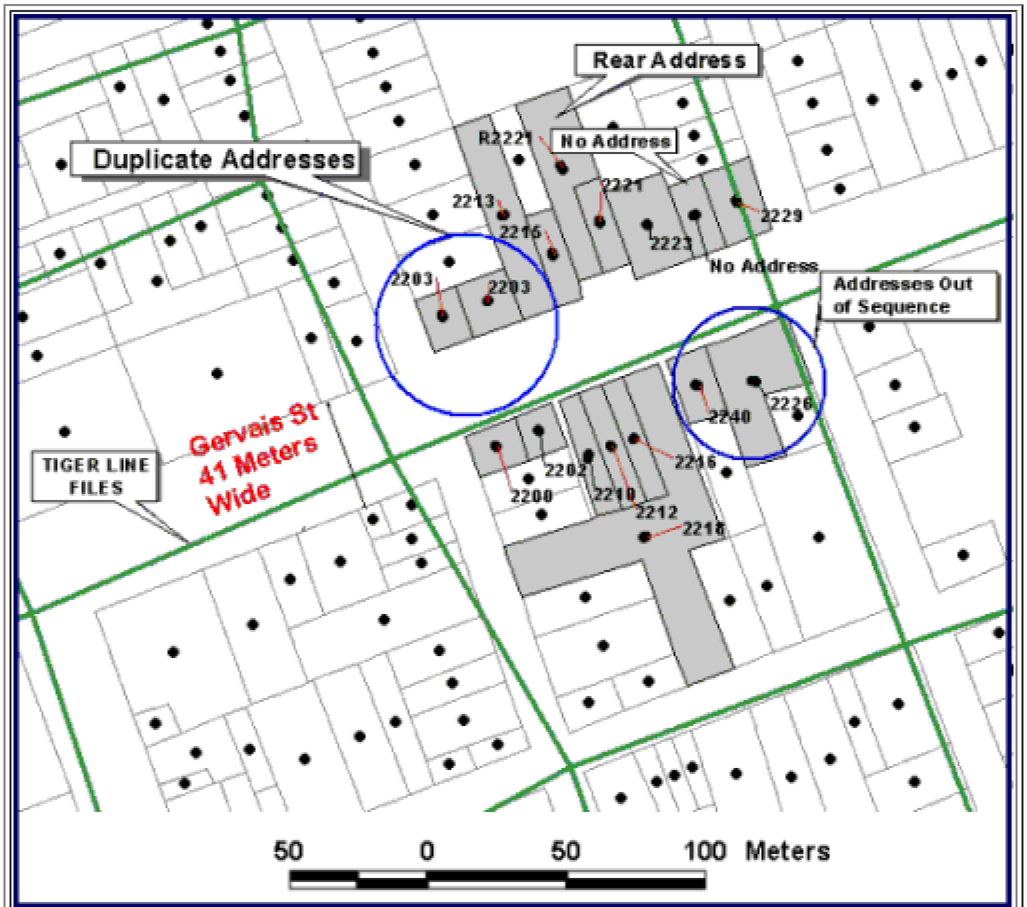
What are the actual addresses of the 2200 block of Gervais Street?

Figure 18. Uses theoretical range rather than actual address along a street



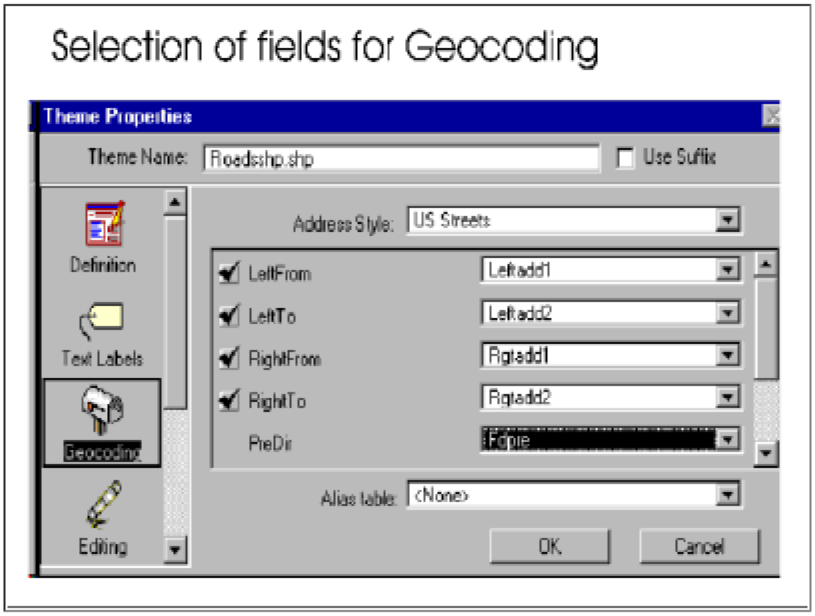
What is the impact of actual versus potential address?

Figure 19. The process often results in clustered points. (This is a set of all business addresses in downtown Columbia, SC.)



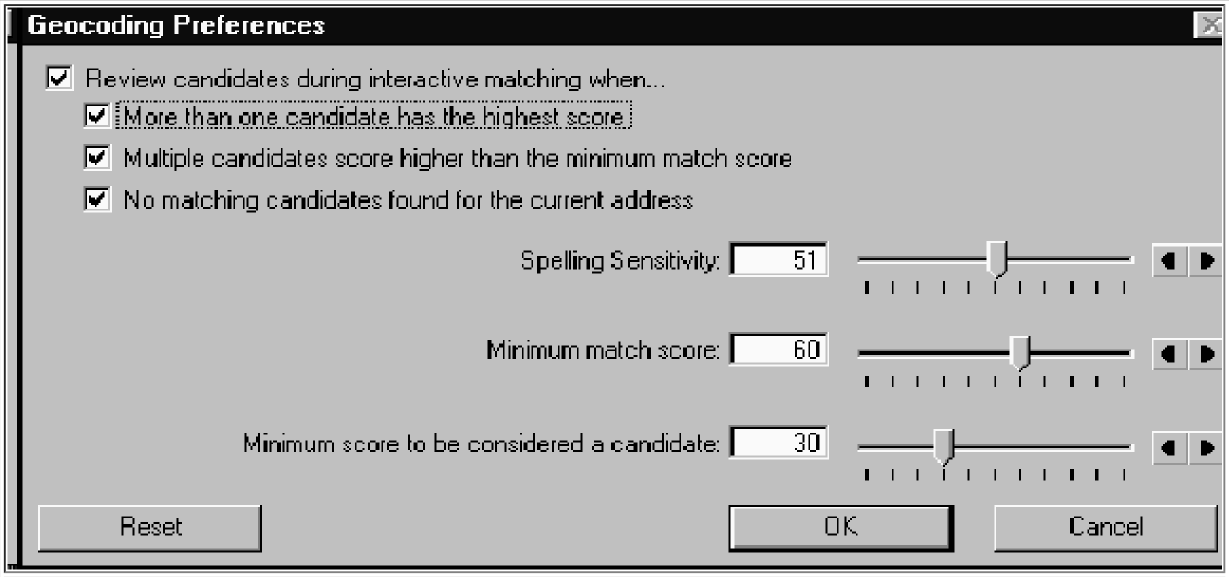
What are the actual addresses of the 2200 block of Gervais Street?

Figure 20. See actual addresses for 2200 block of Gervais St.



ArcView user interface for georeferencing properties

Figure 21. Because reject processing functions differ by vendor the following examples are based on the georeferencing functions of ArcView 3.0 which is produced by Environmental Systems Research Institute (ESRI) (http://www.esri.com).



User interface to change preferences for georeferencing

Figure 22. With this system, addresses are matched to specific records in the base map file on the basis of a scoring system.

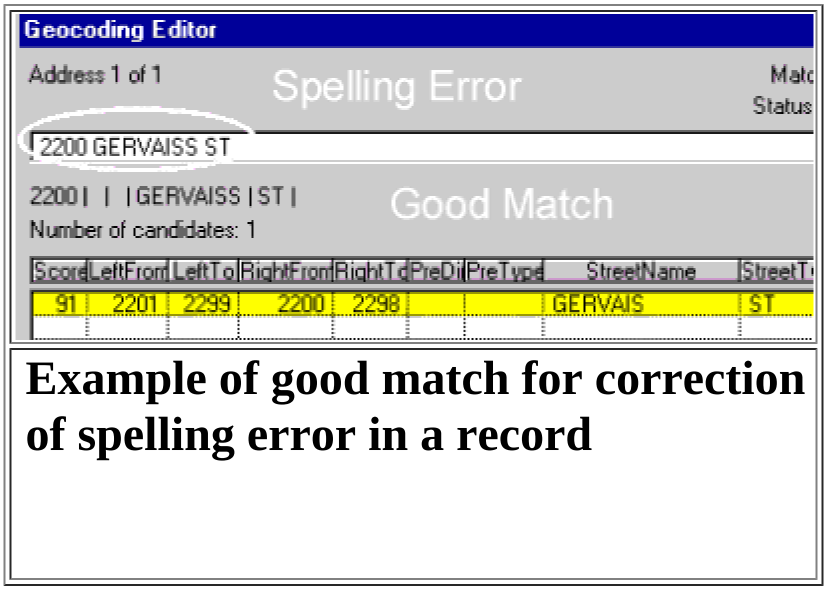


Figure 23. 2200 Gervaiss St

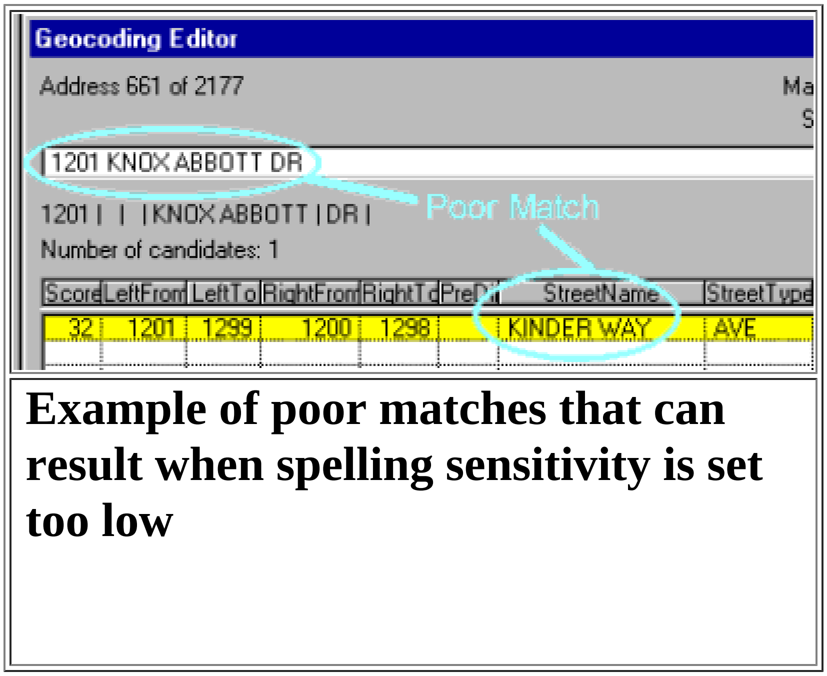
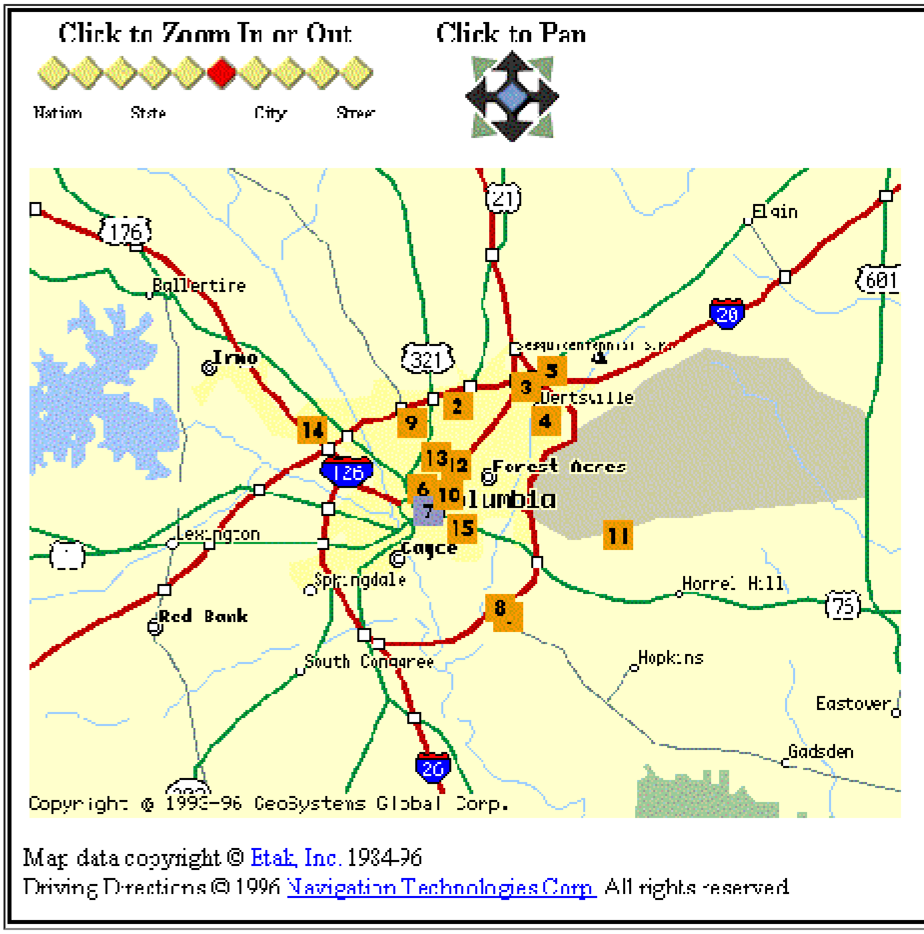


Figure 24. If the spelling sensitivity is set too low, inappropriate matches will be made.



