The Global Spatial Data Model (GSDM): A New Paradigm for Spatial Information

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Key words:

Spatial data, functional model, stochastic model, digital revolution, earth-centered earth-fixed (ECEF), geodetic datums, spatial data accuracy, covariance, correlation, interoperability.

ABSTRACT:

Spatial data are 3-dimensional (3-D). Modern measurement systems collect data in 3-D. Computer data bases store digital 3-D spatial data. Human perception of spatial relationships is primarily visual and intuitively related to 2-D horizontal and 1-D vertical. Conventional methods of handling 3-D geospatial data are unnecessarily complex due to 1) the traditional separation of horizontal and vertical, 2) using mixed units (angular for latitude/longitude and length for vertical), and 3) using 2-dimensional map projections to ”flatten the earth.”

A universal 3-dimensional global spatial data model (GSDM) has been defined (Burkholder 1997c) which is based upon assumptions of 3-D measurements and digital data storage. It is equally applicable world-wide, offers a simple data exchange format which supports interoperability and seamless integration, and uses standard deviations to describe spatial data accuracy. The GSDM accommodates all modes of spatial data measurement, does not distort physical distances as does a map projection, uses one set of solid geometry equations, portrays an accurate view of spatial data from any perspective selected by the user, preserves computational and geometrical integrity by using coordinate differences, stores point location information in a BURKORD™ 3-D data base which optionally stores the positional covariance matrix of each point and, where the covariance matrix is stored, gives the 3-D standard deviation of each point with respect to the defined datum in the geocentric or local east/north/up reference frame. Rigorous statistics for network accuracy and local accuracy between points can also be obtained if correlations between points have been stored.

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1. INTRODUCTION

The digital revolution is a phrase used to describe a fundamental shift in the way spatial information is collected, handled, manipulated, stored, and used. In times past, a survey was conducted for a specific purpose and a map was often both the end product of the survey and the storage medium for spatial data. With the advent of computers, GPS, and other space age technology, a more common practice is to collect measurements, store them in an electronic file, manipulate the digital information with appropriate alogrithms (models), and generate maps, plans, charts, and diagrams from the data base. The map is no longer a primary storage medium (analog images on photographic plates are a possible exception).

With regard to using spatial data, "we are where we are because of where we came from." As new technology became available, existing manual processes were automated and productivity has multiplied many-fold as a result of using faster computers and vastly larger electronic storage capacity. Traditional practice treats horizontal (2-D) and vertical (1-D) data separately and such separate uses will certainly continue for the foreseeable future. But, the difference will be that 2-D and 1-D will be derived from an existing 3-D data base instead of combining 2-D and 1-D to build a 3-D data base. The new paradigm comes from looking at spatial data in the abstract, defining it concisely, listing spatial data types (Burkholder 2001), accommodating various measurement systems, and examining how the geometrical pieces are related. The practice of putting new wine into old bottles is questioned. The GSDM is a new bottle model which can enhance modern use of digital spatial data.

The crux of the issue is that 3-D geospatial data needs a single origin to be handled efficiently. In the past, horizontal has been defined as perpendicular to the plumb line and described in terms of latitude and longitude. Vertical is defined as parallel to the plumb line and elevation is intuitively described as distance from mean sea level. Human perception of geospatial data is still horizontal and vertical, but efforts to combine them into a rigorous 3-D computational environment are frustrated by continued use of disparate origins. Although enormous effort has been devoted to modeling the difference, there is no known concise geometrical relationship between the earth's center of mass and zero elevation. The approach here is to begin with a 3-D rectangular coordinate system whose origin is attached to the earth's center of mass and to derive other quantities. Orientation for the right-handed rectangular coordinate system is provided by aligning the Z axis with the earth's mean spin axis and postion is defined by a tripplet of metric geocentric X/Y/Z coordinates. The spatial accuracy of each position is defined by its covariance matrix. Everything else (latitude, longitude, height, map projection coordinates, inversed distances, directions, and volumes) is derived from the primary X/Y/Z values. The quality of each derived quantity is traceable to the primary coordinate values and their covariances. Time can be the fourth dimension.

2. FUNDAMENTAL CONCEPTS AND ASSUMPTIONS:

Fundamental issues include:

2.1 Science can be defined as the process of organizing knowledge in such a manner that inferences and conclusions are consistent with beginning assumptions and subsequent observations. The goal in this paper is to identify the beginning assumptions and to describe logical development of the global spatial data model as being consistent with modern practice and scientific/mathematical principles.

