Chapter 1

The Global Spatial Data Model (GSDM) Defined

Abstract:
A definition of the GSDM is given at www.globalcogo.com/gsdmdefn.pdf. Geospatial data representing real world locations are three-dimensional (3-D) and modern measurement systems collect data in a physical 3-D environment. The GSDM is a collection of mathematical concepts and procedures that can be used to collect, organize, store, process, evaluate, and use 3-D spatial data. It consists of a functional model that describes the geometrical relationships and a stochastic model that describes the probabilistic characteristics--statistical qualities--of spatial data. Although the terms spatial and geospatial data are often used interchangeably, spatial data are taken to be those generic data describing the size and shape of an object while geospatial data are referenced to planet Earth. The GSDM includes both the algorithms for processing spatial data and procedures that can be used to provide a defensible statistical description of spatial data quality. That means measurement professionals can focus on building and/or using systems which generate reliable spatial data components and spatial data users in various disciplines can devote attention to using and interpreting the data with the assurance that all parties generating and/or using the data are "on the same page", i.e. using a common spatial data model.

Chapter 2

Featuring the 3-D Global Spatial Data Model (GSDM)

Abstract:
The GSDM is built on the assumption of a single origin for 3-D geospatial data and formally defines procedures for handling spatial data that are consistent with digital technology and modern practice. In that respect, the GSDM is a newly defined model. With the advent of affordable digital technologies, the demand for spatial data products continues to grow. Enormous gains in productivity have been achieved by automating procedures for handling spatial data and by exploiting the advantages of digital storage. However, traditional (horizontal and vertical) spatial data models fail to exploit fully the wealth of information available. In a sense, the spatial data user community continues to "put new (digital) wine into old bottles". The GSDM is a new bottle model that preserves the geometrical integrity of 3-D spatial data.
Chapter 2 also introduces beneficial applications of the GSDM for:

1. The U.S. National Academy of Public Administration.
2. The National Oceanic and Atmospheric Administration and BIG DATA.
3. The Federal Geographic Data Committee and the National Spatial Data Infrastructure.
4. The Coalition of Geospatial Organizations.
5. Off-shore positioning and mapping underground mines and boreholes
6. Or as a reference for driverless vehicles – both land based and airborne.
7. Spatial data accuracy – both absolute and relative.

Chapter 3

Spatial Data and the Science of Measurement

Abstract:
With spatial data concisely defined, this chapter describes how spatial data and their accuracy are related to the measurement process and one's choice of a measurement system. The goal is to describe how 3-D spatial data can be manipulated more efficiently and how spatial data accuracy can be established without ambiguity using the GSDM as the foundation for the global spatial

data infrastructure. Three coordinate systems used by the GSDM and spatial data types are described as a prerequisite to a discussion of the measurements used (both direct and indirect) to generate spatial data. The role of physical constants, measurement uncertainty, and errorless spatial data are discussed along with considerations of primary and derived spatial data. Finally, suggestions are offered for ways to preserve the value of existing spatial data.

Chapter 4
Summary of Mathematical Concepts

Abstract:
This chapter begins with a description of mathematics and lists many of the conventions routinely used when working with spatial data. The role of logic is discussed briefly before discussion of various mathematical operations – beginning with operations fundamental to arithmetic and progressing through topics of algebra, geometry, solid geometry, trigonometry, spherical trigonometry, calculus (differential and integral), probability and statistics, matrix algebra, and least squares. Examples related to spatial data manipulation are included along with discussions of models (functional and stochastic) and error propagation. The goal in this chapter is to provide a concise summary of mathematical concepts ranging from fundamental add/subtract operations to esoteric operations with linear algebra, least squares, and error propagation. It is intended to provide the beginner with an overview of what might be encountered in a career devoted to use of spatial, to provide a summary of mathematical concepts for those managing workflow processes, and to show how the GSDM also supports manipulation of spatial data on a global scale – including automation of high-level spatial data positioning and accuracy computations for robotic applications.