Results of web-based search for seafood markets in Columbia, SC

Figure 25. A series of five maps of the location of the Palmetto Seafood Company generated by Bigbook.

Address

a phrase denoting a location.

Address Matching

the technique of linking data from separate files by means of a common attribute, the street address. See also Geocoding.

Address Range

the range of house numbers along a specific street segment; in address matching an X,Y location is interpolated along a street centerline based on the address range values.

Addressing System

a set of rules for assigning addresses along a transportation network (streets, freeways, railroads); addresses in this context may be almost anything that identifies a point along a segment: house numbers, callbox numbers,

mileposts, block/lot numbers, and/or post office box numbers.

Directional Numbering

house numbering system in which house numbers increase away from an origin in a cardinal direction (North, South, East, West); the line that separates north from south numbers is called a baseline; a meridian separates east-west numbers; the orientation of the system may be rotated east or west of due north; if such rotation is substantial, house numbers may be designated SW, SE, NW or NE.

Dual Numbering

situation in which the same street segment carries house numbers from two different house numbering systems.

Geocodes

any of a number of geographic location systems, including street address, area code, ZIP and ZIP + 4, census tract, tax parcel, and latitude/longitude coordinates.

Geocoding

the process of assigning a geographic location from an address record. See also Address Matching.

House Numbering System

a convention for the assignment of addresses to buildings, residences and occupancies.

House Numbering Scheme

a convention for using one or more house numbering systems at a particular place, such as a community or city; for example, a scheme may employ one numbering system for east-west streets, and another system for north-south streets in the same community.

Linear Numbering

addressing system in which numbers increase in a linear fashion away from a specified Origin (e.g., mileposts along a highway).

Master Address File

the inventory of a particular phenomena (e.g., Best Buy customers) by address; also referred to as an application database.

Order Numbering

house numbering system in which houses are numbered in the order that residences are built.

Parity Convention

house numbering system "rule" specifying that opposite sides of the street have all odd or all even numbers.

Reject Processing

an interactive process in which addresses are made to match the records in the spatial address file; this process involves changing street names, street types, etc., and also includes matching to a more general geocode (zip or zip + 4) rather than to a street address.

Situs Address

site specific, or location address (as opposed to a mailing address, which does not necessarily correspond with the site location).

Street Centerline

line representing the center of a street segment; a digital street centerline file is used in conjunction with a master address file to assign an address to a specific geographic location; spatial discrepancies in the street centerline file may lead to erroneous address matching (or no match at all); it is therefore critical that the centerline coverage be as accurate as possible.

Street Components

the non-name components of an address, including street type (Avenue, Road, Boulevard, etc.) and street direction (North, South, East, West).

Street Name

the legal name of a particular street , generally assigned by a municipal or county agency.

Tax Parcel

an area (generally represented as a centroid) corresponding to an individual property; the use of tax parcels in geocoding allows a one-to-one match

between address records and unique geographic locations; the use of other geocodes (census tracts, wire centers, ZIP and ZIP + 4 regions) will result in the assignment of multiple address records to the same centroid location.

Wire Center

the basic geographic unit used in the telecommunications industry; a subdivision of a telephone area code, identified by the first three digits of a phone number (e.g., 777-1234).

ZIP Code (Zone Improvement Plan)

a system of 9-digit codes that identifies specific delivery points; the first five digits identify the individual post office or metropolitan area delivery station associated with the address.

ZIP + 2

ZIP designation (e.g., 66044-35) identifying a sector or geographic portion of a zone; it can also indicate a portion of a rural route or part of a P.O. Box section.

ZIP + 2 Centroid

as defined by Geographic Data Technology, Inc., the point that is the average of all ZIP + 4 centroids in the ZIP + 2 sector; because the ZIP + 2 centroid reflects the distribution of ZIP + 4 centroids, it is a good indicator of address concentration.

ZIP + 4

ZIP designation (e.g., 66045-3545) identifying a specific block face (an average of six to ten houses), apartment house bank of boxes, firm, building or other specific delivery location; there are over 50,000 ZIP + 4 locations in Richland and

Lexington Counties in South Carolina.

ZIP + 4 Centroid

as defined by Geographic Data Technology, Inc., the point

corresponding to the house number which is closest to the mid-address of the ZIP + 4 address range.

Unit 017 - Global Positioning System Overview

by Peter H. Dana, Department of Geography, University of Texas at Austin, USA

This section was edited by Kenneth Foote, Department of Geography, University of Texas Austin.

Advanced Organizer

Topics covered in this unit

- This unit provides an overview of the Global Positioning System including
  - a description of the space, control and user segments.
  - a description of the basic services provided by GPS.
  - a discussion of position and time determination from GPS signals.
  - a discussion of GPS error sources and methods for overcoming some GPS errors.
- The overview discusses GPS project planning and costs.
- The overview does not discuss details of GPS signals and data formats, but does provides references to relevant sources.

Learning Outcomes

- After learning the material covered in this unit, students should be able to:
  - List the major GPS segments as defined by the Department of Defense.
  - Explain how a GPS receiver computes position and time from GPS signals.
  - Describe the major error sources for GPS positioning projects.
  - Explain the various forms of Differential GPS.
  - Propose suitable equipment and processes for various levels of positioning accuracy.

Full Table of Contents

Metadata and Revision History

Unit 017 - Global Positioning System Overview

1. The Global Positioning System: a Satellite Navigation System

- The Global Positioning System is an earth-orbiting-satellite based system that provides signals available anywhere on or above the earth, twenty-four hours a day, that can be used to determine precise time and the position of a GPS receiver in three dimensions.
- GPS is funded by and controlled by the U. S. Department of Defense (DOD) but can used by civilians for georeferencing, positioning, navigation, and for time and frequency control.
- GPS is increasingly used as an input for Geographic Information Systems particularly for precise positioning of geospatial data and the collection of data in the field.
- Effective use of the GPS system does require training, appropriate equipment, and knowledge of the limitations of the system.
- Some technical topics concerning GPS signals and data formats go beyond the scope of the present overview, but are addressed in sources listed in the references including the http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html

1.1. Segments of the Global Positioning System

1.1.1. Space Segment

- The *Space Segment* of the system consists of the 24 GPS satellites.
  - These space vehicles (SVs) send radio signals from space.
  - Their configuration provides user with between five and eight SVs visible from any point on the earth.
  - Figure 1. GPS Satellite
  - Figure 2. GPS Constellation

1.1.2. Control Segment

- The *Control Segment* consists of a system of tracking stations located around the world.
  - These stations measure signals from the SVs, compute orbital data, upload data to the SVs, then the SVs send data to GPS receivers over radio signals.

- Figure 3. GPS Master Control and Monitor Network
- Figure 4. GPS Control Monitor

1.1.3. User Segment

- The *User Segment* consists of the GPS receivers and the user community.
  - GPS receivers convert SV signals into position, velocity, and time estimates.
  - Four satellites are required to compute the four dimensions of X, Y, Z (position) and T (time).
  - Figure 5. Four GPS Satellite Solution
  - GPS receivers are used for navigation, surveying, time dissemination, and other research.
  - Navigation receivers are made for aircraft, ships, ground vehicles, and for hand carrying by individuals.
  - Figure 6. GPS Navigation

1.2. GPS Positioning Services

1.2.1. Precise Positioning Service (PPS)

- Authorized users with cryptographic equipment and keys and specially equipped receivers use the Precise Positioning System.
  - The PPS provides (95% of the time) a 22 meter horizontal accuracy, a 27.7 meter vertical accuracy, and a 100 nanosecond time accuracy.
  - Authorized users include U. S. and Allied military, certain U. S. Government agencies, and selected civil users specifically approved by the U. S. Government.

1.2.2. Standard Positioning Service (SPS)

- Civil users worldwide use the SPS without charge or restrictions.
- Most receivers are capable of receiving and using the SPS signal.
- Prior to May 2, 2000, The SPS accuracy was intentionally degraded by the DOD by the use of Selective Availability (SA).
  - With SA the SPS provided (95% of the time) a 100 meter horizontal accuracy, a 156 meter vertical accuracy, and a 340 nanoseconds time accuracy.
  - Without SA the SPS provides a much improved performance, perhaps as good as 20 meters horizontal and 30 meters vertical. No new specification for the SPS without SA has been issued as of 7/01/2000.

1.3. GPS Satellite Signals and Data

- The SVs transmit two microwave carrier signals.
  - The L1 frequency (1575.42 MHz) carries the navigation message, the SPS code signals known as the C/A (coarse acquisition) Code, and the P (precise) Code used for the PPS.
  - The L2 frequency (1227.60 MHz) carries the P Code used for the PPS. The phase

difference between the P-Code on L1 and L2 is used to measure the ionospheric delay by PPS equipped receivers tracking both frequencies.
  - A C/A Code modulates the L1 carrier phase.
    - The C/A code is a repeating 1 MHz Pseudo Random Noise (PRN) Code.
    - This noise-like code consisting of a repeating sequence of 1023 bits modulates the L1 carrier signal.
    - There is a different C/A code PRN for each SV.
    - GPS satellites are often identified by their PRN number, the unique identifier for each pseudo-random-noise code
  - Figure 7. GPS Signals

- The GPS Navigation Message consists of time-tagged data bits marking the time of its transmission by the SV and includes:
  - Clock data parameters describe the SV atomic clock and its relationship to GPS time.
  - Ephemeris data parameters describe SV orbits for short sections of the satellite orbits.
  - An ionospheric model that is used in the receiver to approximates the phase delay through the ionosphere at any location and time.
  - The amount to which GPS Time is offset from Universal Coordinated Time. This correction can be used by the receiver to set UTC to within 100 nanoseconds.
  - Figure 8. Navigation Data Bits

---

2. Using GPS

2.1. One Receiver Using Civilian Code-Phase Tracking

- The receiver tracks the satellites by aligning a set of receiver-generated C/A Codes with the received C/A Code sequences from the satellites.

- These measurements of code alignment times are called pseudo-ranges because they not actual range measurements, but are relative times of arrival all offset by the receiver clock bias common to each C/A code generated in the receiver.

- The GPS receiver gathers and interprets the Navigation Message transmitted by the SVs it is tracking, computing a position for each satellite at the moment of C/A code transmission.

- The measured pseudo-ranges are corrected for SV clock bias, ionospheric delay and other offsets.

- The coordinates of the receiver are computed by finding a position where the set of pseudo-ranges intersect when a common receiver clock offset is accounted for.
  - Figure 9. Intersection of Pseudo-Ranges

- GPS time in the receiver is computed from the receiver clock offset that allows the corrected pseudo-ranges to converge at the receiver position.

- Four satellites (normal navigation) can be used to determine three position dimensions and time.

2.1.1. Position

- Position dimensions are computed by the receiver in Earth-Centered, Earth-Fixed X, Y, Z (ECEF XYZ) coordinates.

- Figure 10. ECEF X, Y, and Z

- Position in XYZ is converted within the receiver to geodetic latitude, longitude and height above the ellipsoid.

- Figure 11. Geodetic Coordinates

- Latitude and longitude are usually provided in the geodetic datum on which GPS is based (WGS-84).
  - Receivers can often be set to convert to other user-required datums.
  - Position offsets of hundreds of meters can result from using the wrong datum.
  - Receiver position is computed from the SV positions, the measured pseudo-ranges, and a receiver position estimate.
  - Four satellites allow computation of three position dimensions and time.
  - Three satellites could be used determine three position dimensions with a perfect receiver clock.
    - In practice this is rarely possible and three SVs are used to compute a two-dimensional, horizontal fix (in latitude and longitude) given an assumed height.
    - This is often possible at sea or in altimeter equipped aircraft.
  - Five or more satellites can provide position, time and redundancy.
  - Twelve channel receivers allow continuous tracking of all available satellites, including tracking of satellites with weak or occasionally obstructed signals.

2.1.2. Time

- Time is computed in the same solution as position and is used to correct the offset in the receiver clock, allowing the use of inexpensive oscillators in low-cost receivers.

- Time is computed in *SV Time*, *GPS Time*, and *UTC*.
  - SV Time is the time maintained by each satellite's atomic clocks.
  - SV clocks are monitored by ground control stations and occasionally reset to maintain time to within one millisecond of GPS time.

- *SV Time* is set in the receiver from the GPS signals.
  - SV Time is converted to GPS Time in the receiver using the SV clock correction parameters.

