Spatial Data, Coordinate Systems, and the Science of Measurement

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Abstract: Many disciplines work with spatial data and use a geographic information system (GIS) to reference geospatial data. Based upon a concise definition of spatial data, this paper describes how spatial data and their accuracy are related to the measurement process and one's choice of a coordinate system. The goal is to describe how 3-dimensional spatial data can be manipulated more efficiently and how spatial data accuracy can be established without ambiguity using the global spatial data model (GSDM) as the foundation for GIS's and the National Spatial Data Infrastructure (NSDI).

INTRODUCTION:

Spatial data are three-dimensional. Modern instruments record three-dimensional measurements and process them electronically. Results are stored digitally in a computer database. Maps are inherently two-dimensional (they flatten the earth) and humans traditionally view spatial relationships in terms of "horizontal" and "vertical". A global spatial data model (GSDM) has been defined (Burkholder 1997) which is equally applicable around the world, accommodates modern measurement technologies, incorporates digital data processing and storage, preserves the 3-dimensional character and geometrical integrity of spatial data, and provides each user with enviable flexibility in using the data. A BURKORD® 3-D data base stores

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geocentric X/Y/Z coordinates and the associated covariance matrix for each point. It will also store point correlations. For more information, see Burkholder (1999 & 1998) and/or www.zianet.com/globalcogo. Although not exhaustive, this paper summarizes characteristics of pertinent coordinate systems, defines spatial data, and looks at measurement processes by which spatial data are generated. The accuracy of spatial data is also considered and a distinction is made between primary and derived spatial data.

SPATIAL DATA DEFINED:

Use of the GSDM can foster greater insight into the relationships between coordinate systems and how they are used to handle spatial data. Spatial data are described as those numerical values which represent the location, size, and shape of objects found in the physical world. Examples include points, lines, directions, planes, surfaces, and objects. For purposes of this paper, spatial data are **defined** simply as the distance between endpoints of a line in Euclidean space. The endpoints may be non-physical entities such as the origin or axis of a coordinate system. An endpoint may also represent the location of some physical feature such as a survey monument, building corner, benchmark, or other object. Geometrical elements such as planes, surfaces, and other objects formed by the movement and aggregation of distances also qualify as spatial data. Although straight line distances are generally presumed, the measure of a distance can also be along a curved line, in either linear or angular units, without violating the definition. The term "geospatial data" has been used to identify spatial data referenced to the physical earth (geo-referencing). Without going into the differences between spatial data and the attributes of spatial data, the definition of spatial data as used here includes, but is not limited to, geospatial data.

COORDINATE SYSTEMS GIVE MEANING TO SPATIAL DATA:

When working with spatial data, assumptions are made about the underlying coordinate system. Since each reader deserves to know at all times, "with respect to what," an attempt is made to be very specific about the underlying coordinate system and whether the spatial data are absolute or relative. As a matter of convention (and not to be confused with the length of a vector), absolute spatial data are taken to be with respect to a defined coordinate system while relative spatial data are taken to be the difference between two absolute values in the same system. A coordinate is an absolute distance with respect to the defined coordinate system and an azimuth is an absolute direction with respect to the zero reference. Coordinate differences (in the same system) are spatial data components and used as relative values. An angle, defined as the difference between two directions, is also a relative value. Absolute data are often used to store spatial information while relative data are more often associated with measurements.

Admitting the use of undefined terms, relying upon prior knowledge, and acknowledging a difference between a reference system and a reference frame, the information presented here is intended to be consistent with current definitions of coordinate systems, such as those described by Hothem and Soler (1988). The functional model portion of the GSDM is a collection of geometrical relationships traditionally viewed in terms of one or more coordinate systems (Burkholder 1998).

Three coordinate systems which are an integral part of the GSDM are:

1. A foundation 3-dimensional (3-D) geocentric coordinate system for spatial data is called the earth-centered earth-fixed (ECEF) rectangular cartesian coordinate system and defined by the National Imagery and Mapping Agency (NIMA) (DMA 1991), see Figure 1. With its origin at the earth's center of mass, the X/Y plane is coincident with the earth's equator and the Z axis is defined by the location of the Conventional Terrestrial Pole (CTP). The X axis is defined by the arbitrarily fixed location of the Greenwich Meridian and the Y axis is at longitude 90° East, giving a right-handed coordinate system.