Chapter 5
Geometrical Models for Spatial Data Computations

Abstract:
This chapter provides a summary of existing models commonly used for manipulating spatial data. Conventions associated with the conventional 2-D plane Euclidean coordinate system used for "flat-Earth" computations are discussed first followed by a discussion of the differences between the generic 2-D math/science system and the surveying/engineering system used extensively for surveying, mapping, and civil works projects. Standard coordinate geometry routines used for traversing, inverses, geometrical intersections, curves, spiral curves, and radial surveying follow. Vertical curves, volumes, and prismoidal formula are next. In the big picture, traditional models for handling 3-D spatial data include the spherical Earth model often used in geography, the ellipsoidal Earth model used in geodesy and engineering, and the hybrid model of 2-D map projections coupled with elevation as used in many applications. The chapter closes with a short discussion of the GSDM and highlights the fact that spatial data computations and manipulations are more efficiently handled in 3-D space – eliminating the need to distort a distance by reducing it to the ellipsoid or to a mapping surface.

Chapter 6
Overview of Geodesy

Abstract:
Geodesy/Geomatics: Geomatics is an umbrella term used to describe both a body of knowledge and the scope of professional activities having to do with generation, manipulation, storage, and use of spatial data. In a non-exclusive way, geomatics includes traditional disciplines such as surveying,

mapping, geodesy, and photogrammetry. Geomatics also overlaps with other newer disciplines such as remote sensing, imaging, and information sciences. Of all such disciplines, geodesy provides the geometrical foundation for the rest. This chapter summarizes the field of geodesy with a focus on geometrical geodesy which embodies geometrical relationships and physical geodesy which uses gravity to answer questions about why points are where they are and how they move. The goals of geodesy are included in a summary of "political geodesy" relative to public policy and the National Spatial Data Infrastructure (NSDI). The historical development of geodesy includes significant scientific pioneers such as Mercator and Newton and parallels the development of measurement science including the definition of the meter, refinement of time-keeping, and mathematical concepts of least squares. Speculation about the impact of geodesy on the use of spatial data in the twenty-first century closes out the chapter.

Chapter 7
Geometrical Geodesy

Abstract:
Geometrical geodesy deals with the size and shape of a nearly spherical Earth. If planet Earth were reduced to a globe having a diameter of 1.0000 meter at the equator, the spin axis would 0.99665 meter, only 3.35 millimeters less. As postulated by Newton, this flattening at the poles is due to the Earth spinning on its axis. This sea-level shape of the Earth is a continuous equipotential surface called the geoid and is approximated by a mathematical ellipse rotated about its minor axis – the spin axis of the Earth. This 3-D mathematical ellipsoid is the fundamental reference surface for geodetic computations. The equations of the 2-D ellipse are developed first, followed by equations for the 3-D ellipsoid. Equations for the geodetic "forward" and "inverse" and other traditional geometrical computations are developed and presented. Since many of those geometrical relationships are integral to the GSDM, the 3-D nature of geodetic computations is interspersed throughout. The Chapter closes with a specific focus on the efficiencies offered by using the 3-D GSDM. Looking ahead, spatial data computations are also performed using a conformal mapping computational model (see chapter 11). With no loss of geometrical integrity, the GSDM supports equivalent spatial data computations in 3-D space - avoiding mathematical complexities encountered in traditional geodetic and conformal mapping computations.

Chapter 8
Geodetic Datums

Abstract:
Issues of geodetic datums are quite dynamic compared to geometry of the ellipsoid. The reader is encouraged to consult the National Geodetic Survey (NGS) web site (www.ngs.noaa.gov) to obtain information about plans for replacing both the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88) and to obtain information about implementation as related to spatial data applications. The anticipation is that the GSDM will be compatible with the 2022 geodetic datums.

A datum is a reference to which other values are related. The simplest form of a datum could be coordinates and elevation assigned to a stake pounded in the ground. Any change in those values could be interpreted as a different datum. The global perspective of datums is much more involved and a discussion of datums is critical to successful use of 3-D digital spatial data.

The chapter discusses historical development of both horizontal and vertical datums leading up to current NGS efforts to replace the NAD 83 and the NAVD 88. That evolution includes discussion of datum definitions, realization through High Precision Geodetic Networks (HPGN), High Accuracy Reference Networks (HARN), can continuously operating reference stations (CORS). Datum transformations are discussed briefly and the role of the 3-D GSDM is highlighted.