- *GPS Time* is a "paper clock" ensemble of the Master Control Clock and the SV clocks.
    - It is measured in weeks and seconds from 24:00:00, January 5, 1980 and is steered to within one microsecond of UTC.
    - GPS Time has no leap seconds and is ahead of UTC by several seconds.

- *Universal Coordinated Time (UTC)* is computed from GPS Time using the UTC correction parameters sent as part of the navigation data bits.

2.1.3. Velocity

- Velocity is computed from change in position over time, the SV Doppler frequencies (the change in carrier frequency due to the combined movement of the satellites and the receiver), or both.

2.2. GPS Errors

- GPS errors are a combination of noise, bias, blunders.
    - Figure 12. Noise, Bias, and Blunders

2.2.1. Noise Errors

- Noise errors are the combined effect of PRN code noise (around 1 meter) and noise within the receiver noise (around 1 meter).

- Noise and bias errors combine, resulting in typical ranging errors of around fifteen meters for each satellite used in the position solution.

2.2.2. Bias Errors

- Bias errors result from Selective Availability and other factors.
    - **Selective Availability (SA)** is the intentional degradation of the SPS signals by a time varying bias.
    - SA is controlled by the DOD to limit accuracy for non-U. S. military and government users.
    - The potential accuracy of the C/A code of around 30 meters is reduced to 100 meters (95% of the time).

- Other Bias Error sources:
    - **SV clock errors** uncorrected by Control Segment can result in one meter errors in position.
    - **Tropospheric delays**: 1 meter position error.
        - The troposphere is the lower part (ground level to from 8 to 13 km) of the atmosphere that experiences the changes in temperature, pressure, and humidity associated with weather changes.
    - **Unmodeled ionosphere delays**: 10 meters of position error.
        - The ionosphere is the layer of the atmosphere from 50 to 500 km that consists of ionized air.

- **Multipath**: 0.5 meters of position error.
    - Multipath is caused by reflected signals from surfaces near the receiver that can either interfere with or be mistaken for the signal that follows the straight line path from the satellite.
    - Multipath is difficult to detect and sometimes hard to avoid. Care in antenna placement at fixed sites, special antenna configurations, and special tracking techniques can help sometimes.

2.2.3. Blunders

- Blunders can result in errors of hundred of kilometers.
    - Control segment mistakes due to computer or human error can cause errors from one meter to hundreds of kilometers.
    - User mistakes, including incorrect geodetic datum selection, can cause errors from 1 to hundreds of meters.
    - Receiver errors from software or hardware failures can cause blunder errors of any size.

2.3. Geometric Dilution of Precision (GDOP)

- GPS ranging errors are magnified by the range vector differences between the receiver and the SVs.
    - Poor GDOP, a large value representing a small unit vector-volume, results when angles from receiver to the set of SVs used are similar.
        - Figure 13. Poor GDOP
    - Good GDOP, a small value representing a large unit vector-volume, results when angles from receiver to SVs are different.
        - Figure 14. Good GDOP

- GDOP is computed from the geometric relationships between the receiver position and the positions of the satellites the receiver is using for navigation.

- GDOP Components:
    - **PDOP** - Position Dilution of Precision (3-D)
    - **HDOP** - Horizontal Dilution of Precision (Latitude, Longitude)
    - **VDOP** - Vertical Dilution of Precision (Height)
    - **TDOP** - Time Dilution of Precision (Time)

- While each of these GDOP terms can be individually computed, they are formed from covariances and so are not independent of each other.
    - A high TDOP, for example, will cause receiver clock errors which will eventually result in increased position errors.

- **2.4. Satellite Visibility**
    - GPS satellite signals are blocked by most materials. GPS signals will not mass through buildings, metal, mountains, or trees. Leaves and jungle canopy can attenuate GPS signals so that they become unusable.
    - In locations where at least four satellite signals with good geometry cannot be

tracked with sufficient accuracy, GPS is unusable.

- Planning software may indicate that a location will have good GDOP over a particular period, but terrain, building, or other obstructions may prevent tracking of the required SVs.
    - Figure 15. Good predicted GDOP, Poor Visibility

2.5. Differential GPS (DGPS) Techniques

- The idea behind all differential positioning is to correct bias errors at one location with measured bias errors at a known position.
- A reference receiver, or base station, computes corrections for each satellite signal for all satellites in view.
- DGPS receivers require software that can apply individual pseudo-range corrections for each SV prior to computing a position solution.

2.5.1. Differential Code-Phase GPS (Navigation)

- Differential corrections may be used in real-time or later, with post-processing techniques.
    - Real-time corrections can be transmitted by radio link.
    - The U. S. Coast Guard transmits DGPS corrections over radiobeacons covering much of the U. S. coastline.
    - Private companies broadcast corrections by ground-based FM-radio signals or satellite radio links.
    - Corrections can be recorded for post processing.
    - Many public and private agencies record DGPS corrections for distribution by electronic means.
- To remove Selective Availability (and other bias errors), differential corrections should be computed at the reference station and applied at the remote receiver at an update rate of five to ten seconds, fast enough to keep up with the rapid changes in the SA bias.
    - Figure 16. Differential Code-Phase Navigation
    - Figure 17. Errors Reduced by Differential Corrections
- DGPS is not able to eliminate all sources of error discussed in the next section.
- Bias errors are less common at great distance from the reference receiver.
- 300 to 500 km are considered reasonable reference-remote separations for Code-Phase DGPS.

2.5.2. Differential Carrier-Phase GPS (Surveying)

- Positions can also be calculated by tracking the carrier-phase signal transmitted by the SVs
    - Figure 18. Carrier Phase Tracking
- All carrier-phase tracking is differential, requiring both a reference and remote receiver tracking carrier phases at the same time.
- In order to correctly estimate the number of carrier wavelengths at the reference and remote receivers, they must be close enough to insure that the ionospheric delay difference is less than a carrier wavelength.
- This usually means that carrier-phase GPS measurements must be taken with a remote and reference station within about 30 kilometers of each other.
- Using L1-L2 ionospheric measurements and long measurement averaging

periods, relative positions of fixed sites can be determined over baselines of hundreds of kilometers.
- Special software is required to process carrier-phase differential measurements.
- Carrier-phase tracking of GPS signals has resulted in a revolution in land surveying.
- A line of sight along the ground is no longer necessary for precise positioning.
- Positions can be measured up to 30 km from reference point without intermediate points.
- This use of GPS requires specially equipped carrier tracking receivers.
    - Figure 19. Differential Carrier-Phase Positioning
- Post processed static carrier-phase surveying can provide 1-5 cm relative positioning within 30 km of the reference receiver with measurement time of 15 minutes for short baselines (10 km) and one hour for long baselines (30 km).
- Rapid static or fast static surveying can provide 4-10 cm accuracies with 1 kilometer baselines and 15 minutes of recording time.
- Real-Time-Kinematic (RTK) surveying techniques can provide centimeter measurements in real time over 10 km baselines tracking five or more satellites and real-time radio links between the reference and remote receivers.

---

3. GPS Project Costs

- Receiver costs vary depending on capabilities.
    - Small civil SPS receivers can be purchased for under $200.
        - Most output NMEA sentences with position information for use with computer serial ports.
        - Many can accept DGPS corrections from real-time sources.
    - Receivers that can store files for post-processing with base station files cost more ($2000 to $5000).
    - Receivers that can act as DGPS reference receivers and carrier phase tracking receivers (and two are often required) can cost many thousands of dollars ($5,000 to $40,000).
    - RTK systems require two receivers and radio links and may cost $60,000.
    - Military PPS receivers may cost more or be difficult to obtain.
- Other costs include the cost of multiple receivers when needed, post-processing software, and the cost of specially trained personnel.
- Project tasks can often be categorized by required accuracies which will determine equipment cost.
    - Low-cost, single receiver SPS projects (100 meter accuracy)
    - Medium-cost, differential SPS code Positioning (1-10 meter accuracy)
    - High-cost, single receiver PPS projects (20 meter accuracy)
    - High-cost, differential carrier phase surveys (1 mm to 1 cm accuracy)
    - High-cost, Real-Time-Kinematic (1 cm) with real time accuracy indications
    - Figure 20. GPS Applications, Costs, and Signals

---

4. Review and Study Questions

4.1. Essay and Short Answer Questions

- Essay Questions
  - Will GPS technology really make much difference to most GIS applications?
  - What GIS applications can make the best use of GPS technology? Which application will be affected the least?
  - To what extent is the problem of georeferencing a major obstacle to the creation of global GIS?
- Short Answer
  - No matter how inexpensive and wide-spread GPS technology becomes, why will it not entirely solve the problem of creating precise and accurate GIS datasets?

4.2. Multiple-choice questions

Choose the best or most appropriate answer(s) to the question.

- What is selective availability?
  - 1. The limited window of time during which GPS signals are within line-of-sight of a receiving antenna.
  - 2. The intentional degradation of GPS signals is to deny full access to unauthorized users.
  - 3. The Department of Defense classification of GPS users with access to the encrypted satellite signal.
- What is differential GPS?
  - 1. A method for correcting GPS measurements by comparing bias errors between a known location and the position of a "roving" GPS receiver.
  - 2. The variance between Code and Carrier Phase GPS positioning.
  - 3. Multipath or imaging problems that cause position errors in a GPS code-tracking receiver.
  - 4. The design variations between the US (GPS) and the Russian (GLONASS) satellite positioning systems.
- High accuracy, survey quality GPS is usually associated with:
  - 1. Differential code phase tracking.
  - 2. Low-cost GPS.
  - 3. Differential carrier phase tracking.
  - 4. No post-processing software.
- The latitude, longitude, and altitude displayed by a GPS receiver represent:
  - 1. An estimate of the receiver's antenna position.
  - 2. The height above mean sea level.
  - 3. The three-dimensional position fix with millimeter accuracy.
  - 4. The height above the reference ellipsoid.

---

5. Reference Materials

5.1. Print References

- Global Positioning System Standard Positioning Service Specification, 2nd Edition, June 2, 1995, available on line from United States Coast Guard Navigation Center. This is a primary source for details about GPS C/A code implementation.
- GPS Joint Program Office. 1997. ICD-GPS-200C: GPS Interface Control Document. ARINC Research. This document contains additional information about GPS P-code implementation.
- Hoffmann-Wellenhof, B. H. Lichtenegger, and J. Collins. 1994. GPS: Theory and Practice. 3rd ed. New York: Springer-Verlag. A review of GPS for the surveyor. Chapters on planning GPS surveys.
- Institute of Navigation. 1980, 1984, 1986, 1993, 1998. Global Positioning System monographs. Washington, DC: The Institute of Navigation. A complete set of papers in five volumes that cover all aspects of GPS receiver design, GPS applications, and DGPS specifications.
- Kaplan, Elliott D. ed. 1996. Understanding GPS: Principles and Applications. Boston: Artech House Publishers. A complete description of GPS and GPS applications. A good choice for a single GPS reference work.
- Leick, Alfred. 1995. GPS Satellite Surveying. 2nd. ed. New York: John Wiley & Sons. This book covers GPS surveying in detail including network error analysis and carrier phase details.
- Parkinson, Bradford W. and James J. Spilker. eds. 1996. Global Positioning System: Theory and Practice. Volumes I and II. Washington, DC: American Institute of Aeronautics and Astronautics, Inc. A very complete set of papers spanning all of the GPS literature. Full of engineering details as well as application specific chapters.
- Wells, David, ed. 1989. Guide to GPS positioning. Fredericton, NB, Canada: Canadian GPS Associates. One of the first overviews of GPS positioning techniques. Still useful as a guide to surveying theory.

5.2. Web References

5.2.1. US Federal Agencies

- United States Coast Guard Navigation Center NOAA
- National Geodetic Survey Division Home Page

5.2.2. University-Related Pages

- Sam Wormley's GPS Page
- Alfred Leick's GPS Page
- University NAVSTAR Consortium (UNAVCO)

5.2.3. Other Relevant Web Pages

- The Institute of Navigation
- The following are related sections by the same author in *The Geographer's Craft Project* at the University of Texas Austin:
  - Dana, Peter H. 1995. Global Positioning System Overview,
  - Dana, Peter H. 1995. Geodetic Datum Overview,
  - Dana, Peter H. 1995. Coordinate Systems Overview,
  - Dana, Peter H. 1995. Map Projections Overview,

Citation

To reference this material use the appropriate variation of the following format:

> Dana, Peter H. (1997) Global Positioning System Overview, *NCGIA Core Curriculum in GIScience*, http://www.ncgia.ucsb.edu/giscc/units/u017/u017.html, posted August 28, 1997.

Last revised: July 7, 2000.

