Datums, Map Projections, and Coordinate Systems

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Professional Land Surveyors of Colorado
Arvada Center for the Arts & Humanities
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Presenter: Earl F. Burkholder, PS, PE, F.ASCE

- Served as NMPS President 2009.
- Retired from NMSU Surveying faculty in July 2010.
- Involved in ABET Accreditation 1981 to recent.
- Wrote book, The 3-D Global Spatial Data Model (GSDM).
- Is currently Past Chair – ASCE Geomatics Division EXCOM.
- Current focus is considerations of Spatial Data Accuracy.
- Promotes use of 3-D COGO and error propagation software.
- Map Projections was topic of Grad School Thesis.
- Is currently preparing Second Edition of book on 3-D.

4 hr. session is broken into two parts:

- **Datums, Map Projections, and Coordinate Systems**
  - Introduction & Conceptual view of Spatial Data
  - Plane and Solid Geometry relationships
  - Map Projections - Making a 2-D map of a 3-D world
  - Coordinate systems (Questions?)
- **Low Distortion Projections – Design/Application/Comps.**
  - Cartography, making maps and portraying the world.
  - Defining a Map Projection
  - Design considerations
  - Computing projection parameters
  - Using a Low Distortion Projection (LDP) (Questions?)

Surveying & Mapping includes:

- **Making measurements of physical features: lines, distances.**
- **Using written/graphic descriptions of land ownership.**
- **Reconciling measurements with the record. This is HUGE!**
- **Performing services for and providing products to clients.**
- **Although "land" surveying is critical, focus here is technical.**

Spatial data are used to make maps and to describe ownership:

- **Geometrical pieces: distances, angles, orientation, units.**
- **What is difference between horizontal and vertical? (3-D?)**
- **All measurements are "with respect to something."**
- **Distances are between points – monuments.**
- **Coordinates define absolute position relative to a P.O.B.**

What is difference between absolute and relative?

- Absolute is defined as with respect to an origin.
- Relative is with respect to a nearby point/object/feature.
- Relative is difference between two points in same system.
- A DATUM is a predefined "system" which provides context.
- Commonly recognized datums include:
  - Horizontal: NAD 83, NAD 83(xx), NAD27. These are 2-D!
  - Vertical: NAVD88, NGVD29, Sea-level. These are 1-D!
- What is a 3-D datum? 4-D anyone?
  - WGS84 is defined by DoD, NAD83 is defined by NGS.
  - ITRF is defined by the international scientific community.
- In many cases, ITRF & WGS84 can be used interchangeably.

Horizontal Datums:

- NAD 27 – Clarke ellipsoid, origin at Meade's Ranch, foot units
- NAD 83 – GRS 1980 ellipsoid, origin at center of Earth, meters.
- Used extensively for mapping and 2-D surveys

Vertical Datums (Origin is best-fitting equipotential surface):

- Sea Level Datum of 1929 – name change for NGVD 29.
- NAVD 88 origin is 1 arbitrary point – serves US and Canada.

3-D Datums (Origin is earth's center of mass):

- NAD 83 is 3-D datum with horizontal & vertical components.
- WGS 84 is 3-D datum established/used by U.S. DoD & GPS
- ITRF is 3-D datum defined by scientific community.

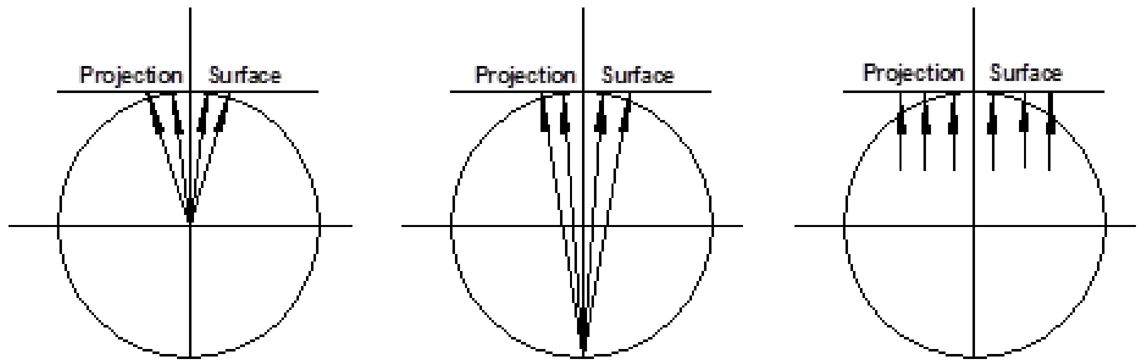
More context for users of spatial data:

- We live in a 3-D world & make 3-D measurements.
- Plane geometry involves easting and northing coordinates.
- For flat-earth view, what is the best label for "up"?
- Horizontal & vertical handled separately – why?
- Maps/plats/drawings show 2-D – or plan/profile.
- Contour lines show elevation. Can you visualize 3-D?
- Using new technology; flat-earth view is too limiting!
- Need a way to preserve 3-D data on a 2-D map.
- Map projections are used to "flatten the earth."