2.2 A spatial data primative (Burkholder 2001) is defined as the distance between endpoints of a line in Euclidean space. The line can be curved or straight (latitude and longitude coordinates are examples of curved lines). The endpoints of a line can be non-physical entities such as an origin, a coordinate axis, or a coordinate point. An endpoint can also be physically defined by a point such as the earth's center of mass, a survey monument, building corner, or any other uniquely defined location. Objects (planes, surfaces, solids) are formed by the aggregation of spatial data elements. Geospatial data are those referenced specifically to the physical earth. The definition of spatial data used here includes, but is not limited to, geospatial data. Effects of relativity are not considered.

2.3 The earth-centered earth-fixed (ECEF) geocentric rectangular (X/Y/Z) coordinate system as defined by the DMA (1991) is used as the primary standard for all geospatial data. It provides a single orgin for 3-D spatial data and the rules of solid geometry and vector algebra are universally applicable anywhere within the bird-cage of orbiting GPS satellites. Defining features of the ECEF system (a 3-D datum) include:

2.3.1 The origin is located at the earth's center of mass.
2.3.2 The Z axis is defined by the Conventional Terrestrial Pole (CTP).
2.3.3 X and Y are in plane of the equator, perpendicular to the Z axis.
2.3.4 The X axis is at zero longitude, nominally the Greenwich Meridian.
2.3.5 The Y axis is positioned at 90° east longitude according to the right-handed rule for rectangular coordinates.
2.3.6 A meter is the unit of length.

2.4 The defining components of a GPS base line vector (in terms of the ECEF system) are $\Delta X/\Delta Y/\Delta Z$. A network of points (either local, global, or both) is built using base line components, optionally accompanied by their respective covariance matrices. Spatial data generated by other means can be readily expressed in terms of $\Delta X/\Delta Y/\Delta Z$.

2.5 Differences between a reference frame, coordinate system, and a 3-D datum need more explanation than is provided here. For example, see Snay & Soler (1999, 2000a, 2000b, & 2000c). A formal definition for a 3-D geodetic datum is left to others. Notes are:

2.5.1 It has been documented that the earth's center of mass moves with respect to points on the crust. (Careful now – with respect to movement, are we standing at the station watching the train go by or riding in the train watching the station go by?) The

International Terrestrial Reference Frame (ITRF) is updated periodically to reflect the movement. Three-dimensional positions and station velocities are published for CORS stations in terms of both ITRF and NAD 83 reference frames (Snay et al 2001).

2.5.2 Subject to a formal concise definition of a 3-D geodetic datum, it appears the NAD83 is a 2-D datum which is often combined with NAVD88 elevations to obtain 3-D. The WGS 84 is all three, a 3-D datum, a coordinate system, and an ellipsoid?

2.5.3 Realization of a 3-D datum requires competent connection of points on the earth to the earth's center of mass via the ECEF coordinate system according to some named epoch and defined reference frame (Strange 2000).

2.5.4 Given the ECEF system is attached to a formal reference frame (NAD 83, ITRF, or other), the primary location of a point and the positional accuracy of same are given by the X/Y/Z coordinates and the associated covariance matrix. Correlations between points are optionally stored as well. Derived quantities on various datums include:

2.5.4.1 Latitude/longitude/height/elevation on the named datum.
2.5.4.2 State plane and/or UTM coordinates.
2.5.4.3 Local coordinate differences with respect to any user-selected Point of Beginning (P.O.B.).
2.5.4.4 Standard deviation of any computed quantity (if supported by stored covariances).
2.5.4.5 Local and network accuracy between points (if supported by stored correlations).

3. CONSTRUCTING THE GLOBAL SPATIAL DATA MODEL (GSDM):

As described in Burkholder (1998a), a model is chosen as a trade-off between simplicity and appropriateness. The goal is to use the simplest model which adequately accommodates physical reality. The flat-earth model is attractive for plane surveying, the spherical earth model has traditionally been used for geography and navigation, the ellipsoidal model, with all of its complexity, is needed for geodesy, and the map projection model has been used very beneficially in many disciplines to protray a curved earth on a flat surface. Although the map projection model can greatly simplify coordinate computation with points shown on the map, the serious defect is that a map projection is strictly a 2-dimensional model and spatial data are 3-D. A simple 3-D model is needed which preserves both geometrical integrity and mathematical rigor. The global spatial data model (GSDM) is simple because it uses rectangular coordinates along with proven rules of solid geometry and it is appropriate because it accommodates existing geometrical relationships without distorting physical measurements. Using the stated assumptions and putting the pieces together carefully, the GSDM was defined as having both a functional model (geometrical relationships) and a stochastic model (defining the positional uncertainty of each point). The BURKORD™ 3-D Diagram in Figure 1 shows how the various coordinate systems and spatial data types are related to each other. Equations for moving from one box to another can be found in Burkholder (1997b and 1998a). Use of the stochastic model is discussed in detail in Burkholder (1998b and 1999).