Unit 017 - Global Positioning System Overview

Table of Contents

Advanced Organizer
- Topics Covered in this Unit
- Intended Learning Outcomes
- Metadata and Revision History

Body of Unit
- 1. The Global Positioning System: A Satellite Navigation System
  - 1.1 Segments of the Global Positioning System
    - 1.1.1 Space Segment
    - 1.1.2 Control Segment
    - 1.1.3 User Segment
  - 1.2 GPS Positioning Services
    - 1.2.1 Precise Positioning System (PPS)
    - 1.2.2 Standard Positioning System (SPS)
  - 1.3 GPS Satellite Signals and Data
- 2. Using GPS
  - 2.1 One Receiver Using Civilian Code-Phase Tracking
    - 2.1.1 Position
    - 2.1.2 Time
    - 2.1.3 Velocity
  - 2.2 GPS Errors
    - 2.2.1. Noise Errors
    - 2.2.2. Bias Errors
    - 2.2.3. Blunders
  - 2.3 Geometric Dilution of Precision (GDOP)
  - 2.4 Satellite Visibility
  - 2.5 Differential GPS (DGPS) Techniques
    - 2.5.1 Differntial Code-Phase GPS (Navigation)
    - 2.5.2 Differential Carrier-Phase GPS (Surveying)
- 3. GPS Project Costs
- 4. Review and Study Questions
  - 4.1 Essay and Short Answer Questions
  - 4.2 Multiple Choice Questions
- 5. References
  - 5.1 Print References
  - 5.2 Web References
    - 5.2.1 US Federal Agencies
    - 5.2.2 University Related Pages
    - 5.2.3 Other Relevant Webpages

Citation

Unit 017 - Global Positioning System Overview

Metadata and Revision History

1. About the main contributors

- author: Peter H. Dana, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098
- editor: Kenneth E. Foote, Department of Geography, University of Texas at Austin, Austin, TX, USA, 78712-1098

2. Details about the file

- unit title:
  - Global Positioning System Overview
- unit key number:
  - Unit 017

3. Key words

- GPS
- Global Positioning System
- Precise Positioning
- Navigation

4. Index words

- reference ellipsoid ("reference ellipsoid")
- geodetic datum ("geodetic datum")
- Cartesian coordinates ("Cartesian coordinates")
- Earth Centered, Earth Fixed Coordinates ("ECEF")

5. Prerequisite units

- 008 - Representing the Earth

6. Subsequent units

- 018 - Mapping the Earth

- 066 - Populating the GISystem
- 082 - Kinds of Geospatial Data
- 096 - Handling Uncertainty
- 136 - Making it Work

7. Revision history

- 28 August 1997. Converted from Geographer's Craft GPS Overview
- 10 February 1998. Module shortened to lecture length
- 19 March 1998. Additional revisions and corrections
- 14 May 1998. Revised after reviews
- 15 July 1998. Minor revisions.
- 7 July 2000. External links updated.
- 11 July 2000. Update on removal of selective availability added by author.

Back to the Unit:

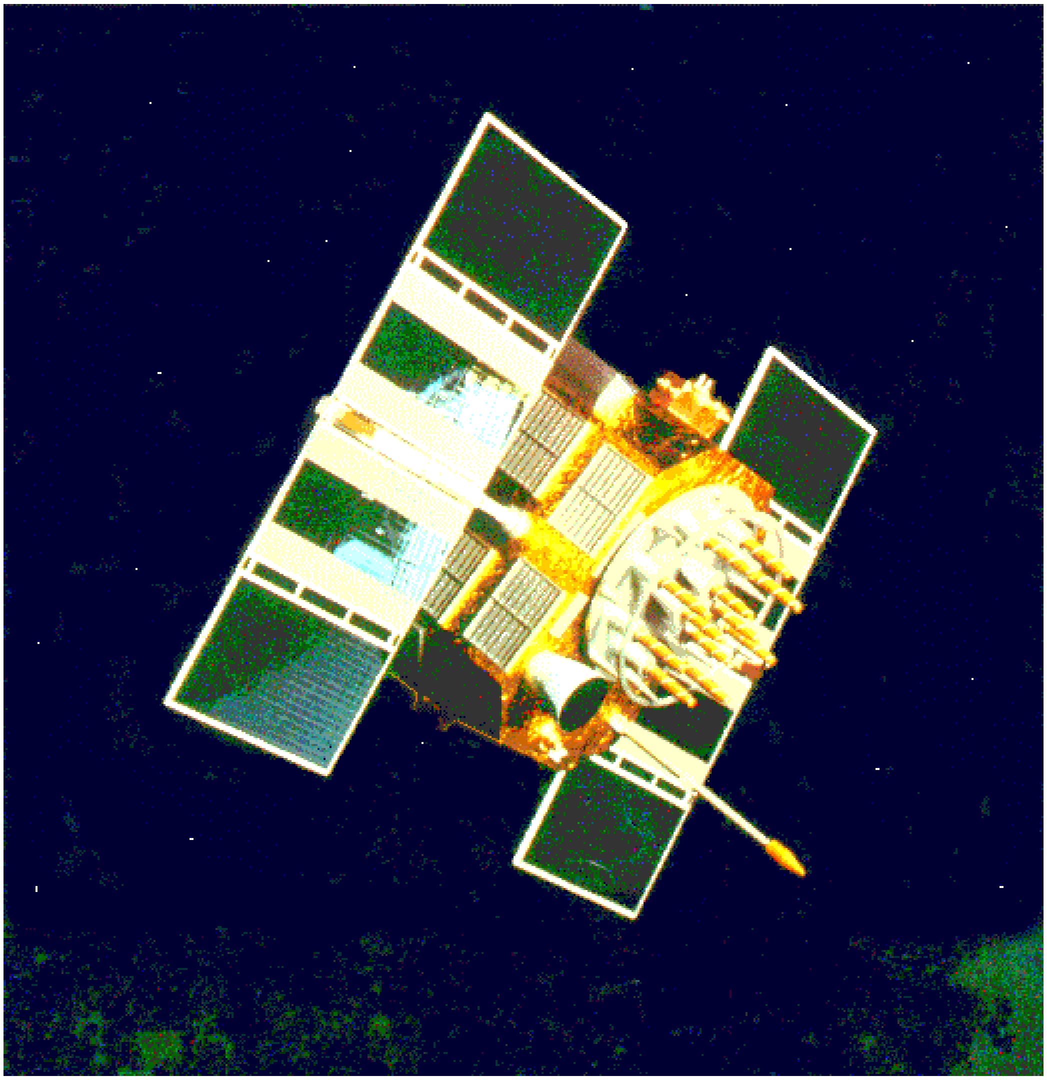


Figure 1. GPS Satellite

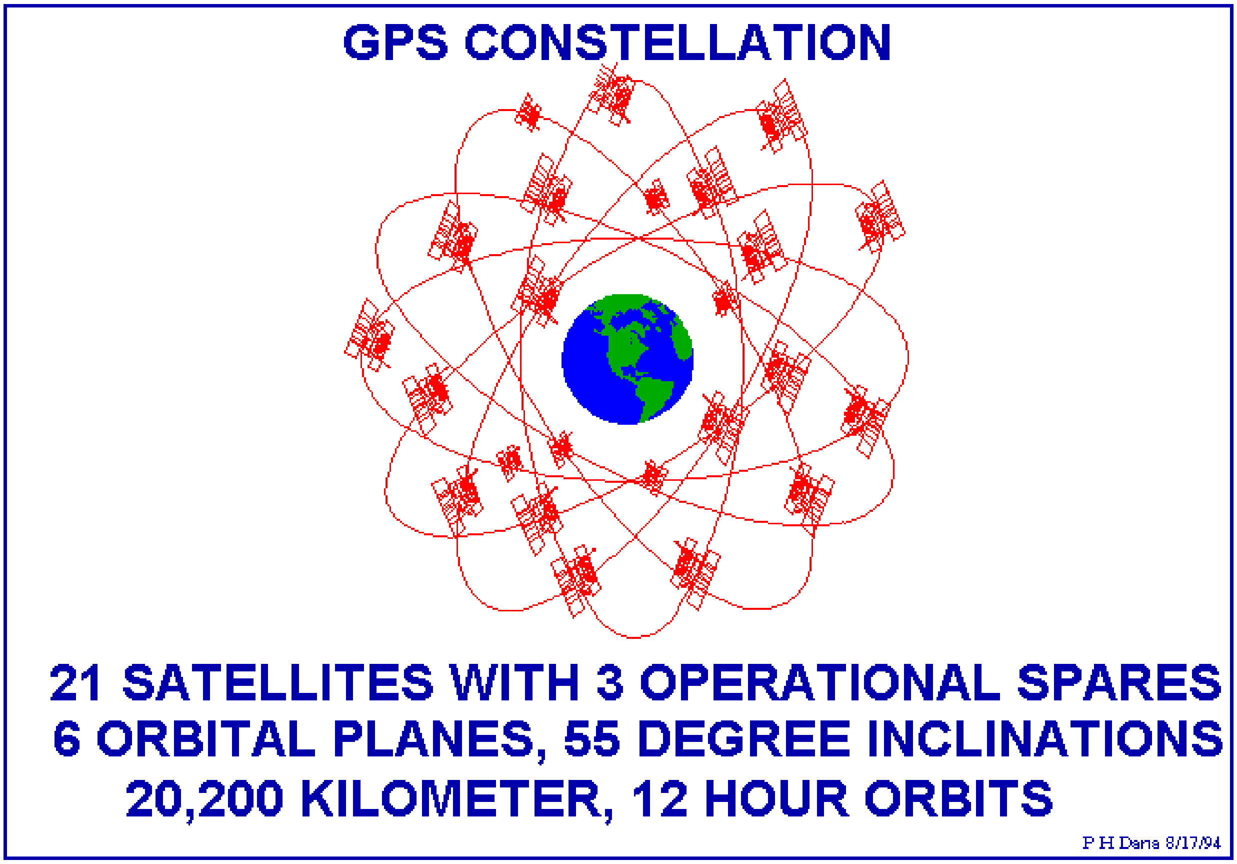


Figure 2. GPS Constellation

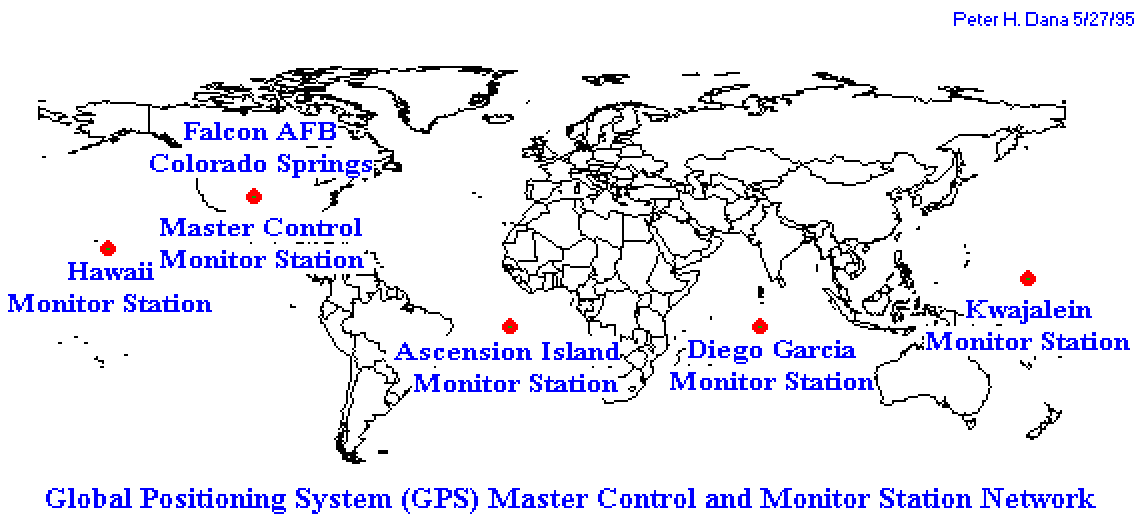


Figure 3. GPS Master Control and Monitor Network

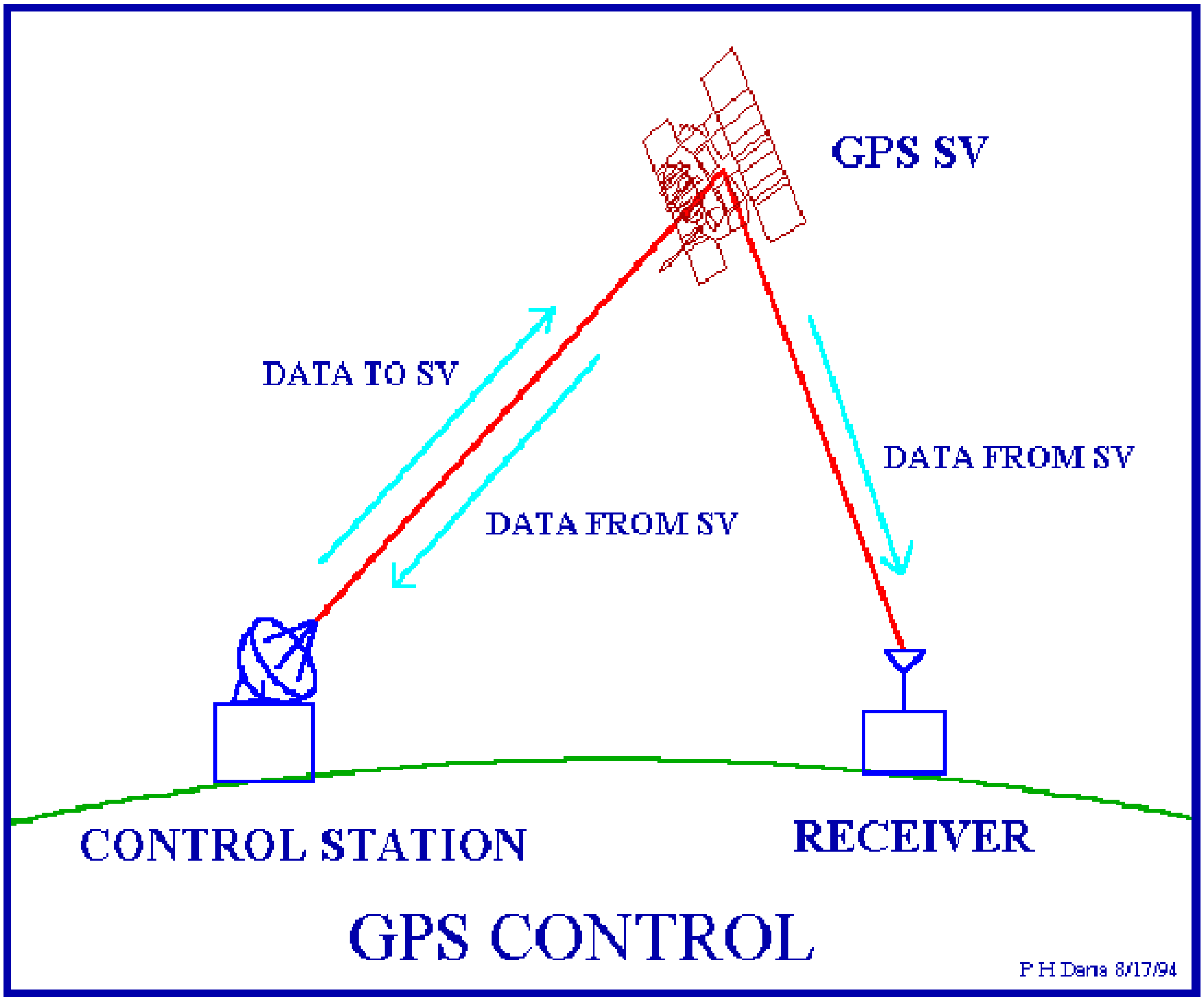