Chapter 9

Physical Geodesy

Abstract:
Physical geodesy is the branch of science that relates the internal distribution of mass within the Earth to its corresponding gravity field. A physical realization of gravity is that a plumb bob always points down. A level surface is always perpendicular to the plumb line and a particular level surface approximating mean sea level is an equipotential surface called the geoid. Newton's description of gravity and implications of gravity with respect to the geoid and the third dimension are discussed. The geoid is the traditional reference for the third dimension but additional concepts such as elevation, orthometric heights, dynamic heights, and ellipsoid heights are also considered. Physical measurements including tide gage readings, differential levels, gravity surveys, GPS data, and remote sensing operations all contribute to the challenges of understanding and correctly determining the third dimension. Geoid modeling provides a link between the ellipsoid height obtained from GPS operations and traditionally defined elevation. Significant resources have been devoted to geoid modeling and huge advances have been made. But, when considering issues of absolute and relative third-dimension distances, an alternative is to use ellipsoid height in the place of elevation. The GSDM accommodates geoid modeling as a separate operation but ellipsoid height is an integral part of the GSDM and the associated efficiencies will become a driving force for eventual adoption of a World Vertical Datum – see a forecast for future in Chapter 6.

Chapter 10

Satellite Geodesy and Global Navigation Satellite Systems

Abstract:
Goals of satellite geodesy include using Earth-orbiting satellites to determine the size and shape of the Earth, to obtain a greater understanding of the Earth's gravity field, and to define the position of points on or near the surface of the Earth and in near space. The first two goals are primarily scientific in nature but the third goal is more applications oriented. It should be noted that global navigation satellite systems (GNSS) is a generic description that includes various positioning systems and that the global positioning system (GPS) is the original positioning system using the U.S. NAVSTAR satellite constellation. Sometimes the terms GPS and GNSS can be used interchangeably but at times specificity dictates use of one acronym or the other.

This chapter contains an overview of principles and systems involved in meeting those goals. A description of the basic principles and components of the first generation of GPS follows a brief history of satellite positioning and procedures for using those data. Although use of GNSS data has become ubiquitous, the underlying geometrical model is seldom of interest to end users beyond engineering, surveying, and mapping applications. This 2nd Edition notes that the future of survey control networks as described in the first edition has already arrived but also notes that the 3-D GSDM will continue to support spatial data applications well into the future.

Chapter 11

Map Projections and State Plane Coordinates

Abstract:
Cartography is the science of making maps and includes representations of spatial data. A map projection is a 2-D model whereby the curved Earth is represented on a flat map. A small portion of the surface of the Earth appears to be flat, however, when dealing with larger portions of the surface, it is impossible to portray the curved Earth on a flat map without distortion. Conformal projections are used extensively in engineering, surveying, and mapping because angles are preserved but distances are distorted. Small surface areas are projected with low distortion while greater distortions are associated with larger projected surface areas. This chapter includes a summary of map projections and describes development and use of the state plane coordinate system (SPCS) in the United States. A disadvantage is that a map projection is strictly a two-dimensional model while spatial data are inherently 3-D. The GSDM preserves geometrical integrity of spatial data by storing spatial data in a 3-D database of ECEF coordinates. Once the user chooses a local origin, the direction and distance to any or all points in the 3-D database (or cloud) can be viewed without being distorted. The chapter closes with a short discussion of low distortion projections (LDPs).

Chapter 12

Spatial Data Accuracy

Abstract:
The GSDM includes both a functional model of geometrical relationships and a stochastic model. This chapter focuses on the stochastic model and highlights the importance of spatial data quality while providing well-defined procedures for establishing, tracking, storing, and computing spatial data accuracy. The beginning part of the chapter acknowledges the impact of the digital revolution and describes the analog/digital transition as related to digital spatial data. The difference between absolute and relative quantities is explained and significant attention given to the difference between measurements and observations. That is followed by development of formal error propagation as determined by a least squares adjustment of a network. The resulting covariance matrix for each adjustment is stored in a 3-D database and includes both variances and covariances. Network accuracies are determined from the variances. The off-diagonal elements of the covariance matrix contain the correlation information. These correlations are used to compute the local accuracy between specified point pairs. An example of a small network adjustment formulated in terms of the GSDM rounds out the chapter and includes computation of both network and local accuracies.