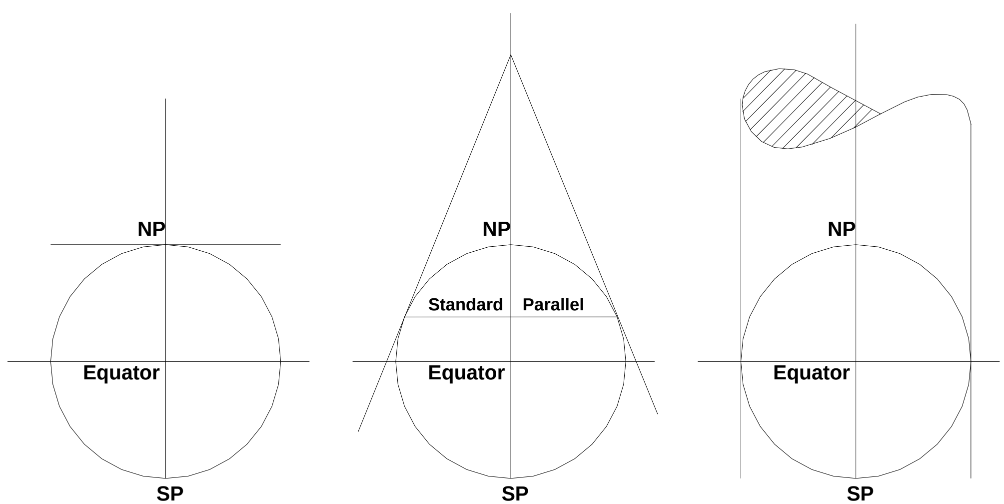
http://www.globalcogo.com/CR002.pdf

Local coordinates - many spatial data users.

- **Portrays relative relationships.**
- **x & y or north & east flat-earth values**
- **Is origin well defined and monumented?**
- **Elevation is ‘up’**
- **Vertical origin is geoid – approximated by mean sea level.**



(a) Gnomonic (b) Stereographic (c) Orthographic



(a) Tangent Plane (b) Lambert Conic Conformal (c) Mercator

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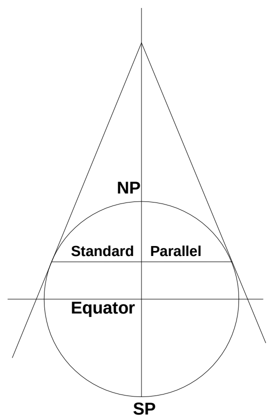
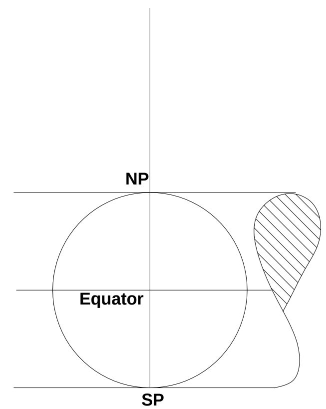
Datums, Map Projections, Coordinate Systems - Burkholder

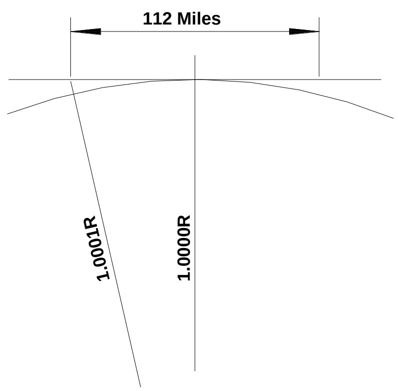
Specifically, for state plane coordinate systems:



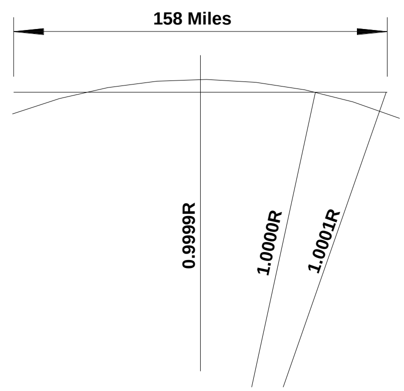
Lambert Conic Conformal



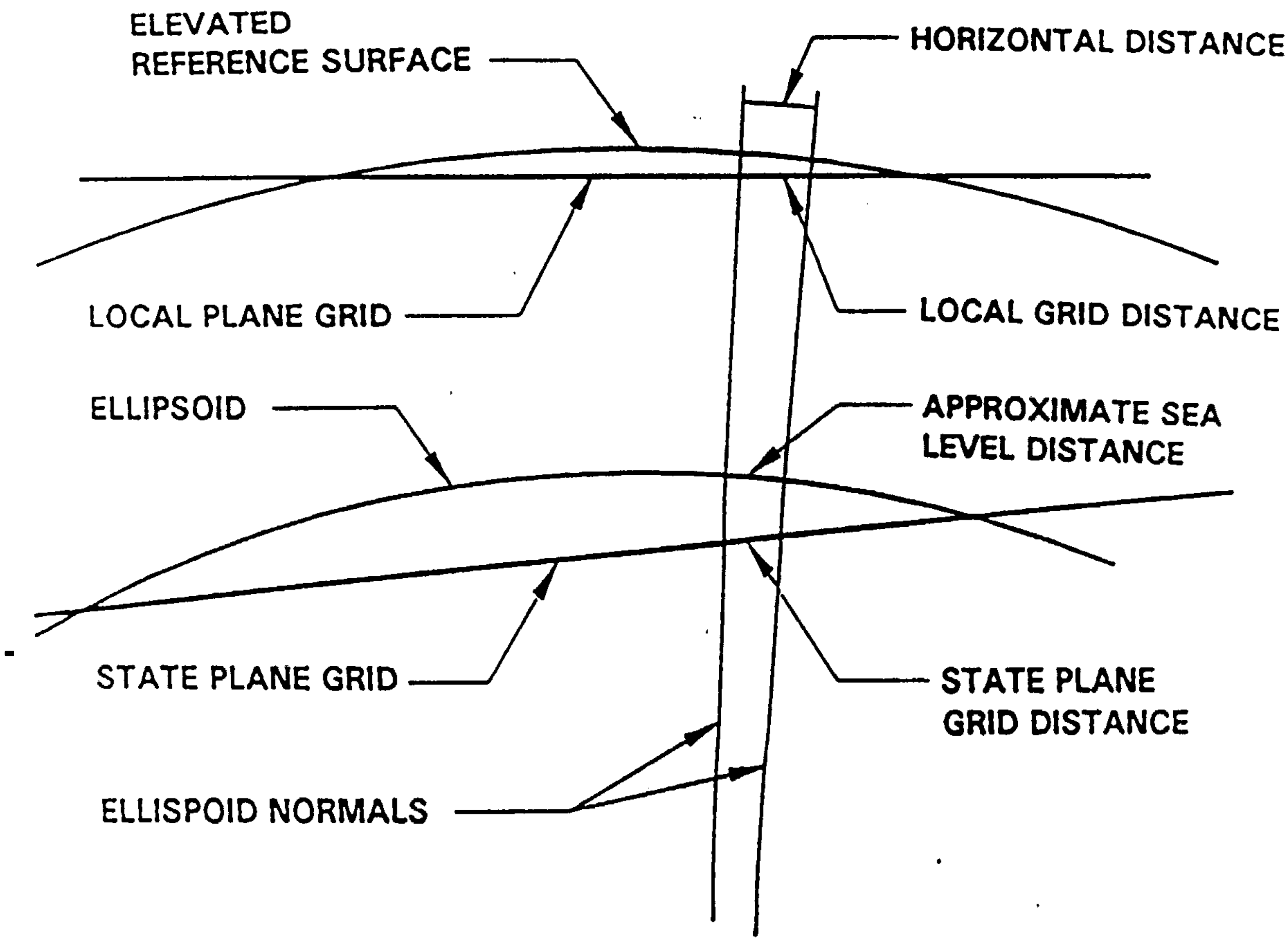
Transverse Mercator



Tangent Projection
(Distances are only stretched)



Secant Projection
(Distances are both stretched and compressed)


ELEVATED
REFERENCE SURFACE
HORIZONTAL DISTANCE
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APPROXIMATE SEA
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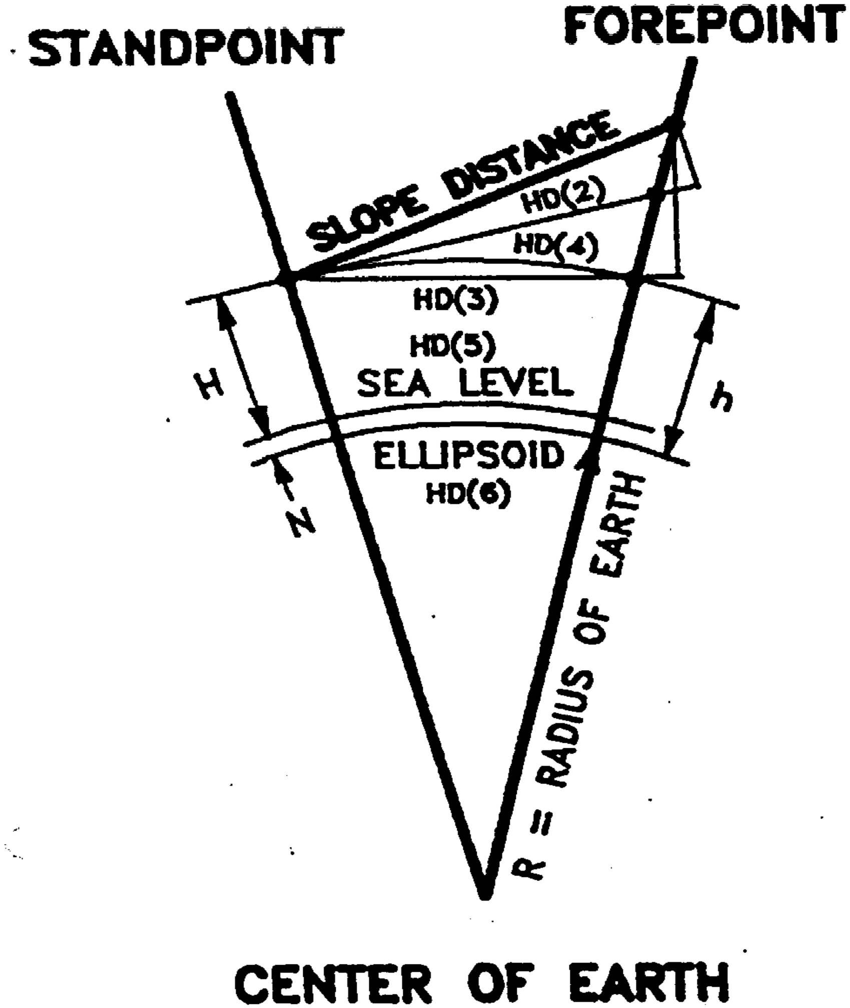
STATE PLANE GRID
STATE PLANE
GRID DISTANCE
ELLISPOID NORMALS