The BURKORD™ 3-D Diagram

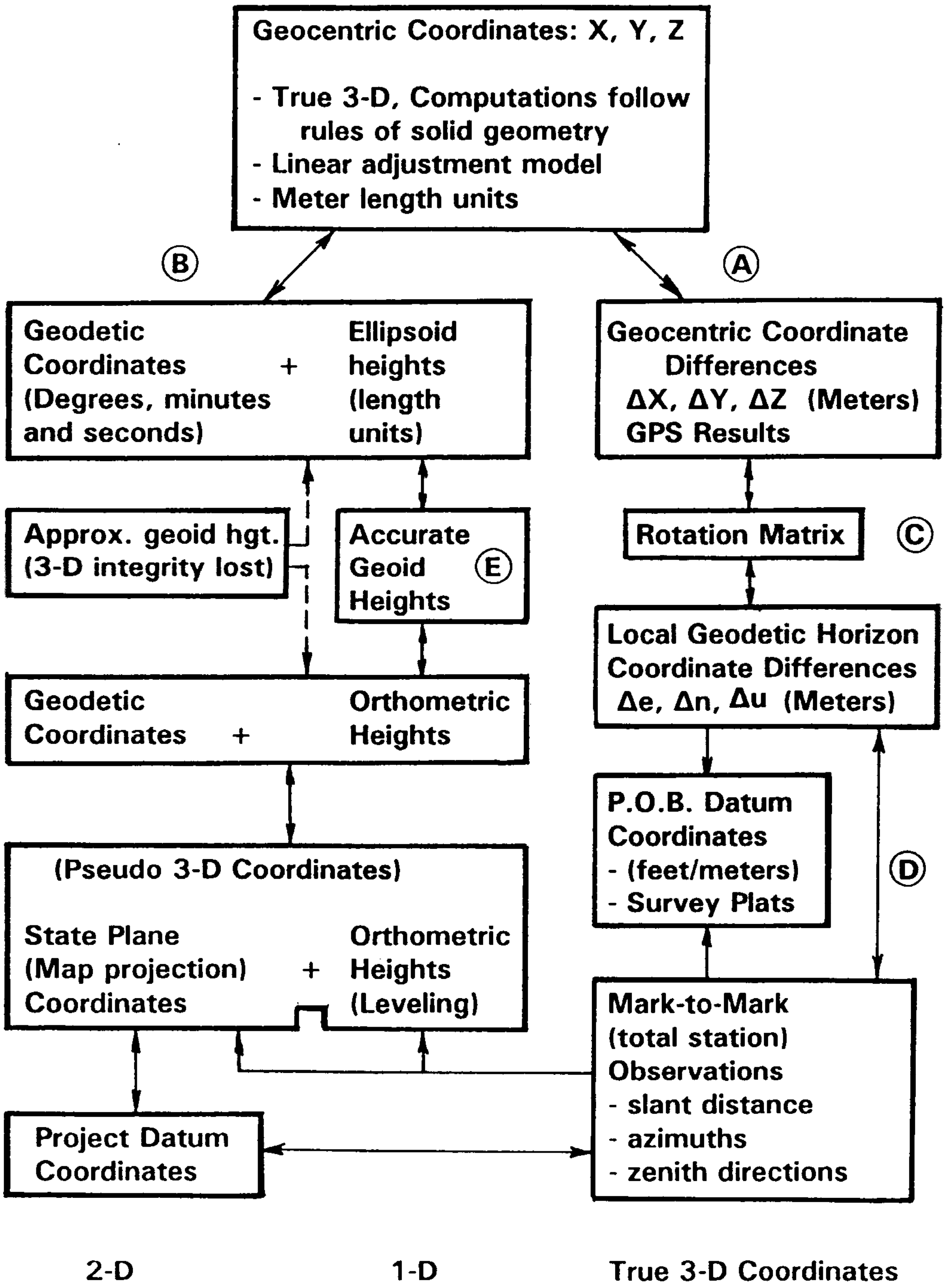

Figure 1 Diagram Showing Relationship of Coordinate Systems

3.1 Features of the Functional Model:

3.1.1 The geocentric X/Y/Z coordinates define the location of any point.

3.1.2 A vector defined by $\Delta X/\Delta Y/\Delta Z$ coordinate differences can also be viewed as local coordinate differences. A rotation matrix and its transpose provide bi-directional conversion between the two reference frames. The latitude and longitude of the standpoint must be specified (or computed from the geocentric X/Y/Z values).