2. A geodetic coordinate system, Figure 2, is used to reference spatial data by geodetic positions on the ellipsoid, a mathematical approximation of the earth's surface. Position is defined in the north/south direction by angular units

(degrees/minutes/seconds) of latitude and in the east/west direction by angular units of longitude. Lines of equal latitude are called parallels and lines of equal longitude are called meridians. The sign convention for latitude is positive north of the equator and negative south of the equator. The sign convention for longitude is positive eastward for a full circle from 0° on the Greenwich Meridian to 360° (arriving again on the Greenwich Meridian). A west longitude, as commonly used in the western hemisphere, is acceptable and mathematically compatible if used as a negative value.

Geodetic latitude and longitude are 2-dimensional curvilinear coordinates given in angular units. The third dimension, ellipsoid height, in this world-wide coordinate system is the distance above or below the mathematical ellipsoid and is measured in length units, meters being the international standard. With the conceptual separation of horizontal and vertical, this system of geodetic coordinates more closely matches physical reality in a global sense than does the ECEF system and remains very useful for cartographic visualizations. But, the geodetic coordinate system is computationally more complex and more cumbersome to use than rectangular components when working with 3-D spatial data.

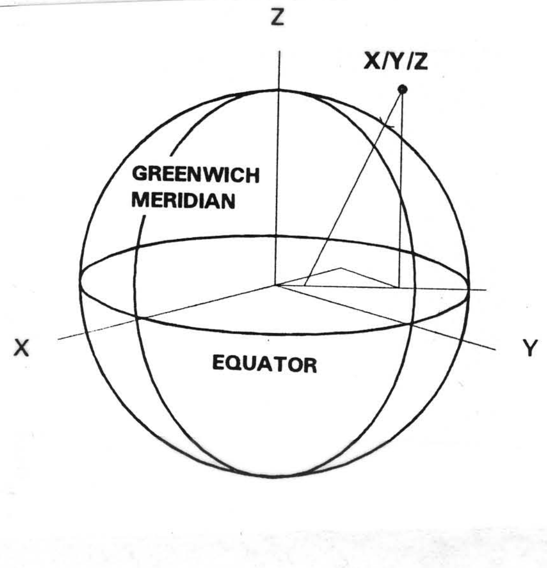

Figure 1 Geocentric Coordinates

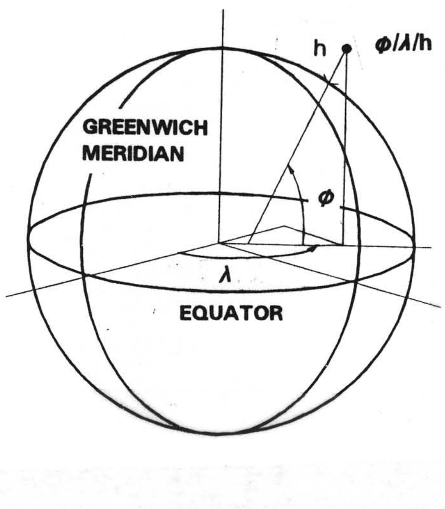

Figure 2 Geodetic Coordinates

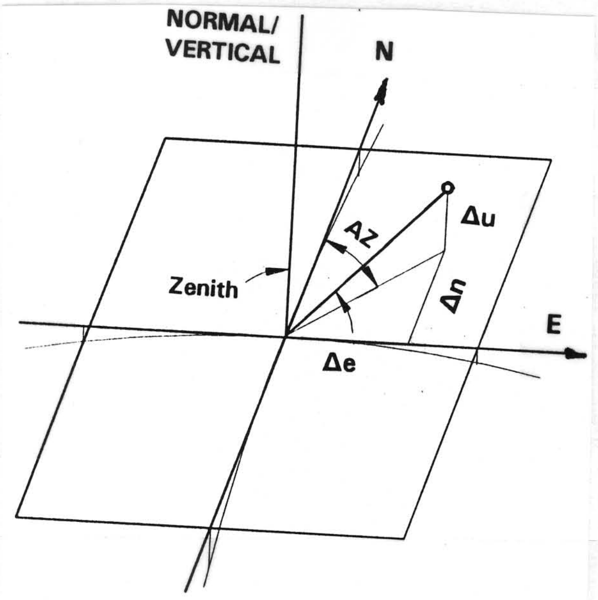

Figure 3 Local Coordinates

3. Local coordinate systems, Figure 3, portray the location of spatial data with respect to some user specified reference and/or origin. A local coordinate system can be defined such that horizontal and vertical relationships are both accurately portrayed and 3-D relationships are preserved. However, many local coordinate systems enjoy true 3-D geometrical integrity only to the extent that a flat earth can be assumed. If spatial data issues are addressed strictly on a local basis, the error caused by such flat-earth assumptions can be negligible. However, as one works over larger areas, needs greater precision in small areas, or needs to establish compatibility between local coordinate systems, the flat-earth model is not adequate for referencing spatial data. But, used as a component of the GSDM, the local flat-earth model can support visualization and use of 3-D data without being adversely affected by curved-earth distortions. That means local rectangular (flat-earth) relationships can be utilized in a global environment without compromising the geometrical integrity of spatial data.

Given descriptions of a geocentric ECEF coordinate system, a geodetic coordinate system, and a local coordinate system, the following spatial data types are listed:

1. Absolute geocentric X/Y/Z coordinates are perpendicular distances in meter units from the respective axes of an ECEF reference system.

2. Absolute geodetic coordinates of latitude/longitude/height are computed from ECEF coordinates with respect to some named model (geodetic datum).

3. Relative geocentric coordinate differences, $\Delta X/\Delta Y/\Delta Z$, are obtained by differencing compatible geocentric X/Y/Z coordinate values.