STANDPOINT
FOREPOINT
SLOPE DISTANCE
HD(2)
HD(4)
HD(3)
HD(5)
SEA LEVEL
H
h
N
ELLIPSOID
HD(6)
R = RADIUS OF EARTH
CENTER OF EARTH

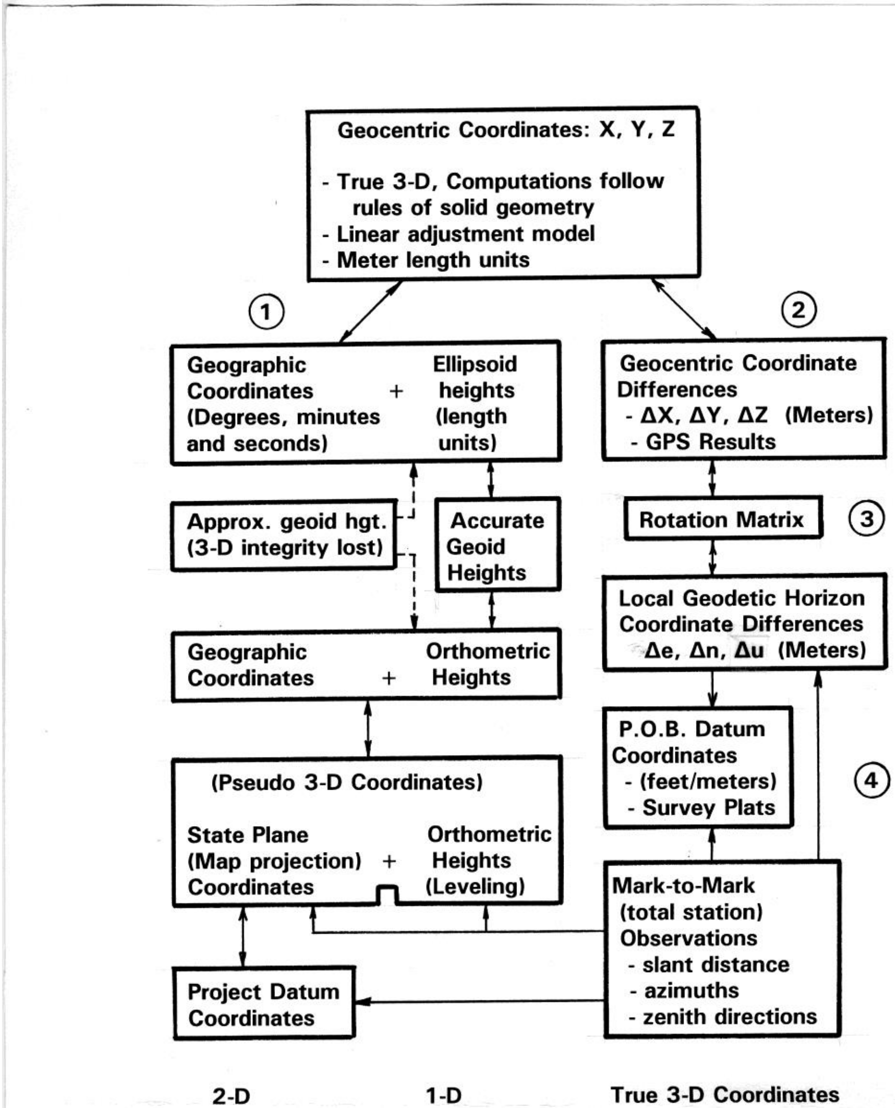
Points to remember:

- Map projections are strictly 2 dimensional.
- Conformal map projections are mathematical.
- Distances on the map & ellipsoid are different.
- Distance on ellipsoid is not same as distance at ground.
- When is a foot not a foot? What about weights/measures?
- How much distortion is allowed/permitted?
- A tolerance of 1:10,000 was adopted in 1930's.
- Corrections are needed to preserve data integrity.
- Conformal projections preserve angles.

http://www.globalcogo.com/GM012.pdf

<u>Geodetic</u> & geographic (ellipsoidal/spherical)

- **Computations on ellipsoid or sphere.**
- **Latitude and longitude curvilinear values.**
- **Position in degrees-minutes-seconds.**
- **Equations are cumbersome and complex.**
- **Third dimension is ellipsoid height or altitude.**
  Elevation has a separate origin.