3.1.3 The local coordinate differences are used as rectangular flat-earth components.

3.1.4 The latitude/longitude/height of any point is a derived quantity.

3.1.5 Two methods of computing elevation include:

3.1.5.1 The elevation of a point can be computed from ellipsoid and geoid heights.

3.1.5.2 The difference in elevation from one point to another can be computed by adding the curvature and refraction correction to the Δu component.

3.1.5.3 In either case, the quality of an elevation depends upon the quality of data used to compute it.

3.1.6 The local tangent plane distance is computed from Δe and Δn. This is the same as HD(1) in Burkholder (1991) and identical to plane surveying departures & latitudes.

3.1.7 The 3-D azimuth from standpoint to forepoint, although different, is almost identical to the geodetic azimuth and is computed as $\tan^{-1}(\Delta e/\Delta n)$, see Burkholder (1997d).

3.1.8 The local Δe and Δn components with respect to a user selected P.O.B. can be used as local tangent plane coordinates with the P.O.B. as the origin. Like plane surveying, the local azimuths are same as grid azimuths with respect to the true meridian through the P.O.B.

3.2 Features of the Stochastic Model:

The stochastic model associated with the GSDM is a formal application of standard error propagation procedures as described in two standard texts, Mikhail (1976) and Wolf/Ghilani (1997). Burkholder (1998b) is a general article about positional tolerance and the GSDM while Burkholder (1999) is a rigorous, detailed discussion which includes a mathematical definition for local accuracy and network accuracy. Specific features include:

3.2.1 The geocentric covariance matrix (3x3 symmetrical – 6 unique values) is stored with each point.

3.2.2 The standard deviation of each local component ($\Delta e/\Delta n/\Delta u$) or the entire point covariance matrix can be input as appropriate. Or, geocentric values can be input.

3.2.3 Although the geocentric covariance matrix is the only one stored, the local covariance matrix of a point is computed upon demand using equation (5) of Burkholder (1999).

3.2.4 A BURKORD™ data base optionally stores correlation between points. That information is used in equation (9) of Burkholder (1999) to obtain local accuracy. If point correlations are zero, the same equation (9) is used to obtain network accuracy.

3.2.5 The standard deviation of derived quantities is computed using standard error propagation procedures. An example inverse between points (direction and distance) with standard deviations follows.

4. EXAMPLE USING POINTS ON/NEAR NMSU CAMPUS:

A BURKORD™ computer printout on the following pages shows (a more detailed example is posted at www.zianet.com/globalcogo/example.html):

4.1 Headings and administrative information.
4.2 Defining input for 2 A-order stations, ”Reilly” on campus and ”Crucesair” at the airport.
4.3 3-D geocentric coordinate difference traverse (GPS base line) to two other points.
4.4 A listing of the 4 points as stored in the data base; 1 line per point. Note, format is point number, X/Y/Z coordinates, covariance values, and point name/description.
4.5 Expanded listing for point 1001 showing both geocentric and local corvariance matrices.
4.6 Computed inverses between stated points which show in sequence:
4.6.1 Standpoint geocentric coordinates, latitude/longitude/height, and local standard deviations.
4.6.2 The computed $\Delta X/\Delta Y/\Delta Z$ components along with their standard deviations.
4.6.3 The computed $\Delta e/\Delta n/\Delta u$ components along with their standard deviations.
4.6.4 The local tangent plane distance and azimuth along with their standard deviations.
4.6.5 Forepoint geocentric coordinates, latitude/longitude/height, and local standard deviations.
4.7 A listing of local tangent plane coordinate differences with respect to a user-selected P.O.B.

5. IMPLEMENTATION:

Using the GSDM is a matter of deciding to do so. The equations and procedures are all public domain. The phrase ”global spatial data model” is generic and can be freely used. The term ”BURKORD” has been trademarked and applies to 1) prototype software written by the author for performing 3-D coordinate geometry and error propagation computations and 2) design of a 3-D data base for storing geocentric X/Y/Z coordinates and associated covariances and correlations.