4. Relative geodetic coordinate differences, $\Delta\phi/\Delta\lambda/\Delta h$, are obtained as the difference of compatible (common datum) geodetic coordinates.

5. Relative local coordinate differences, $\Delta e/\Delta n/\Delta u$, are local components of a space vector defined by relative geocentric coordinate differences.

6. Absolute local coordinates, e/n/u, are distances from some origin whose definition may be mathematically sufficient in 3 dimensions, 2 dimensions, or 1 dimension. Examples are:

   - Point-of-Beginning (P.O.B.) datum coordinates as defined in Burkholder (1997). These derived coordinates enjoy full mathematical definition in 3 dimensions, suffer no loss of geometrical integrity in the GSDM, and serve the local needs of many spatial data users.

   - Map projection (state plane) coordinates which are well defined in 2 dimensions with respect to some named origin and geodetic datum.

   - Heights/elevations which are 1 dimensional distances above or below some named reference surface. In the past, mean sea level was assumed to be acceptable as a vertical reference but, due to the difficulty of finding mean sea level precisely, modern vertical datums are referenced to an arbitrary equipotential reference surface (Zilkowski, et. al, 1992). Ellipsoid heights are derived with respect to a named reference ellipsoid and geoid height is the difference between height and elevation at a point.

7. Arbitrary local coordinates may be 1 dimensional (assumed elevations), 2 dimensional (assumed plane coordinates) or 3 dimensional (spatial objects, rectangular coordinates, or assumed elevations and plane coordinates). Although useful in some applications, arbitrary local coordinates are generally not compatible with other local systems and have limited value in the broader context of geo-referencing. Many computer graphics and data visualization programs use arbitrary local coordinates.

The GSDM efficiently handles spatial data which fall into categories 1, 3, and 5 (absolute geocentric coordinates, relative geocentric coordinate differences and relative local coordinate differences). Spatial information is stored most efficiently using digital geocentric coordinates, manipulated most readily using geocentric coordinate differences, and displayed for human visualization and analysis using relative local coordinate differences. Spatial data consisting of geodetic coordinates and geodetic coordinate differences (categories 2 and 4) are useful for cartographic portrayal and, to the extent they can be competently related to category 1, generally are not a problem. Category 6 spatial data (local coordinate differences) can be incorporated into the GSDM if and only if they enjoy full 3-D mathematical definition. Without additional survey measurements, attempts to incorporate category 7 data into the GSDM are not viewed as fruitful.

SPATIAL DATA VISUALIZATION IS WELL DEFINED:

Spatial data are used extensively in computer graphics, visualization programs, computer aided design and drafting, and in the manipulation of spatial objects. The GSDM provides for the connection of spatial data to the physical earth, but otherwise makes no attempt to impose conditions on the use of spatial data. It is anticipated that the scope, utility, and value of many spatial data manipulation, visualization, and 3-D coordinate geometry (COGO) programs may be enhanced by taking advantage of the physical earth connection as defined by the GSDM.