Figure 4. GPS Control Monitor

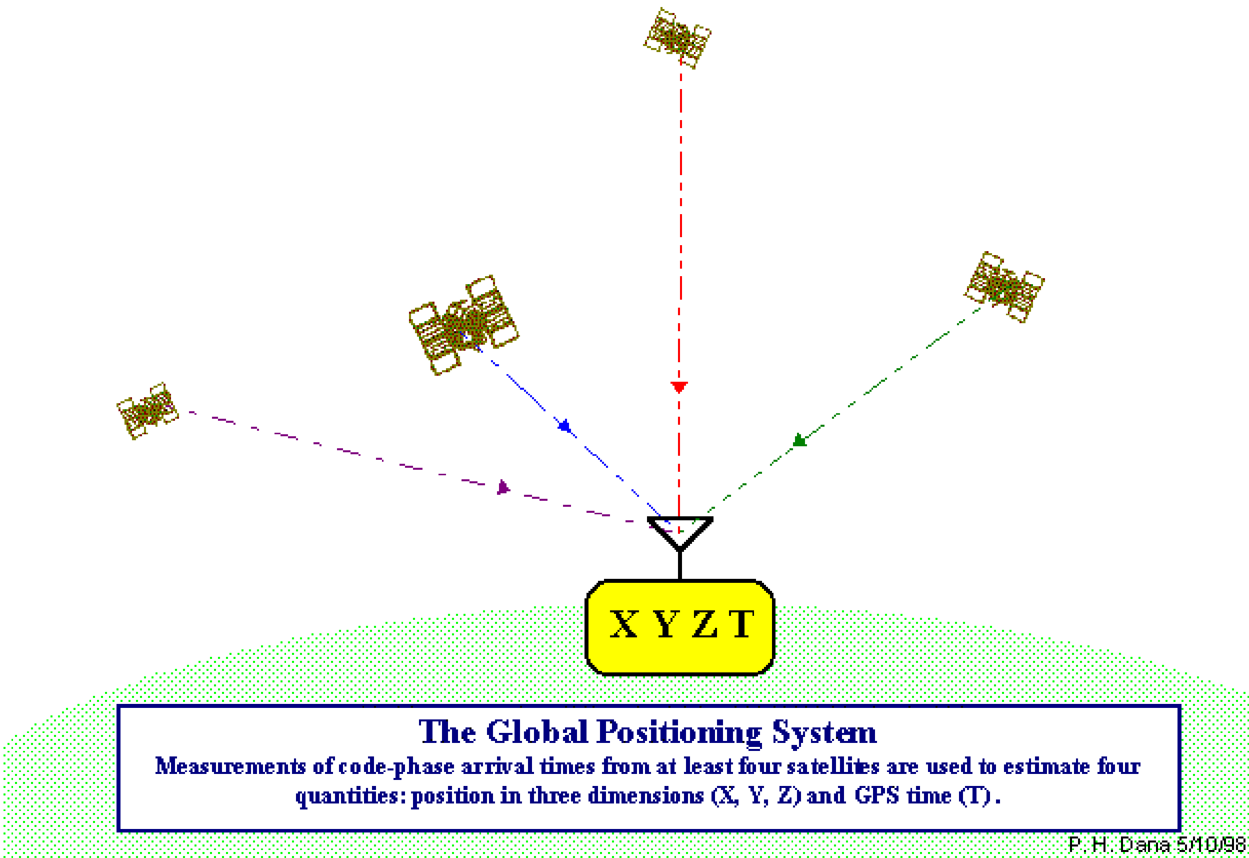


Figure 5. Four GPS Satellite Solution

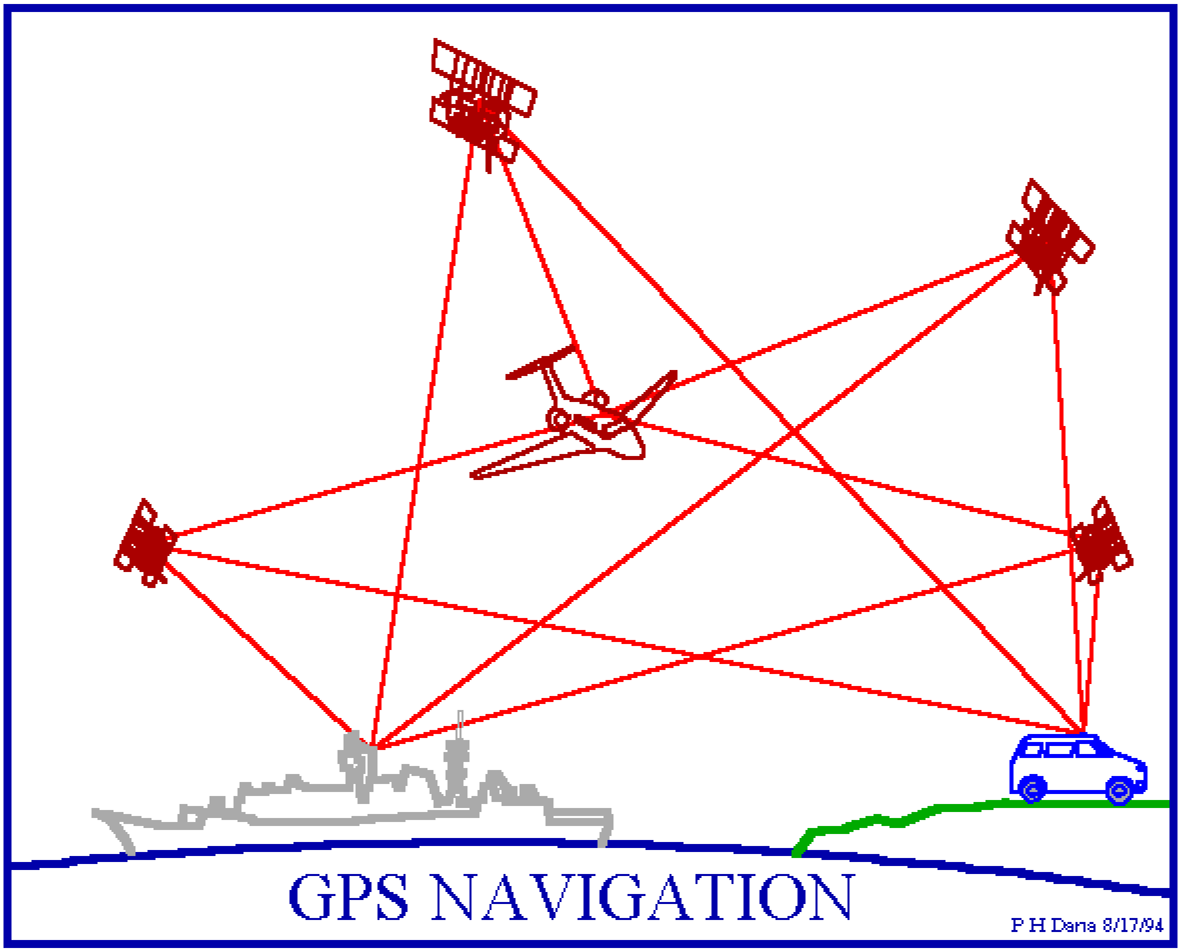


Figure 6. GPS Navigation

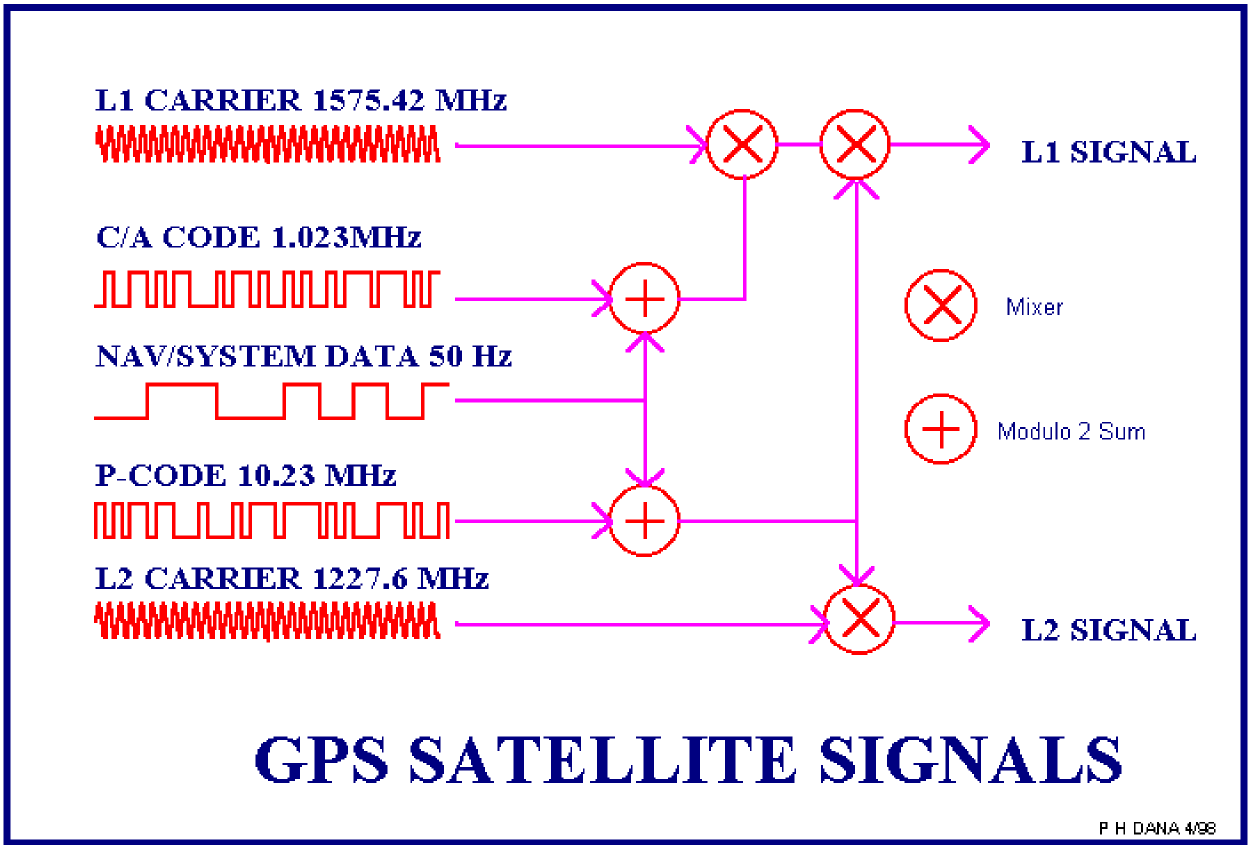


Figure 7. GPS Signals

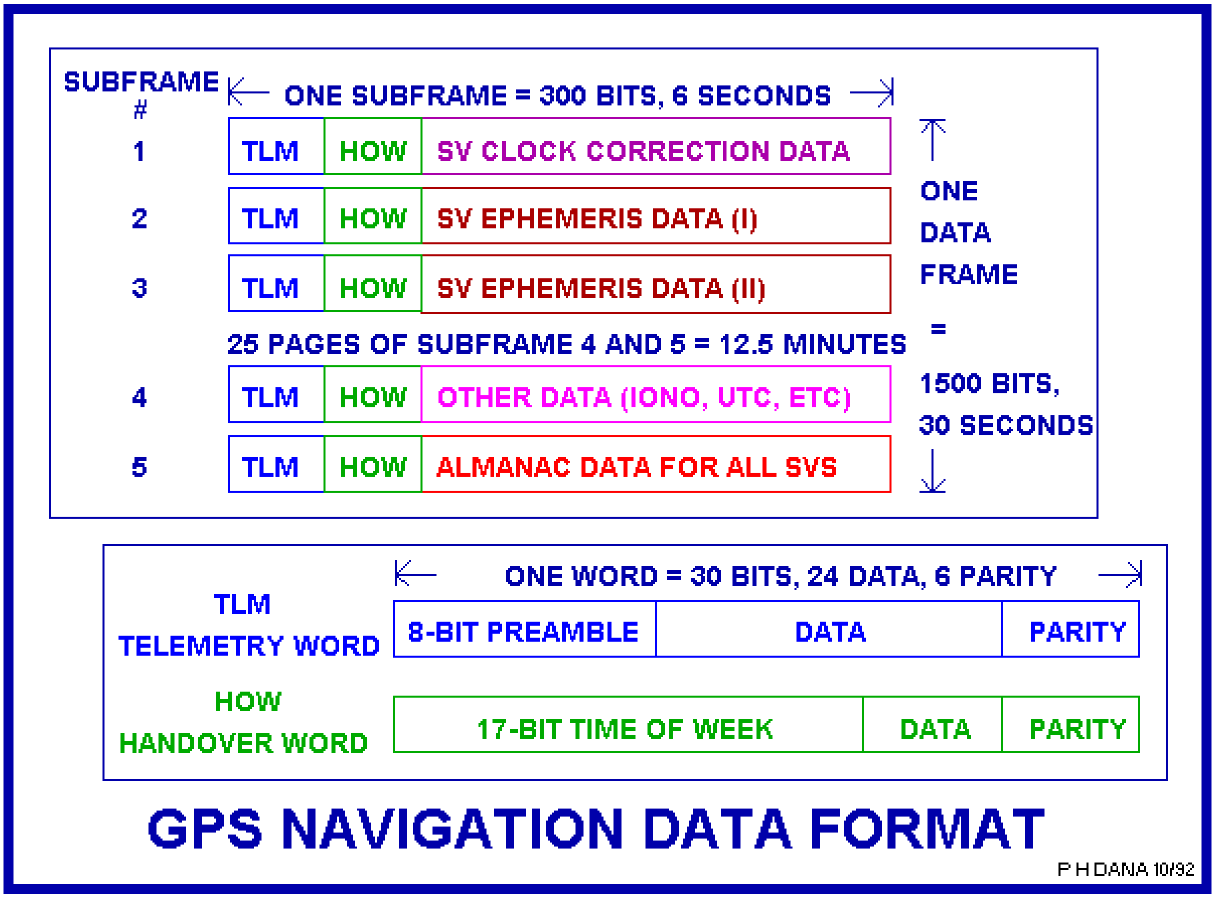