Geocentric Coordinates: X, Y, Z
- True 3-D, Computations follow rules of solid geometry
- Linear adjustment model
- Meter length units
1
2
Geographic Coordinates (Degrees, minutes and seconds) + Ellipsoid heights (length units)
Geocentric Coordinate Differences
- ΔX, ΔY, ΔZ (Meters)
- GPS Results
Approx. geoid hgt. (3-D integrity lost)
Accurate Geoid Heights
Rotation Matrix
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Local Geodetic Horizon Coordinate Differences
Δe, Δn, Δu (Meters)
Geographic Coordinates + Orthometric Heights
P.O.B. Datum Coordinates
- (feet/meters)
- Survey Plats
4
(Pseudo 3-D Coordinates)
State Plane (Map projection) Coordinates + Orthometric Heights (Leveling)
Mark-to-Mark (total station) Observations
- slant distance
- azimuths
- zenith directions
Project Datum Coordinates
2-D
1-D
True 3-D Coordinates

Coordinate systems/geometry

- **Coordinate systems:**
  1. Geocentric, Earth-centered Earth-fixed
  2. Geodetic, traditional latitude/longitude.
  3. Map projection – state plane coordinates.
  4. Local – assumed or modified map projection (LDP)
- **Basic elements and conventions**
  - Meter is unit of length (display other as required).
  - Use right-handed rectangular as possible.
  - Rules of solid geometry (vector algebra & matrices).

Points to remember (Again):

- Map projections are strictly 2 dimensional.
- Map projections are mathematical, not graphical.
- Distances on the map & ellipsoid are different.
- Distance on ellipsoid is not same as at ground.
- When is a foot not a foot?
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Questions?

Time for a break – be back in 30 minutes.

- The first part looked at Datums, Coordinate Systems, and generic Map Projections.
- The next part will focus specifically on Low Distortion Projections (LDP's)

This session looks specifically at Low Distortion Projections (LDP)

- **Questions to audience:**
  - What is a LDP and why are you interested in a LDP?
  - How will a LDP be beneficial in your work?
- **Step back and look at philosophical issues:**
  - Map projections are the prerogative of Cartographers.
  - Cartography is study/practice of making maps – includes:
    - i. Deciding what is to be mapped.
    - ii. Representing terrain of objects/features.
    - iii. Exclude irrelevant information.
    - iv. Goal is to reduce complexity – generalization.
    - v. Map design decides what to show.

Contrasting roles of cartographer and surveyor

- **Cartographer concerned with map model/projection.**
  (Primarily as discussed on previous/next slide.)
- **Surveyor is concerned with:**
  - **Geometrical integrity of information on the map.**
  - **Deciding what information is to be conveyed.**
  - **Appearance of the map (colors).**
  - **Completeness of information on map.**
  - **Permanence of the information.**
  - **Storage and retrieval of maps.**

Examples of concerns for Cartographers, Surveyors/GIS, etc.:

- **Topology is concerned with what lies next to what.**
- **Thematic maps highlight a particular message for reader.**
- **Discrete global grids use pixels - of varying sizes (raster).**
- **Geometrical integrity (vector) is essential for:**
  - **Surveyors/engineers/photogrammetrists/others**
- **What is the impact of the digital revolution?**
  - **For Cartographers?**
  - **For Surveyors/GIS et. al.?**
- **Spatial data are digital and 3-D (4-D if you count time).**
- **This consequence leads to re-examination of many issues.**

Some of those geometry related issues include:

- **Measurements are made in 3-D; relative distances.**
- **Reference frame is defined by others – absolute coordinates.**
- **Where is starting place – Point of Beginning (P.O.B.)?**
  - **What is stability/permanence of P.O.B?**
  - **What does it take for selection/use of common P.O.B.?**
- **How can we best provide answers/data to client?**
  - **Does client know what they want?**
  - **Surveyors provide survey plat/description to landowner.**
  - **Sometimes client specifies unrealistic results (data format).**
  - **What proprietary considerations are to be made?**

Examples of projections commonly encountered:

- State plane coordinate systems.
  - Lambert Conic Conformal for states "long" east/west.
  - Transverse Mercator for states "long" north/south.
  - Oblique Mercator, central axis at some non-north azimuth
- Universal Transverse Mercator (UTM)
  - 6 degrees wide, 60 zones around the world
  - Grid scale factor 0.9996 (1:2,500) at center of zone.
  - Stop short of poles, defined for 80° South to 84° North.
- GPS Localization – can be considered a LDP