DIRECT/INDIRECT MEASUREMENTS CONTAIN UNCERTAINTY:

Spatial data are created by measurement and no measurement is perfect. In a simple case, a distance is determined by direct comparison of some unknown length with a standard such as a ruler, steel tape, or wavelength. Whether the distance is horizontal or vertical is a condition noted by the person recording the observation. More often, however, spatial data are obtained as the result of an indirect measurement in which one or more spatial data components are computed from the observations, as is the case when a slope distance is resolved into its horizontal and vertical components. In other cases, some physical quantity is observed and a distance is computed using known mathematical relationships (a model). An example is computing a distance from a voltage which represents the phase shift of a sine wave signal in an electronic distance measuring (EDM) instrument. Restating, spatial data measurements may be the result of a direct comparison or, more often, they are computed indirectly from observations of various fundamental physical quantities.

Fundamental physical quantities as expressed in the International System (SI) are:

length - meter, m	temperature - Kelvin, K
time - second, s	luminous intensity - candela, cd
mass - kilogram, kg	amount of substance - mole, mol
current - ampere, A	

Derived physical quantities include (there are others - Nelson, (1999)):

frequency - hertz, Hz	electric charge - coulomb, C
force - newtons, N	electric potential - volt, V
pressure - pascal, Pa	plane angle - radian, rad
energy - joule, J	solid angle - steradian, sr
power - watt, W	

Spatial data are created by measurement of some combination of physical quantities and those measurements are used in models which relate the observed quantity to a physical distance (spatial data) relative to one of the three coordinate systems listed earlier. The accuracy of such spatial data is dependent upon 1) the quality and sufficiency of the measurements, 2) the appropriateness of the models used to compute the spatial data components, and 3) error propagation computations. The GSDM accommodates all three considerations.

MEASUREMENTS USED TO CREATE SPATIAL DATA INCLUDE:

Taping: A calibrated tape is laid flat on a horizontal surface at some specified tension and temperature. The measurement involves a visual comparison of the unknown length with uniform markings on the tape (a fundamental physical quantity). The observation is recorded as a measurement. If the temperature (another physical quantity) is different than the specified calibration temperature or if the tension (a derived physical quantity) is not what it should be, these other measurement conditions must also be noted. Using this additional information and appropriate equations, corrections to the taped distance are computed and applied to this otherwise direct measurement. Whether the computed distance is a direct or an indirect measurement is left to the reader.

Leveling: A level rod with graduations marked on it is held erect in the field of view of an observer looking through the telescope of an automatic (or tilting) level and the distance from the bottom of the rod to the cross-hair intercept is read and recorded. Separate readings are made with the rod resting on other objects. In this case, the difference of two direct readings provides an indirect determination of the relative heights of the two objects. Among others, the accuracy of such an indirect measurement is affected by 1) whether the line-of-sight is perpendicular to the plumb line, 2) the presence of parallax, 3) whether or not a vernier or parallel plate micrometer was used to refine the reading, 4) plumbness of the level rod when the readings were made, and 5) by the distance from the instrument to the rod (curvature & refraction correction).

EDM: An electronic distance measuring (EDM) instrument emits electro-magnetic radiation which is modulated with a known frequency (giving a known wavelength). The signal is returned by a retro-reflector from the forepoint end of a line and the phase of the returned waveform is electronically compared to that of the transmitted signal. The measurement of phase differences on several modulated frequencies provides information used to compute the distance between the EDM and a reflector. Other quantities such as temperature and barometric pressure are also observed to determine corrections which account for the signal traveling through the atmosphere between the standpoint and forepoint at some speed slower than it would have traveled through a vacuum. The point is that several physical quantities are observed and that the physical environment is modeled with equations before a collection of observations can be converted into spatial data.

With later generation pulse laser instruments, the physical distance between EDM and object is determined using the time interval required for a pulse to travel from EDM to object and back. Of course, atmospheric delay must be modeled and direction to the target must be known before a slope distance can be resolved into rectangular components.

Angles: Although not a fundamental physical quantity, angles are commonly measured and used in computing spatial data components. Two examples are 1) using a vertical angle to resolve a slope distance into horizontal and vertical rectangular components and 2) using the bearing or azimuth of a line to find the latitudes and departures of a traverse course. Looking beyond the obvious where an angle is measured directly with a protractor on paper or on the ground using a total station surveying instrument, angles are also measured indirectly as the difference of two directions such as might be observed with a compass or a gyroscope. Whether an angle was measured in the horizontal, vertical, or some other plane is also an important consideration, especially when using angles to resolve the hypotenuse of a triangle into its rectangular components. Two examples are resolving slope distances into horizontal/vertical and traverse courses into latitudes/departures.