Figure 8. Navigation Data Bits

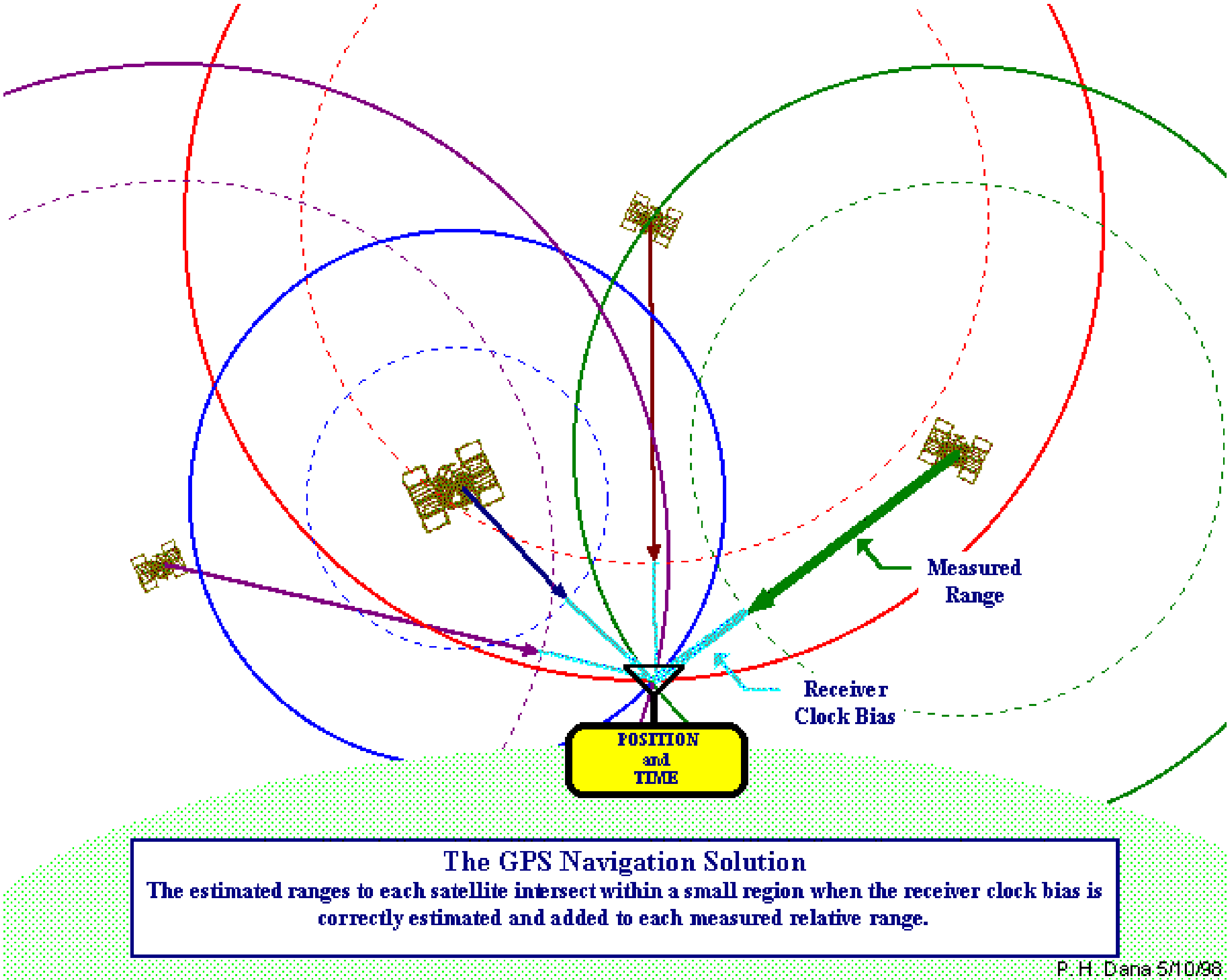


Figure 9. Intersection of Pseudo-Ranges

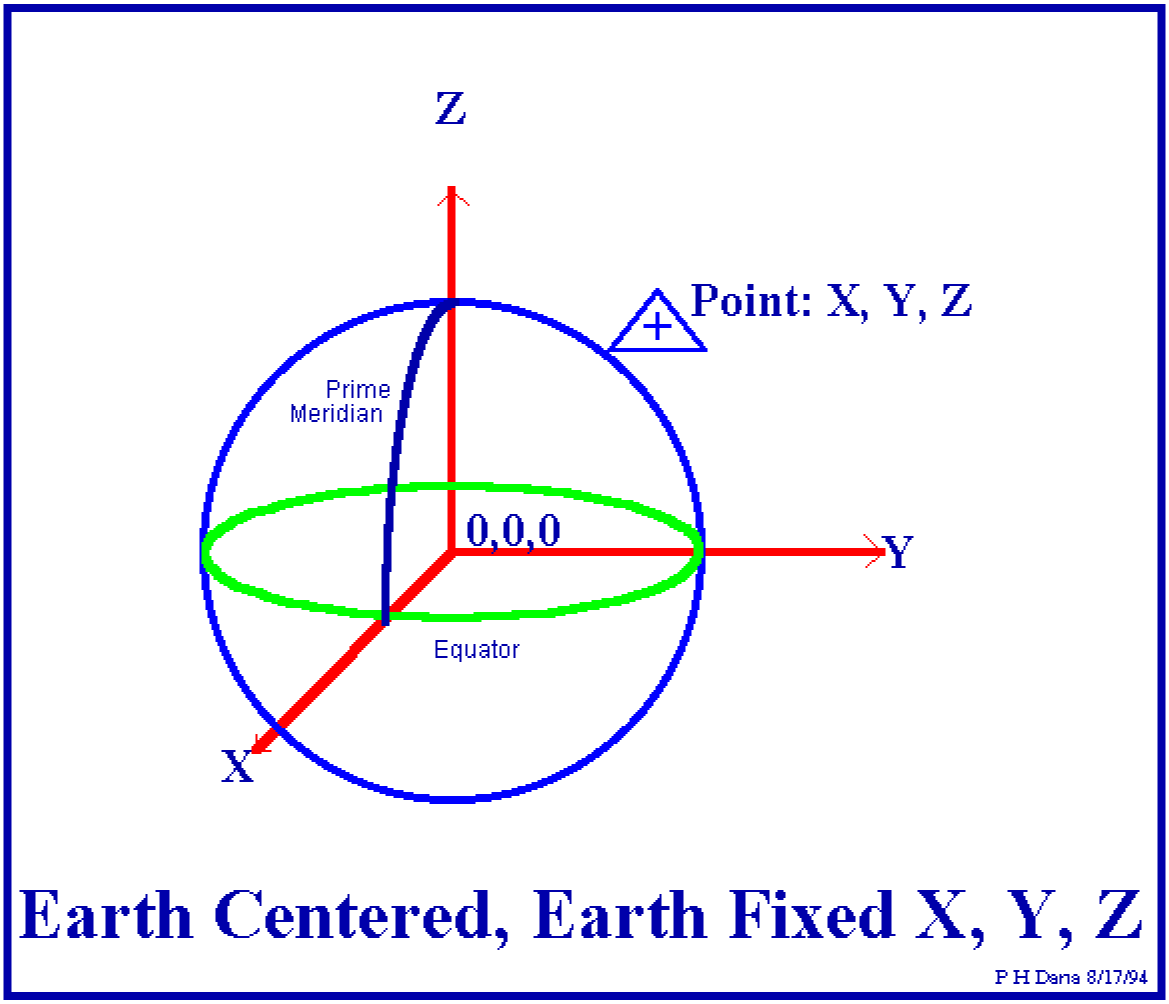


Figure 10. ECEF X, Y, and Z

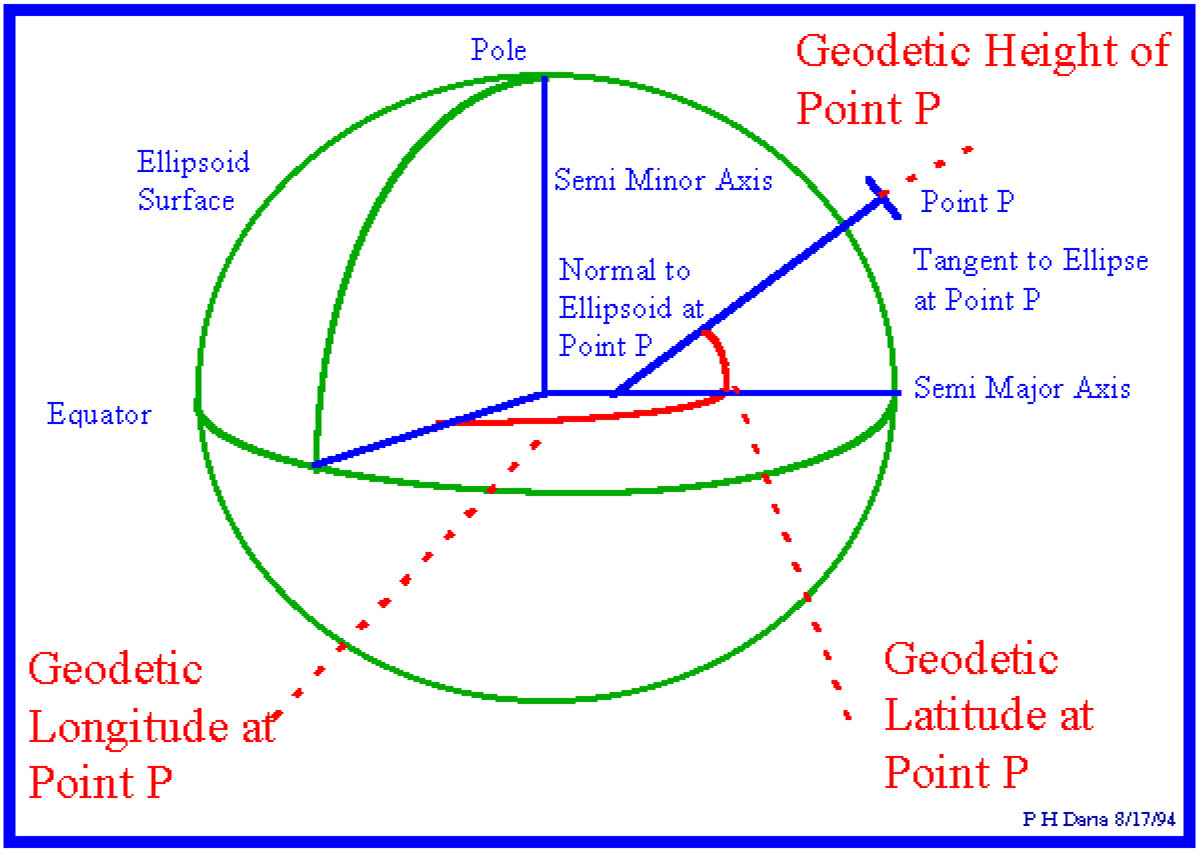
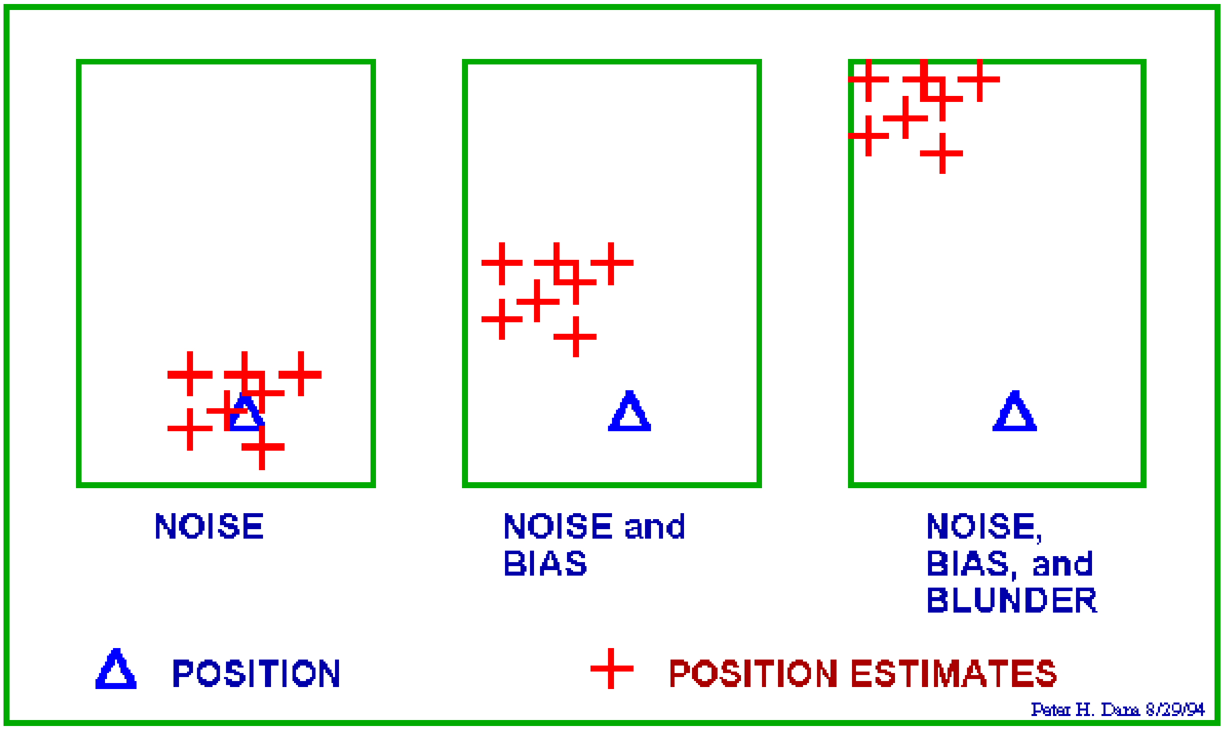