Geocentric X/Y/Z coordinates and related statistics for numerous control points and surveyed points around the world are published by various agencies. Spatial data users (both public and private) in various disciplines around the world already use the geometrical and mathematical relationships described herein. A statement of the obvious is that coordinates in one reference frame should not be mixed with those of another (unless the uncertainty of one or both covers the position of the other – then it doesn’t matter?).

Several points with regard to implementation and use of the GSDM are:

5.1 The GSDM offers a concise set of rules and procedures for realizing the reference frames defined and provided by the scientific community. Transfering data from one reference frame to another is beyond the scope of this paper but can be performed using HTDP program described by Snay (1999).

5.2 It is intended for interoperability between disciplines to be enhanced by using the GSDM. The same model can be used by all spatial data users from high-level scientists who work with the ITRF and take full advantage of the stochastic portion of the GSDM (on one extreme) to "flat-earth" end users whose primary concern is local rectangular directions and distances (on the other extreme). The GSDM covers it all without sacrificing simplicity or geometrical integrity.

5.3 The goal in developing the GSDM was to equip spatial data users with simple tools and procedures which enables them to confidently and efficiently handle large quantities of spatial data. A further goal is to provide for unambiguous assessment of spatial data accuracy.

5.4 The scientific community needs to discuss and publish a formal definition of a 3-D geodetic datum. Such a definition should also include a stochastic component and be very specific with regard to datum, local, and network accuracies. Ideally the GSDM already covers such features.

5.5 The issue of elevation needs further discussion and will be the subject of a future paper.

5.6 Plotting orthophoto maps is greatly simplied using the GSDM. With the location of each pixel identified by ECEF X/Y/Z coordinates, an orthophoto is generated as the plot (Δe & Δn) of any point in the data base with respect to the P.O.B. selected by the user. Each separate sheet/map will have its own P.O.B. The challenge is developing the X/Y/Z of each pixel. According to some researchers, that challenge has already been met.

5.7 Further research is needed to show how local plane surveying and construction layout is easily accomplished using the GSDM. The GPS vendors (and many surveyors) are already doing it with RTK procedures and with GPS mounted on excavation equipment?

5.8 The National Map Project is one which deserves careful planning and consideration. To what extent should it utilize the GSDM as a new bottle model? According to Gibbons (1997) we should be "looking forward" and avoiding the practice of retrofitting new technology to outdated models. See http://nationalmap.usgs.gov.

5.9 The NASA Digital Earth Initiative is another effort which could benefit enormously from using the GSDM? See www.digitalearth.gov and http://digitalearth.gsfc.nasa.gov. Another day, another discussion…….

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 BURKORD(TM) COMPUTES 3-D COORDINATE GEOMETRY POSITIONS FOR SPATIAL
 DATA UTILIZING GPS VECTORS, LOCAL COORDINATE DIFFERENCES AND
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 USER:   Earl F. Burkholder
 DATE:   January 2, 2002
 PROGRAM:        BURKORD(TM) - VERSION 8G.01, MAY 1999    S/N 8G599001
 DATA FILE:      FIGPAPER.DAT
 OUTPUT FILE:    FIGPAPER.OUT

 CLIENT/AGENCY:  FIG Conference - Washington D.C. April 2002
 JOB/PROJECT:    3-D Example Using Points on/near NMSU Campus

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
 DEFINE X/Y/Z   1001  -1556177.6150 M  -5169235.3190 M   3387551.7090 M  Reilly HARN "A"
   COVAR MATRIX E/N/U/EN/EU/NU  .25E-04  .25E-04  .25E-04  .00E+00  .00E+00  .00E+00 METERS SQD

 DEFINE X/Y/Z   1002  -1571430.6720 M  -5164782.3120 M   3387603.1880 M  Crucesair "A"
   COVAR MATRIX X/Y/Z/XY/XZ/YZ  .25E-04  .25E-04  .25E-04  .00E+00  .00E+00  .00E+00 METERS SQD

 FORWARD BY 3-D DX/DY/DZ  1001 TO  1003     -32.1330    -51.1750    -94.1980  Bromilow
   COVAR MATRIX DX/DY/DZ/DXY/DXZ/DYZ   .10E-05  .40E-05  .10E-05  .00E+00  .00E+00  .00E+00  METERS SQD

 FORWARD BY 3-D DX/DY/DZ  1001 TO  1004    -337.8590    179.1660    104.9890  Wakeman
   COVAR MATRIX DX/DY/DZ/DXY/DXZ/DYZ   .10E-05  .10E-05  .10E-05  .00E+00  .00E+00  .00E+00  METERS SQD