GPS: The global positioning system (GPS) is very versatile in that several kinds of fundamental observations can be used to determine spatial data quantities. An oversimplified view of GPS measurement includes three concepts; 1) distance is the product of rate and a time interval obtained from code phase observations, 2) the Doppler shift of a frequency recorded on the ground as compared to the frequency transmitted by a satellite, and 3) interferometric interaction of the carrier phase signal as recorded simultaneously at two different antennas (carrier phase observations). Without going into detail, the point is that code phase GPS equipment routinely determines absolute geocentric ECEF coordinates and typically converts them to absolute geodetic coordinates before displaying them. On the other hand, GPS carrier phase data collected at two points simultaneously can be processed to give a very precise 3-dimensional space vector between antennas in terms of relative geocentric coordinate differences. The relative accuracy of such GPS observed vectors (with operator care and diligence) routinely exceeds one part in a million. If such a vector is attached to a known control point, a precise 3-D position of the second point can be easily computed. Admittedly, the distinction between absolute positions based on code phase data and relative position based on carrier phase observations is blurred by factors such as differential corrections for code phase data and radio connections between real-time-kinematic carrier phase receivers. In either case, once a GPS position is determined, answers can be viewed in a coordinate system of the users choice.

Photogrammetric mapping: Relative spatial data, both local and geocentric, can be determined efficiently and precisely using geometrical relationships reconstructed from stereoscopic photographs of a common image. A photogrammetric measurement is the relative location of an identifiable feature on a photographic plate with respect to fiducial marks on the same plate as determined with a comparator. A more complex measurement of 3-D spatial relationships based upon principles of photogrammetry requires mechanical reconstruction of the stereoscopic image by achieving the proper relative and absolute orientation of the stereo photographs in a mechanical stereo plotter. A 3-D contour map of the ground surface is the end result of the plotting operation. That traditional photogrammetric mapping process has been computerized and automated and now comes under the banner of softcopy photogrammetry. The end result of the modern computerized process is a 3-D digital model of the terrain. Hardcopy maps, computer displays, and other products, both digital and analog, are made from a common digital spatial data file.

Remote Sensing: ASPRS (1984) describes remote sensing as the process of gathering information about an object without touching or disturbing it. Photogrammetry is an example of remote sensing and ray tracing based upon stereo photographs of a common image is very geometrical. Bethel (1995) also discusses remote sensing and describes interpretative (less metrical) applications of remote sensing which include use of non-visible portions of the electro-magnetic spectrum to record the response of an object or organism to stimuli from a distant source. Sensors include infrared film, digital cameras, radar, satellite imagery, etc and information is stored pixel by pixel in a raster format. Determining the unique spatial location represented by each pixel is a daunting challenge and requires enormous storage capacity.

Other measurement methods are also used to create spatial data. But, regardless of the technology used to measure fundamental physical quantities, the GSDM provides a common universal foundation for expressing fundamental spatial relationships. Various equations (models) are used to convert observations into spatial data components which are then used as measurements[2] in subsequent operations, e.g. traverse computations, network adjustments, making maps etc. The GSDM also accommodates fundamental error propagation in all cases and that information is stored in the covariance matrix for each point.

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[2] Measurements and observations are often taken to be synonymous but a distinction to be made later is that observations are statistically independent while measurements may be correlated.

ERRORLESS SPATIAL DATA MUST ALSO BE ACCOMMODATED:

Several cases exist in which spatial data are considered errorless. Examples include; 1) spatial data created during the design process, 2) physical dimensions (such as the width of a street right-of-way) defined by ordinance or statute, and 3) spatial data whose standard deviations are small enough to be judged insignificant for a given application. In the case of a proposed development such as a highway, bridge, skyscraper, or other civil works project, the planned location of a feature and the numbers representing each feature's size and shape qualify as spatial data. But, they are the result of a design decision instead of a measurement process. Such design dimensions are without error until they are laid out. After being laid out and constructed, the location of the feature or object is determined by measurement and typically recorded on as-built drawings or in project files. Considered that way, the perfection of a design dimension is transitory and ceases to exist when laid out during construction.