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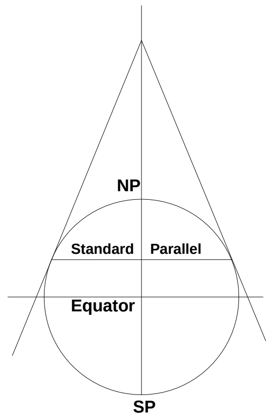
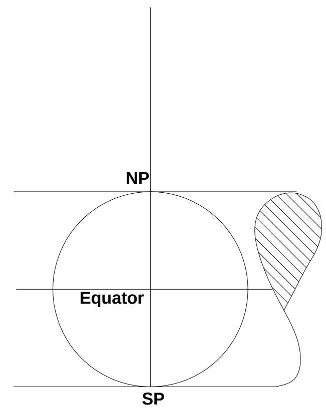


Lambert Conic Conformal



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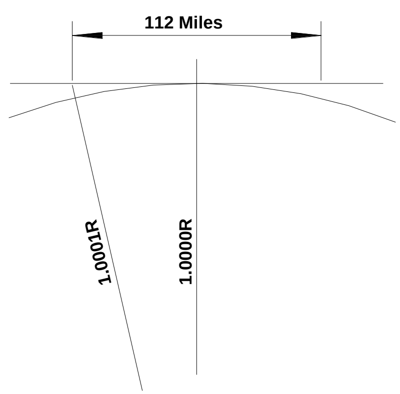

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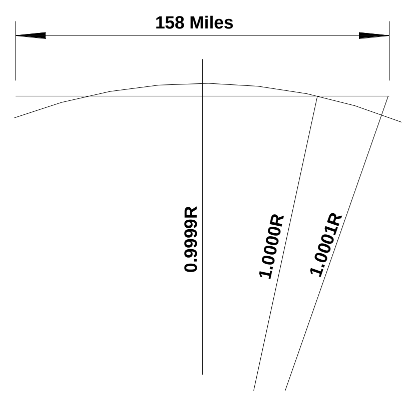

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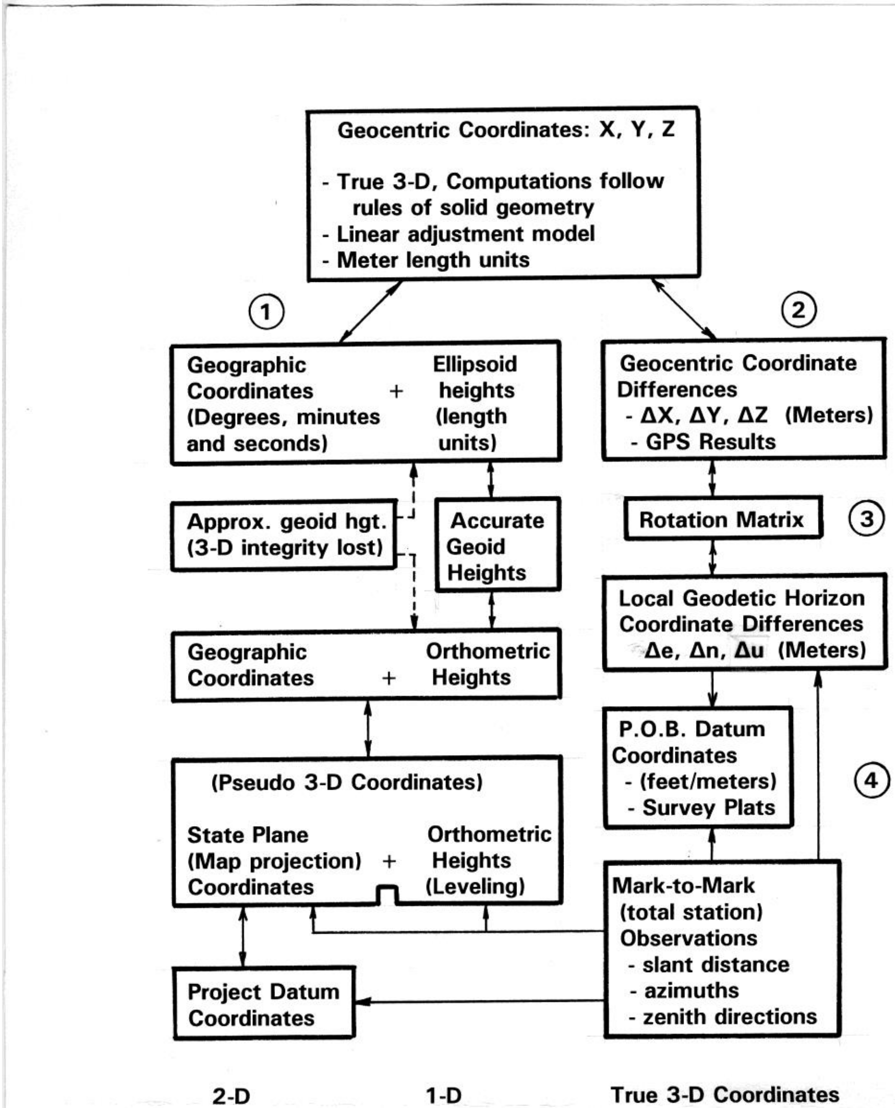
(Distances are both stretched and compressed)