A LISTING OF POINTS IN ACTIVE PROJECT IS:

  1001 -1556177.6150 -5169235.3190  3387551.7090 .000025 .000025 .000025 .000000 .000000 .000000 Reilly HARN "A"
  1002 -1571430.6720 -5164782.3120  3387603.1880 .000025 .000025 .000025 .000000 .000000 .000000 Crucesair "A"
  1003 -1556209.7480 -5169286.4940  3387457.5110 .000026 .000029 .000026 .000000 .000000 .000000 Bromilow
  1004 -1556515.4740 -5169056.1530  3387656.6980 .000026 .000026 .000026 .000000 .000000 .000000 Wakeman
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AN EXPANDED LISTING OF POINT  1001
1001     Reilly HARN "A"                              X         Y         Z          E         N         U
 LAT (N+S-)   32 16 55.929040 X: -1556177.6150  X  .25E-04                     E  .25E-04
 LON (E+W-) -106 45 15.160703 Y: -5169235.3190  Y  .00E+00  .25E-04           N  .00E+00  .25E-04
 EL HGT          1166.5703 M Z:  3387551.7090  Z  .00E+00  .00E+00  .25E-04  U  .00E+00  .00E+00  .25E-04

INVERSE BETWEEN POINTS

1001     Reilly HARN "A"
 X = -1556177.6150  LAT (N+S-)   32 16 55.929040    +/-  .0050 METERS    N
 Y = -5169235.3190  LON (E+W-) -106 45 15.160703    +/-  .0050 METERS    E   STANDARD DEVIATIONS
 Z =  3387551.7090  EL HGT          1166.5703 M    +/-  .0050 METERS    U

  DELTA X/Y/Z WITH SIGMAS    -337.8590M +/-  .007M    179.1660M +/-  .007M    104.9890M +/-  .007M
  DELTA E/N/U WITH SIGMAS    -375.1645M +/-  .007M    128.3724M +/-  .007M     -6.6293M +/-  .007M
  LOCAL PLANE INV: DIST =     396.5197M +/-  .007M  N AZI. = 288 53 23.04 +/-   3.7 SEC

1004     Wakeman
 X = -1556515.4740  LAT (N+S-)   32 17   .095547    +/-  .0051 METERS    N
 Y = -5169056.1530  LON (E+W-) -106 45 29.495387    +/-  .0051 METERS    E   STANDARD DEVIATIONS
 Z =  3387656.6980  EL HGT          1159.9533 M    +/-  .0051 METERS    U

  DELTA X/Y/Z WITH SIGMAS     305.7260M +/-  .007M   -230.3410M +/-  .007M   -199.1870M +/-  .007M
  DELTA E/N/U WITH SIGMAS     359.1568M +/-  .007M   -239.1158M +/-  .007M      5.5524M +/-  .007M
  LOCAL PLANE INV: DIST =     431.4742M +/-  .007M  N AZI. = 123 39 16.14 +/-   3.5 SEC

1003     Bromilow
 X = -1556209.7480  LAT (N+S-)   32 16 52.334086    +/-  .0052 METERS    N
 Y = -5169286.4940  LON (E+W-) -106 45 15.772679    +/-  .0051 METERS    E   STANDARD DEVIATIONS
 Z =  3387457.5110  EL HGT          1165.5203 M    +/-  .0053 METERS    U


LISTING OF POINTS WITH RESPECT TO MASTER P.O.B:          1001  Reilly HARN "A"
 (ASSUMING POSITION OF P.O.B. IS ERRORLESS)
   NUMBER      NORTH  SIGMA     EAST  SIGMA        UP  SIGMA    STATION
    1002    -27.496  .005 -15889.221  .005   139.911  .005    Crucesair "A"
    1003   -110.757  .005    -16.017  .005    -1.051  .005    Bromilow
    1004    128.372  .005   -375.165  .005    -6.629  .005    Wakeman
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BIOGRAPHICAL NOTES:

Earl F. Burkholder teaches in the surveying engineering department at New Mexico State University, Las Cruces, New Mexico. After teaching surveying at Oregon’s Institute of Technology from 1980 to 1993, he was self-employed for 5 years before joining the faculty at NMSU in August, 1998. During 1990/91 he was on sabbatical and spent most of the year at the University of Maine learning more about applications of new technology to modern surveying practice. Concepts of the GSDM grew out of that sabbatical experience and were subsequently formalized during the mid 1990’s while he was self-employed. He is writing a book on the GSDM.