An exception to the transitory nature of an errorless design dimension exists when a dimension is established by ordinance or statute. Such a dimension may be fixed by law, but the physical realization of that dimension is still subject to the procedures and quality of measurements used to establish it. Under ideal conditions there will be no conflict between a statutory dimension and its subsequent remeasurement if the lay-out process was more accurate/reliable than the measurements made to document its location. For example, a 100 foot right-of-way may have been monumented very carefully and current measurements between the monuments are all 100.00 feet, plus/minus 0.005 feet. In that case, the right-of-way width can be shown as 100.00 feet, measured and recorded. Under less-than-ideal conditions, several possible dilemmas are:

1. The right-of-way monuments really are separated by 100.00 feet, but the survey is based upon a state plane coordinate grid and the measured grid distance is 99.97 feet, plus/minus 0.005 feet (possible at elevations over 4,200 feet). Understandably, the monuments are not to be moved so they are separated by a grid distance of 100.00 feet, but some users may be confused

by the implication that a foot is not really a foot. The apparent discrepancy arises from the use of two different definitions for horizontal distance, local tangent plane distance or grid distance (Burkholder 1991).

2. The right-of-way monuments appear stable and undisturbed but the measurement between them is consistently 99.96 feet, plus/minus 0.005 foot (it could happen if the monument locations were staked during cold weather and no temperature corrections were applied to the steel tape measurements at the time). The conflicting principles are that the statutory dimension (of 100.00 feet) must be honored and that the original undisturbed monument controls, even if originally located with faulty measurements.

The intent here is not to solve those problems, but to acknowledge the potential for conflicting principles when working with so-called errorless spatial data. Other authors have written entire text books devoted to survey law, evaluation of evidence, and analysis of survey measurements. The point here is that the GSDM offers a consistent standard environment in which to make comparisons between conflicting data. The GSDM does not distort horizontal distances as does use of map projections and/or state plane coordinates.

When the coordinates of any point are held "fixed," the result is the same as assuming the standard deviations associated with the coordinates are very small or are zero. In many cases, such an assumption is reasonable and defensible because the point's standard deviations are small enough to be insignificant and the implied statement "with respect to existing control" is acceptable. However, each spatial data user making decisions about which control points are held "fixed" should document such decisions specifically so that subsequent users may always know, "with respect to what." With the accuracy of spatial data becoming ever more important, criteria for judging the quality of spatial data should be unambiguous and easy to understand. The stochastic model portion of the GSDM uses 3-D standard deviations to describe the accuracy of spatial data and accommodates errorless spatial data as those data having zero standard deviations (Burkholder, 1999).

PRIMARY SPATIAL DATA ARE BASED UPON MEASUREMENTS AND ERRORLESS QUANTITIES:

Earlier, spatial data were defined as distances. Spatial data types were also listed as distances represented by coordinates or coordinate differences in one of several coordinate systems. And, it should be understood that spatial data in one coordinate system can generally be transformed into spatial data in another coordinate system without loss of geometrical integrity (especially if done using coordinate differences). With that said, primary spatial data are defined as geocentric X/Y/Z coordinates, their associated covariance matrices, and point-pair correlation matrices. Primary spatial data are created by a specific measurement process or determined on the basis of some prescribed geometry. Measurements have standard deviations and covariances associated with them while errorless quantities have zero standard deviations. The GSDM accommodates both measurements and errorless quantities by using standard deviations of all three components at each point, covariances between components, and correlations between points.

Mikhail (1976) describes how measurement and observation are very similar and, in fact, used interchangeably. A mathematical distinction made here is that observations are independent while measurements may be correlated. Stated differently, an observation (whether it is the process or the numerical outcome) is taken to be the actual comparison of some quantity with a standard while a measurement is taken to be either the same as an observation or as a subsequently computed quantity after corrections are applied as dictated by observation conditions. For example, a horizontal distance is said to be measured by an EDM. Actually, an EDM uses 1) the observed phase difference of two electro-magnetic signals on several frequencies (the transmitted/received signal and an internal reference signal), 2) the estimation (observation) of air temperature and barometric pressure for the atmospheric correction, and 3) measurement[3] of the vertical (or zenith) angle.

[3] Each individual face-left/face-right reading on the vertical circle is an observation, but the computed mean is a measurement which, in subsequent computations, is often used as an independent observation.