Chapter 13

Using the GSDM to Compute a Linear Least Squares Network

Abstract:
The first edition of this book contains a least squares adjustment as described in the previous chapter. This chapter includes a larger adjustment and describes formulation of a **linear** least squares solution for geocentric networks. Although no substitute for a more generalized nonlinear least squares solution, this example shows the power and efficiency of using geocentric coordinate differences in a linear least squares solution. A linear least squares solution has an advantage in that time-consuming iterations are avoided. This could be particularly important in time-critical circumstances such as real-time navigation or monitoring the motion of a drone or driverless vehicle. Yes, computer speeds are exceedingly fast, but achieving least squares results

quickly in a real-time environment can benefit from both fast computers and efficient algorithms. Following a description of how a linear least square solution is formulated, a detailed example network based upon RINEX data downloaded from nine stations of the Wisconsin Department of Transportation CORS (WISCORS) network is included. Other applications are described in subsequent chapters. Additional clarification is provided in the last section of this chapter, "Notes pertaining to adjustment."

Chapter 14

Computing Network Accuracy and Local Accuracy Using the Global Spatial Data Model

Abstract:

This chapter includes a detailed example of a network adjustment of 9 CORS stations and documents specific computation of both network accuracy and local accuracy. The terms "network accuracy" and "local accuracy" have only recently come to the fore in geomatics technical literature. Driven, in part, by the digital revolution, those intuitive concepts have enjoyed increasing consideration and are being included in technical standards such as the 2016 Minimum Standards for a NSPS/ALTA survey. The first edition of this book contained a least squares adjustment example that included a mathematical definition for the two terms. That example fostered a discussion in the technical literature as described in Appendix E of this second edition. The example included in this chapter demonstrates computation of the covariance matrix for the network and shows computation of both network and local accuracies. Tight (but not "fixed") tolerances for the control points were held in the example computation. A second computation of the same network with "relaxed" tolerances demonstrates a corresponding reduction in the computed network accuracies but shows that local accuracies (reflecting the internal quality of the network) change very little. Application of these computational procedures can also have significant potential for accuracy computations in a dynamic environment of driverless vehicles – whether land-based intelligent vehicles or airborne drones.

Chapter 15

Using the GSDM – Projects and Applications

Abstract:

Using the GSDM is primarily a matter of choosing to do so. The technology is already in place and all equations and procedures are in the public domain. The ECEF coordinates of most control points are readily available and adding locally determined components ($\Delta X/\Delta Y/\Delta Z$'s - whether by GPS, or otherwise) to those control values will give the X/Y/Z values to be stored in the 3-D database. Using 3-D values from the integrated database, one can compute (derive) other geometrical quantities – directions, distances, angles, volumes, and (if adding geoid modeling) elevations in the system of choice. Such capability provides the opportunity for an endless array of applications. This chapter includes examples of the following applications and closes with a discussion of "the future will be what we make it."

1. A supplemental NMSU Campus Control Network.
2. Hypothesis testing example.
3. Using terrestrial angle observations to locate a finial on campus – and standard deviation of position.
4. Using a 3-D GPS survey to develop a 2-D plat of a USPLSS section survey.
5. Comparing modern results with original layout on the New Mexico Principal Meridian.
6. Determining relative positions on the New Mexico – Texas Boundary in the Rio Grande River.

7. Documentation of GPS leveling project in Wisconsin – shows first-order results.
8. Determining the NAVD 88 elevation of a HARN Station on the NMSU Campus.
9. Determining the shadow height at the NEXRAD facility near Tucson, Arizona.
10. Comparison of 3-D model computations for a point on the NMSU Campus.
11. Underground mapping for boreholes.
12. Laying out a parallel of latitude based on the GSDM.