Elements needed to define a map projection:

- Ellipsoid, semi-major axis and 1/f or semi-minor axis.
- Select projection type:
  - Tangent/secant
  - Lambert, Mercator, Transverse Mercator, Oblique
- Fix projection to ellipsoid:
  - Central Meridian
  - Latitude of origin
  - Orientation of mapping grid, Meridian or oblique.
  - Level of maximum (plus/minus) distortion allowed.
  - Units for distances
  - False northing/easting to avoid negative coordinates

Low Distortion Projections (see again slide 11):

- Driving force is to make grid/ground distances similar
  (Recognize difficulty of flattening the earth.)
- Examples of ways to accomplish that goal (and objections):
  - Raise ellipsoid to mean elevation of area to be mapped.
    (Some view that practice as using non-standard ellipsoid.)
  - Divide existing SPC by combined factor.
    (Works well for limited area but coordinates are not SPC.)
  - Impose ‘scaling’ on mapping equations.
    (Can work well, but departs from formal definitions)
- Few users take “ownership” of process but rely on software vendors to provide a system that “works.”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History of development of LDPs:

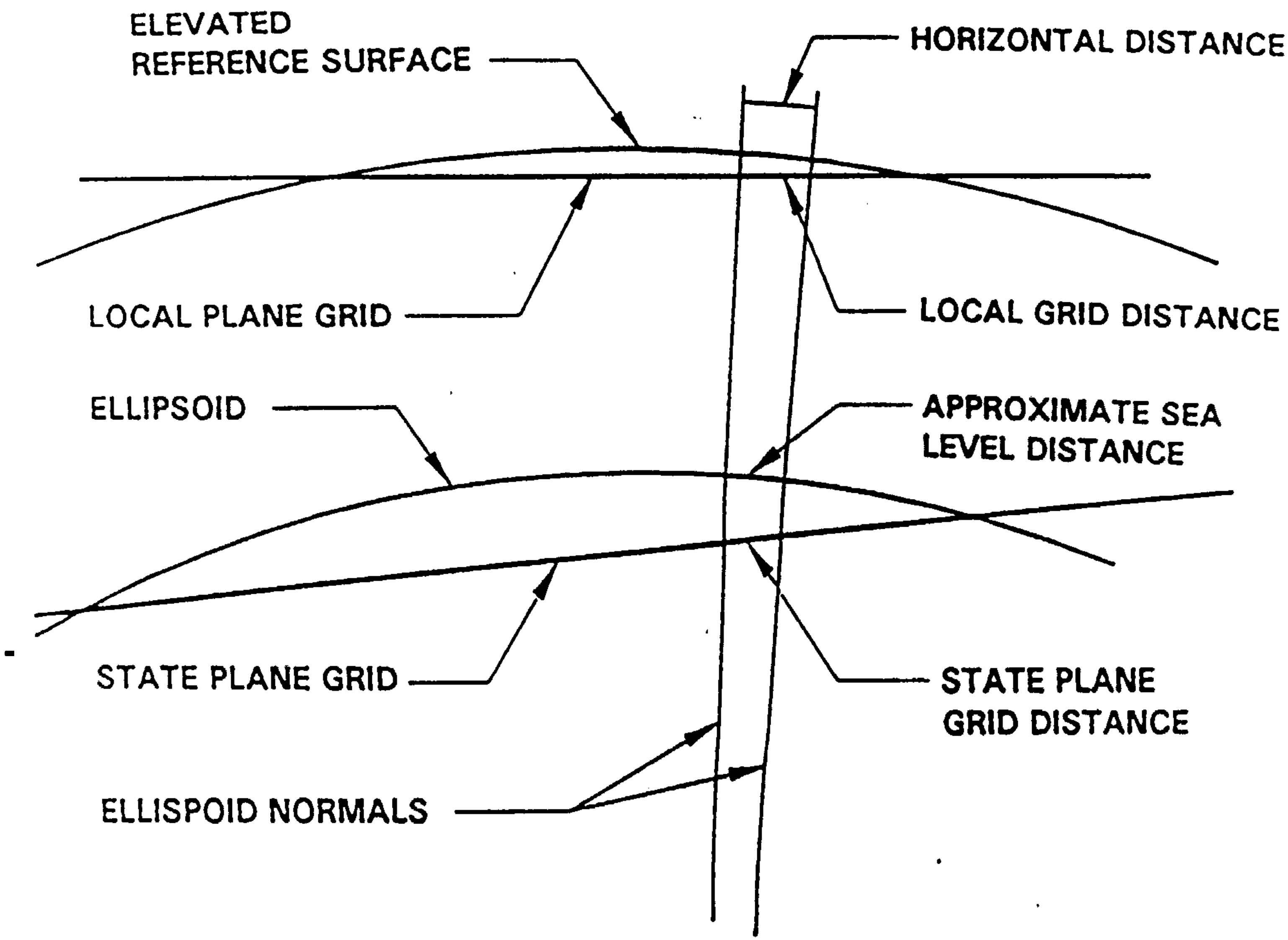
For informal summary of LDPs see

www.globalcogo.com/History-LDP.pdf

- Michigan SPC 1964
  - System designed at 800 feet to avoid elevation reduction
  - Reference surface returned to ellipsoid for NAD83.
- County Coordinate Systems:
  - Wisconsin
  - Minnesota
- State of Oregon – DOT
  - NGS involved in design/adoption
  - Probably best example of successful use of LDP.