These observations are used to compute the horizontal distance which is called a measurement when, in fact, physical quantities other than length were observed. Also note, the same observations are used to compute the vertical component of the slope distance. If one of the observations is changed, it may affect both computed values. Hence, the horizontal and vertical measurements are correlated and not independent. Slope distance and zenith directions are the independent observations.

Having made a distinction between observations and measurements, several other points also need to be made:

- In the strictest sense, primary spatial data should include only errorless quantities and independent observations. However, given the multitude of sensors used to make observations and the number of steps often needed to convert observations into spatial data components (measurements), it would be onerous indeed for each spatial data user to assume responsibility for the integrity of his/her data all the way back to the observation. It is hereby suggested the GSDM will conveniently serve two distinct groups: those responsible for generating quality spatial data and those who use spatial data. The work of scientists, physicists, electrical engineers, and programmers may be completed upon delivering a measurement system which can be used to generate quality spatial data. On the other hand, cartographers, geographers, planners, and others who use spatial data can be less concerned with the science of measurement **given they can rely on quality spatial data provided by others.** The geomatician (geodesist, surveying engineer, photogrammetrist, etc) provides a valuable service to society by serving both groups and the GSDM provides a common standard medium for exchange of ideas and data.

- All primary spatial data have covariance matrices associated with them. In the case of errorless quantities, the covariance matrix is filled with zeros. Otherwise, the covariance matrices are obtained by formal error propagation from basic observations through a competent network adjustment.

- Computation of measurements often results in correlation between computed spatial data components. That correlation is defined and determined by the error propagation computation procedure applied to independent observations and the mathematical equations used to obtain the spatial data components. For that reason, it is necessary to store the full (3x3 symmetric) covariance matrix along with the X/Y/Z coordinates of each point.

- As used here, errorless quantities and unadjusted measurements are the basis of primary spatial data. But, in reality, primary spatial data are the X/Y/Z coordinates and associated covariance values stored following rigorous network adjustments and successful application of appropriate quality control measures.

A statement of the obvious is that primary spatial data having small standard deviations are more valuable than primary spatial data with large standard deviations. Whether a standard deviation is large or small is dependent upon the measurements made and the correct propagation of the measurement errors to the spatial data components. The GSDM handles 3-D spatial data the same way, component by component, regardless of the magnitude of the standard deviations and each user has the option of deciding what level of uncertainty is acceptable for a given application. Additionally, the GSDM is strictly 3-dimensional and makes no mathematical distinction between horizontal and vertical data. But, the GSDM readily provides local $\Delta e/\Delta n/\Delta u$ components which can be used locally as flat-earth distances.

DERIVED SPATIAL DATA ARE COMPUTED FROM PRIMARY SPATIAL DATA:

Spatial data which owe their existence to mathematical manipulation of existing primary spatial data are considered to be derived spatial data. Derived spatial data include geodetic coordinates, UTM coordinates, state plane coordinates, project datum coordinates, and coordinates in other mathematically defined systems. Derived spatial data also includes inversed bearings and distances (as shown on survey plats and subdivision maps), areas, volumes, and elevations. In each case, the accuracy of each derived quantity is computed from the standard deviations (and covariances) of the underlying primary spatial data on which they are based.

A clear distinction between primary spatial data and derived spatial data is critical to efficient collection, storage, management, and use of spatial data. Primary spatial data require measurement of physical quantities and computation of spatial data components according to very specific procedures. For example, taping corrections are needed to determine a precise horizontal distance measured with a steel tape and an EDM measurement needs to be corrected for reflector offset, atmospheric conditions, and slope if the endpoints are at different elevations. The cost of acquiring primary spatial data is still prohibitive in some cases but, due to automation, computerization, and other technical developments, i.e. GPS, spatial data are much less expensive to obtain now than in the past. Even so, by comparison, derived spatial data are generally much less expensive than primary spatial data. Derived data can be computed, used and discarded without detrimental economic consequence. Other than the effort required to assemble the needed primary spatial data and to make the computations, derived spatial data can be generated as often as needed based upon a prescribed algorithm. The challenge is to archive primary spatial data efficiently and to make sure other users know specifically what algorithms were used in generating the derived quantities. The practice of storing derived spatial data is potentially wasteful.