Figure 11. Geodetic Coordinates



igure 12. Noise, Bias, and Blunders

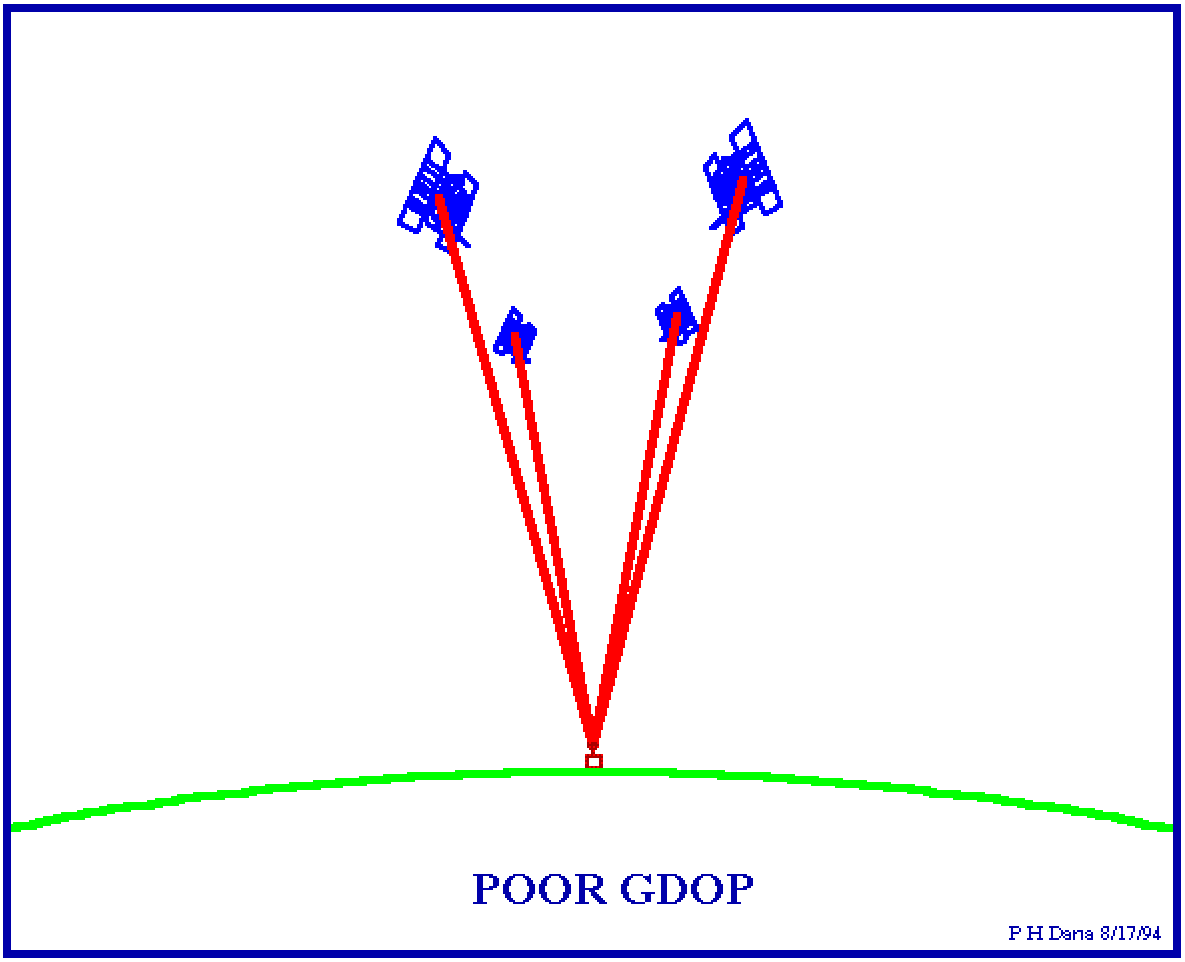


Figure 13. Poor GDOP

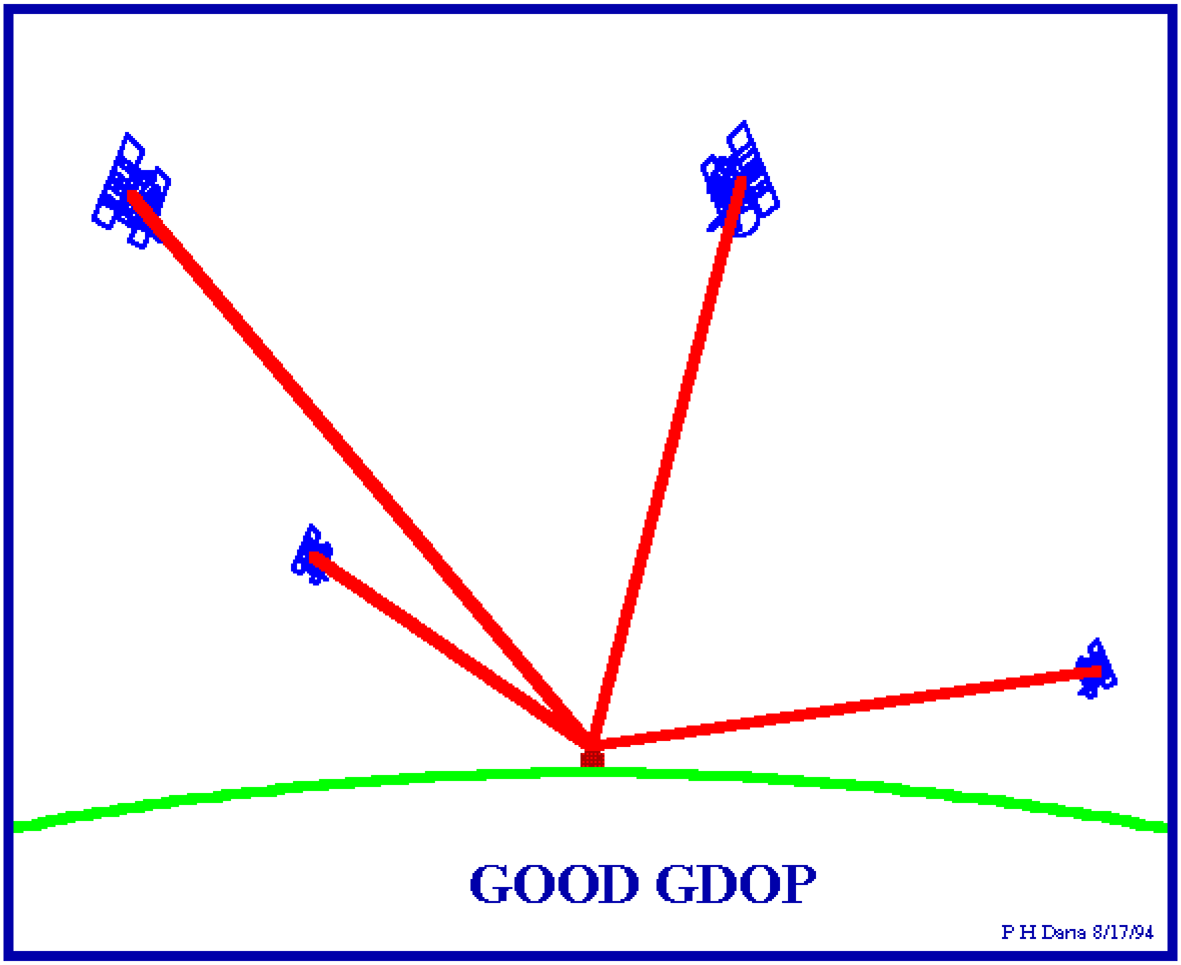


Figure 14. Good GDOP

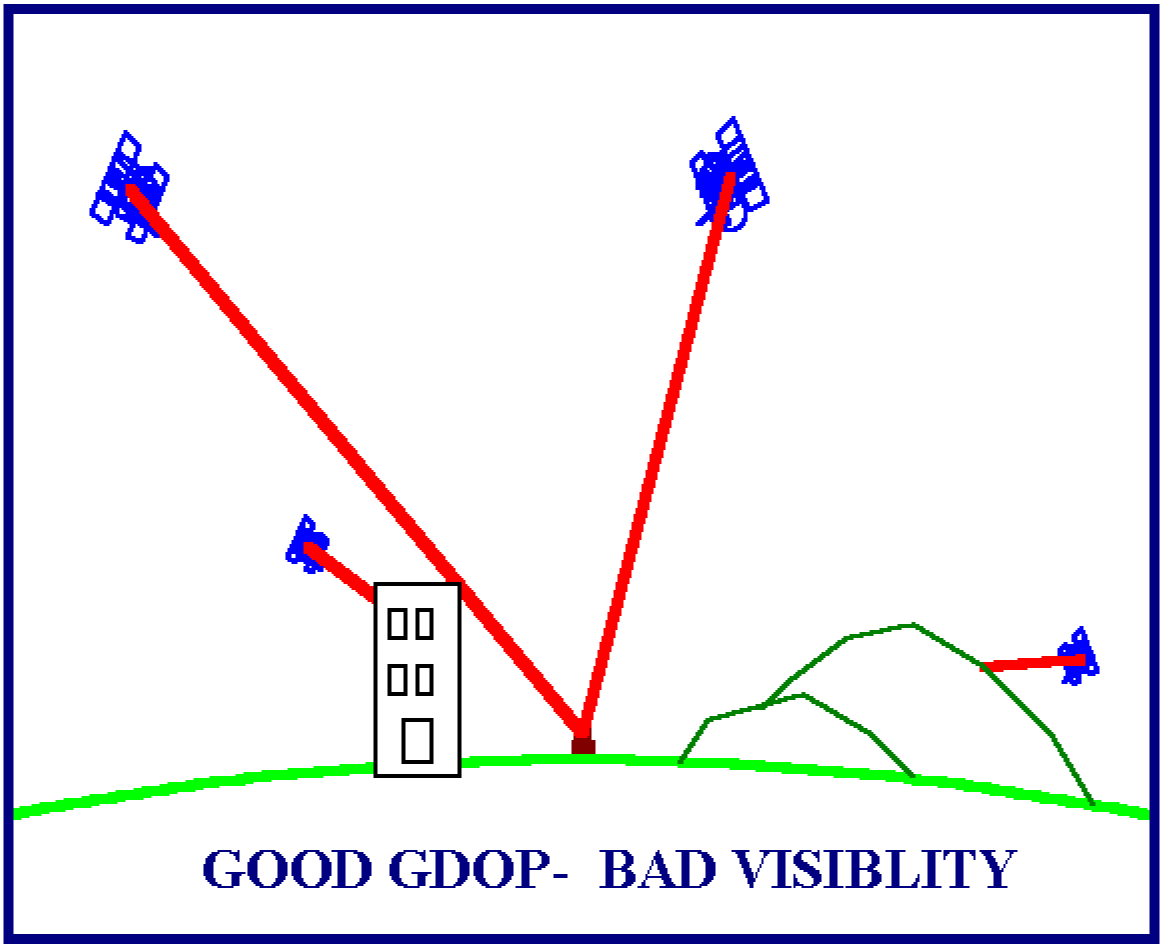


Figure 15. Good predicted GDOP, Poor Visibility

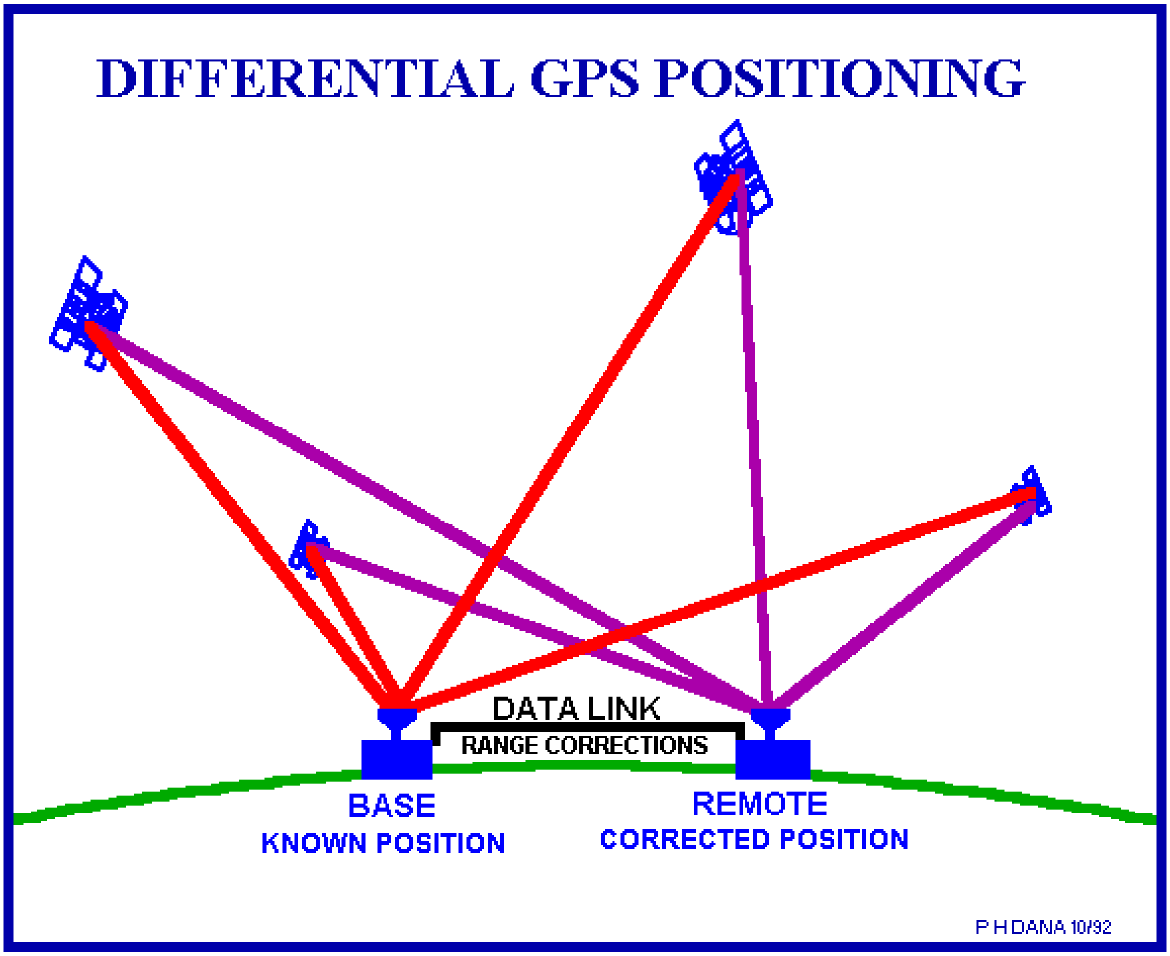


Figure 16. Differential Code-Phase Navigation

GPS ERROR SOURCES

ERROR SOURCE	TYPICAL RANGE ERROR	DGPS (CODE) RANGE ERROR <100 KM REF-REMOTE
SV CLOCK	1 M	
SV EPHEMERIS	1 M	
SELECTIVE AVAILABILITY	10 M	
TROPOSPHERE	1 M	
IONOSPHERE	10 M	
PSEUDO-RANGE NOISE	1 M	1 M
RECEIVER NOISE	1 M	1 M
MULTIPATH	0.5 M	0.5 M
RMS ERROR	15 M	1.6 M
ERROR * PDOP=4	60 M	6 M

PDOP=Position Dilution of Precision (3-D) 4.0 is typical

Figure 17. Errors Reduced by Differential Corrections

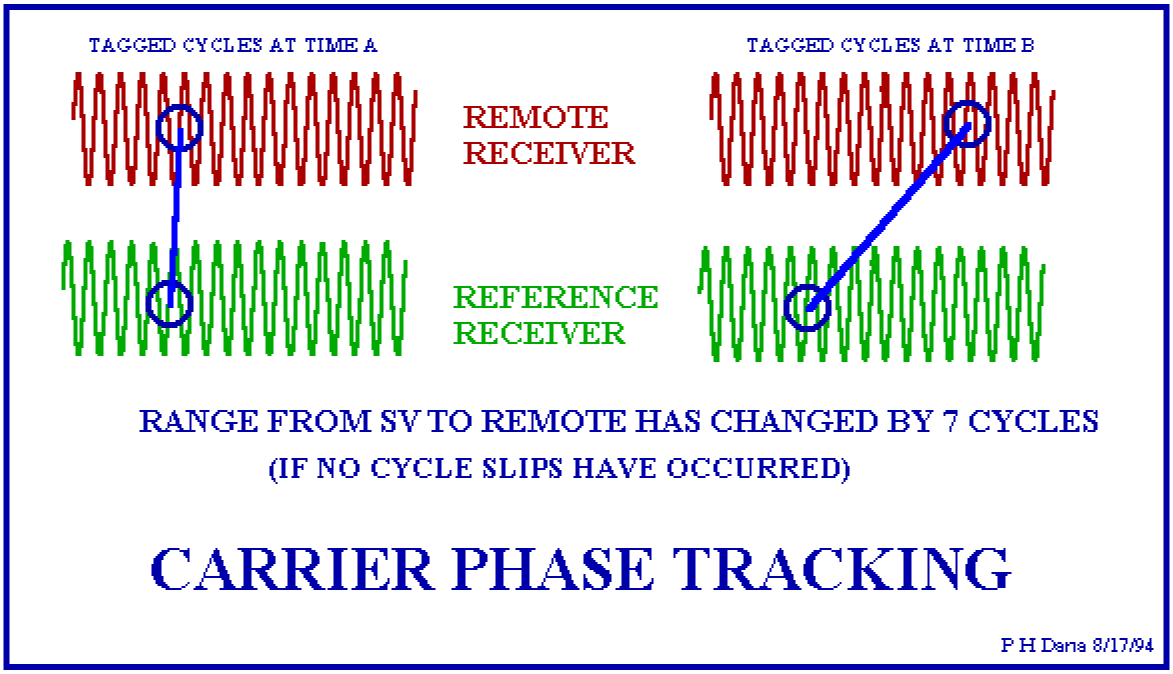


Figure 18. Carrier Phase Tracking

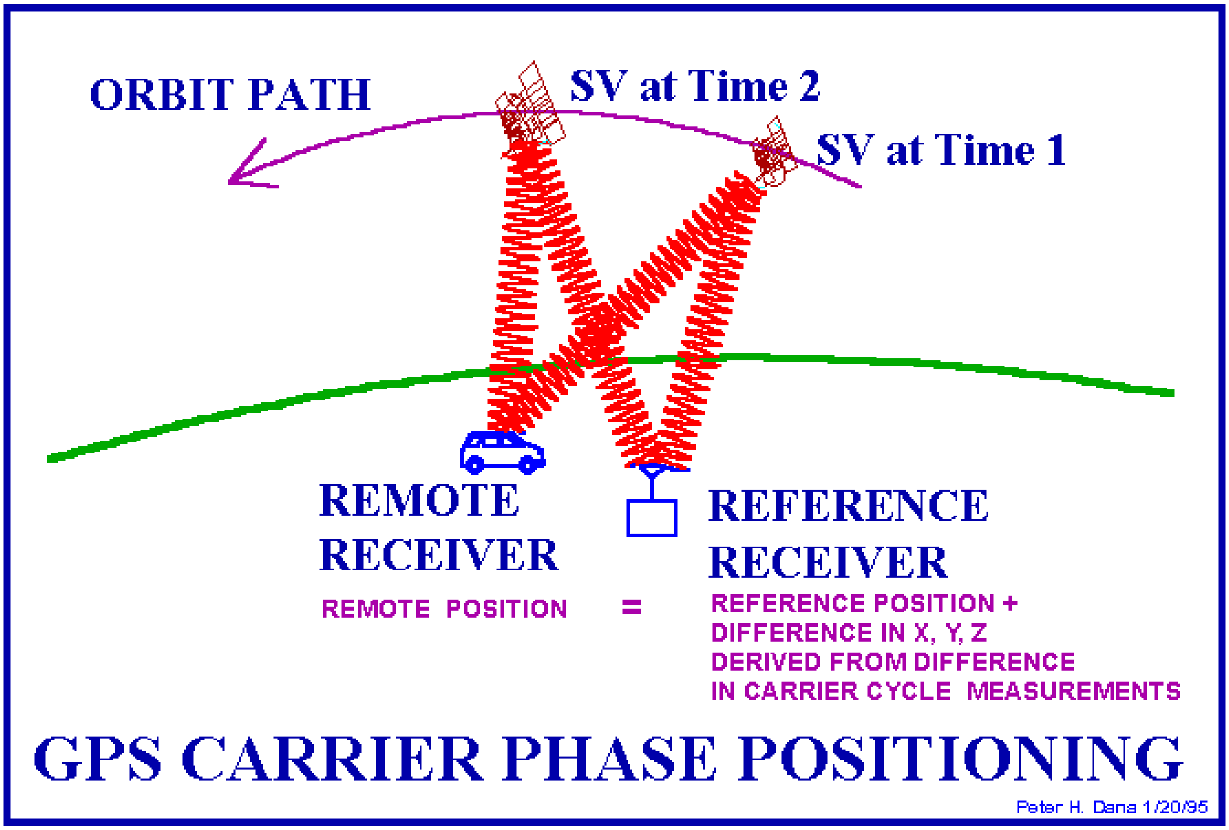


Figure 19. Differential Carrier-Phase Positioning

GPS ACCURACIES, COSTS, AND SIGNALS

GPS APPROACH	ACCURACY ESTIMATE	RECEIVER COST ESTIMATE	GPS SIGNALS				
			L1 C/A CODE	L1 P-CODE	L1 CARRIER	L2 P-CODE	L2 Y-CODE
SPS NAVIGATION	100 M	$1,000	X				
SPS DIFFERENTIAL >30KM	10 M	$5,000	X				
SPS DIFFERENTIAL <30KM	1 M	$5,000	X				
PPS NAVIGATION	10 M	$10,000	X	X		X	
ANTI-SPOOFING NAVIGATION	10 M	$20,000?	X	X	X	X	X
L1 CARRIER PHASE SURVEY	0.1 M	$10,000	X		X		
L1 L2 CARRIER PHASE SURVEY	0.01 M	$15,000	X	X	X	X	

Peter H. Dana 8/28/94

Figure 20. GPS Applications, Costs and Signals