Designing a Low Distortion Projection:

- **Parameters.**
  - Use standard GRS80 ellipsoid
  - Determine geographic location of area to be covered.
  - Determine the average elevation of area.
  - Choose projection type:
    - i. Lambert conic conformal, one or two standard parallels.
    - ii. Transverse Mercator,
    - iii. Oblique Mercator,
- **Computation of zone constants.**
  - Make sure you are using "reliable" equations.
  - Verify your solutions by testing.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Design a LDP to cover Fort Collins at 1,500 m :

- Transverse Mercator with maximum distortion 1:100,000.

  - Use GRS80 ellipsoid + ellipsoid height at Fort Collins

    a = 6,378,137.000 m + 1,500.0 m = 6,379,637.000 m

    1/f = 298.25722210088

  - Pick Central Meridian (CM) as 105° 05’ 00.”0 W
  - Pick latitude of origin as 40° 28’ 00.”0 N
  - Choose central scale factor as 0.99999000
  - Choose false easting on CM 50,000.0 m
  - Choose northing of origin to be 0.000 m
  - Use Localcor.exe program – available from EFB.

USER: Earl F. Burkholder

DATE: February 13, 2015

TRANSVERSE MERCATOR PROJECTION TRANSFORMATIONS

PROJECTION NAME: Fort Collins at 1,500 meters

REFERENCE ELLIPSOID: GEODETIC REFERENCE SYSTEM 1980

A = 6378137.0000 METERS

1/F = 298.2572221008827

REFERENCE ELLIPSOID HEIGHT FOR PROJECTION = 1500.0000 METERS

MODIFIED ELLIPSOID FOR: Fort Collins at 1,500 meters

A = 6379637.0000 METERS

1/F = 298.2572221008827

ZONE PARAMETERS:

CENTRAL MERIDIAN (W)	105 5 0.000000
LATITUDE OF FALSE ORIGIN	40 28 0.000000
FALSE NORTHING AT FALSE ORIGIN	0.0000 METERS
FALSE EASTING ON CENTRAL MERIDIAN	50000.0000 METERS
SCALE FACTOR ON CENTRAL MERIDIAN	0.99990000000

ZONE CONSTANTS:

RECTIFYING SPHERE RADIUS 6368946.6322 METERS

RECTIFYING LATITUDE CONSTANTS:

U(0) = -0.005048250776 V(0) = 0.005022893948

U(2) = 0.000021259204 V(2) = 0.000029370625

U(4) = -0.000000111423 V(4) = 0.000000235059

U(6) = 0.000000000626 V(6) = 0.000000002181

RECTIFYING LATITUDE OF FALSE ORIGIN 40 19 27.116165

GRID MERIDIAN ARC TO FALSE ORIGIN 4482356.3787 METERS

TRANSFORMATIONS:

NAME OF STATION: CSU 2 — FORWARD

LATITUDE: 40 34 32.698970 — NORTHING 12115.8209 METERS

LONGITUDE: 105 5 8.837800 — EASTING 49792.0873 METERS

CONVERGENCE: 0 0 -5.75 — SCALE FACTOR: 0.999990000532

NAME OF STATION: Fort Collins CORS ARP — FORWARD

LATITUDE: 40 35 36.108010 — NORTHING 14075.0369 METERS

LONGITUDE: 105 9 37.568530 — EASTING 43471.8040 METERS

CONVERGENCE: 0 -3 0.61 — SCALE FACTOR: 0.999990524108

Example – two NGS published points in Fort Collins area:

CSU 2	Fort Collins CORS ARP
ø = 40° 34' 32."69897 N	ø = 40° 35' 36."10801 N
λ = 105° 05' 08."83780 W	λ = 105° 09' 37."56583 W

State Plane Coordinates:

CSU 2	Fort Collins CORS ARP
E = 949,473.028 m	E = 943,145.195 m
N = 442,831.252 m	N = 444,760.244 m

LDP Coordinates:

CSU 2	Fort Collins CORS ARP
E(LDP) = 49,792.087 m	E(LDP) = 43,471.804 m
N(LDP) = 12,115.821 m	N(LDP) = 14,075.037 m

For comparison of inverse distances, see

www.globalcogo.com/LDPcompare.pdf

Questions?

Don’t forget Evaluations!

Thank you for coming!