ESTABLISHING AND PRESERVING THE VALUE OF SPATIAL DATA:

Establishing the value and integrity of spatial data is not a trivial undertaking. An oversimplified statement is that the right measurement needs to be made with the correct equipment under well documented conditions and appropriate equations must be used to compute primary spatial data components. Once the components are run through an appropriate least squares network adjustment, they are attached to the chosen 3-D datum and the resulting geocentric X/Y/Z coordinates (and covariances) become the primary spatial data. A thorough treatise on the science of measurement and subsequent computation of spatial data components could fill an entire book. The goal in this paper was to establish a connection between our measurements and spatial data components with the idea of showing how both can be handled more efficiently in the context of the GSDM. But, in addition to the points made in this article about measurements and computations, another question also needs to be asked, "What makes spatial data lose their value?" Often, attention is focused on doing whatever is necessary to get the most data for the least cost; but, avoiding the cost of replacement or the inconvenience of not having desired data also needs to be considered. Therefore, efforts made to preserve the value of spatial data may be efforts well spent. Although less directly, the GSDM also facilitates those efforts by providing a simple standard model which can be used world-wide by all spatial data disciplines and users.

Specifically, spatial data lose their value if:

- Potential users do not know they exist or that they are available.
- They are incomplete, incompatible, or of dubious quality.
- They are in the wrong format or stored in the wrong location.
- A user does not know what to do with them.
- They are replaced by data having smaller standard deviations.

IN CONCLUSION:

This paper:

- Defines spatial data as the distance between points of a line.
- Describes three coordinate systems used to reference spatial data.
- Lists spatial data types as coordinates and coordinate differences.
- Acknowledges that spatial data visualization is highly advanced.
- Admits that spatial data created by measurements contain uncertainties.
- Gives examples of non-trivial spatial data measurements.
- Describes the role of errorless spatial data.
- Defines primary spatial data and derived spatial data.
- Suggests ways to preserve the value of spatial data.

Appendix I - Notation

The following symbols were used in this paper:

$X/Y/Z$	= Geocentric earth-centered earth-fixed (ECEF) coordinates
$\Delta X/\Delta Y/\Delta Z$	= Geocentric ECEF coordinate differences
$\phi/\lambda/h$	= Geodetic coordinates
$\Delta\phi/\Delta\lambda/\Delta h$	= Geodetic coordinate differences
$e/n/u$	= Local rectangular coordinates
$\Delta e/\Delta n/\Delta u$	= Local rectangular coordinate differences

References

ASPRS, 1984; "Multilingual Dictionary of Remote Sensing and Photogrammetry," American Society Photogrammetry & Remote Sensing, Bethesda, Maryland.

Bethel, J.S., 1995; Surveying Engineering, Chapter 53, "Photogrammetry and Remote Sensing," *The Civil Engineering Handbook*; CRC Press, Boca Raton, Fl.

Burkholder, E.F. 1991; "Computation of Level/Horizontal Distance," ASCE Journal of Surveying Engineering, Vol. 117, No. 3, August 1991.

Burkholder, E.F. 1997; "Definition of a Three-Dimensional Spatial Data Model for Southeastern Wisconsin," published by the Southeastern Wisconsin Planning Commission, Waukesha, Wisconsin.

Burkholder, E.F. 1998; "A Practical Global Spatial Data Model (GSDM) for the 21st Century," presented at the Institute of Navigation National Technical Meeting, Long Beach, California, January, 1998.

Burkholder, E.F. 1999; "Spatial Data Accuracy as Defined by the GSDM," ACSM Journal of Surveying & Land Information Systems, Vol. 59, No. 1, pp 26-30.

DMA 1991; "Department of Defense World Geodetic System 1984: Its Definition and Relationships with Local Geodetic Systems," Technical Report 8350.2, Defense Mapping Agency (now National Imagery and Mapping Agency), Fairfax, Virginia.

Mikhail, E. M. 1976; *Observations and Least Squares*, Harper & Row, NY, NY.

Nelson, R.A., 1999; "Guide for Metric Practice," Physics Today - 1999 Buyer's Guide, August, 1999, pp BG11-BG12.

Soler, T, and L. Hothem, 1988; "Coordinate Systems Used in Geodesy: Basic Definitions and Concepts," Journal of Surveying Engineering, Vol. 114, No. 2, pp 84-97.

Zilkoski, D., J. Richards, and G. Young, 1992; "Results of the General Adjustment of the North American Datum of 1988," Surveying & Land Information Systems, Vol 52, No. 3,pp 133-149.