Geometric Design of LDP

Dave Zenk PE, LS
NGS Northern Plains Regional Advisor
MSPS Annual Meeting, February 23, 2023
Brooklyn Park MN

adapted from:

The State Plane Coordinate System: History, Policy, and Future Directions

Michael L. Dennis
NGS SPCS2022 Project Manager

ASCE-UESI Surveying & Geomatics 2018 Conference
April 23, 2018

More Information

New State Plane Coordinate System

- ***State Plane Coordinate System of 2022 (SPCS2022)***
  - Referenced to new 2022 Terrestrial Reference Frames (TRFs)
  - Based on same reference ellipsoid (GRS 80)
  - Same 3 ***conformal*** projection types
    - Lambert Conformal Conic (LCC)
    - Transverse Mercator (TM)
    - Oblique Mercator (OM)
- NGS in process of specifying SPCS2022 characteristics
  - Draft **policy** and **procedures** for public comment
  - **Federal Register Notice** (FRN) on policy and procedures
  - New **report** on State Plane history, policy, and future (***done!***)

NOTE: SPCS2022 policy, procedures, and FRN currently in review
Approved version may differ from what is presented here

Announcements

SPCS2022 Federal Register Notice

- **August 31, 2018** for public comment on draft policy & procedures
- Includes "special purpose" zones

SPCS2022 procedures

- **December 31, 2019** for SPCS2022 zone requests and proposals
  - ***Requests*** are for zone designs by NGS
  - ***Proposals*** are for zone designs by others
- **December 31, 2020** for submittal of approved designs by others
  - Proposal must first be approved by NGS
  - Designs must be complete before NGS review
- After deadlines, requests will be for ***changes*** *to* SPCS2022

History and Future of State Plane

- SPCS created 85 years ago
  - **SPCS 27:** 1933 – 1986 (53 years, with some changes)
  - **SPCS 83:** 1986 – 2022 (36 years, with some changes)
  - **SPCS2022:** 2022 – ? (at least a few decades…)
- SPCS2022 will likely be around for a long time
  - Honor the history and legacy of SPCS…

…while building a system for the future

- High visibility and big impact
  - SPCS used by many in US geospatial community
  - NGS already contacted by 16 states about SPCS2022

National Geodetic Survey Positioning America for the Future geodesy.noaa.gov

NOAA Special Publication NOS NGS 13

The State Plane Coordinate System

History, Policy, and Future Directions

Michael L. Dennis

March 6, 2018

National Oceanic and Atmospheric Administration • National Geodetic Survey

https://geodesy.noaa.gov/library/pdfs/NOAA_SP_NOS_NGS_0013_v01_2018-03-06.pdf

SPCS Special Publication

- History of NGS projections (1853 to present)
- SPCS policies and legislation
- Departures from policy and convention
- Recent developments in projected coordinate systems
- Appendices
  - Defining parameters for ALL zones of ALL versions of SPCS, plus additional information
  - Status of SPCS 83 legislation and foot conversions

geodesy.noaa.gov/SPCS/

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State Plane Coordinate System
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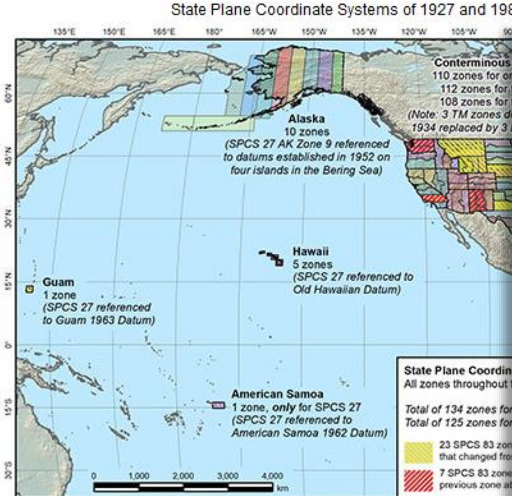
State Plane Coordinate System (SPCS)

SPCS is a system of large-scale conformal map projections originally created in the 1930s to support surveying, engineering, and mapping activities throughout the U.S. and its territories. As a reminder, a map projection is a systematic transformation of the latitudes and longitudes of locations on the surface of a sphere or ellipsoid representing the Earth to grid coordinates (x, y or easting, northing values) on a plane.

Since its inception, SPCS has served as a practical means for NGS customers to access to the National Spatial Reference System (NSRS). These web pages will help you convert coordinates, find related NGS policies and other documents, read about the history and status of current SPCS, and learn about how SPCS will change in 2022.

The map below shows the full extents and all zones of the 1927 and 1983 versions of SPCS (select the map for a higher resolution version). View more detailed maps or a map depicting SPCS 83 legislation.

State Plane Coordinate Systems of 1927 and 1983



Full extents and all zones of the 1927 and 1983 versions of SPCS.

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On "Learn More" page will soon add:

- **Spreadsheets** with complete definitions for all SPCS 27 and SPCS 83 zones
- **Shapefiles** of all SPCS 27 and SPCS 83 zones with parameters as attributes

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Documents

Related documents are listed below.

- Policy on Changes to State Plane Coordinates (PDF, 141 KB)
- Policy of the National Geodetic Survey Concerning Units of Measure for the State Plane Coordinate System of 1983 (PDF, 136 KB)
- NOAA Manual NOS NGS 5 (PDF, 2 MB)
- NOAA Special Publication NOS NGS 13 (PDF, 7 MB)

Webinars

NGS has and will host various webinars about State Plane. These will be added to the following list as they are developed.

- The State Plane Coordinate System: History, Policy, Future Directions (March 8, 2018)
- Building a State Plane Coordinate System for the Future (April 12, 2018)

Website Owner: National Geodetic Survey / Last modified by NGS Infocenter Mar 08 2018

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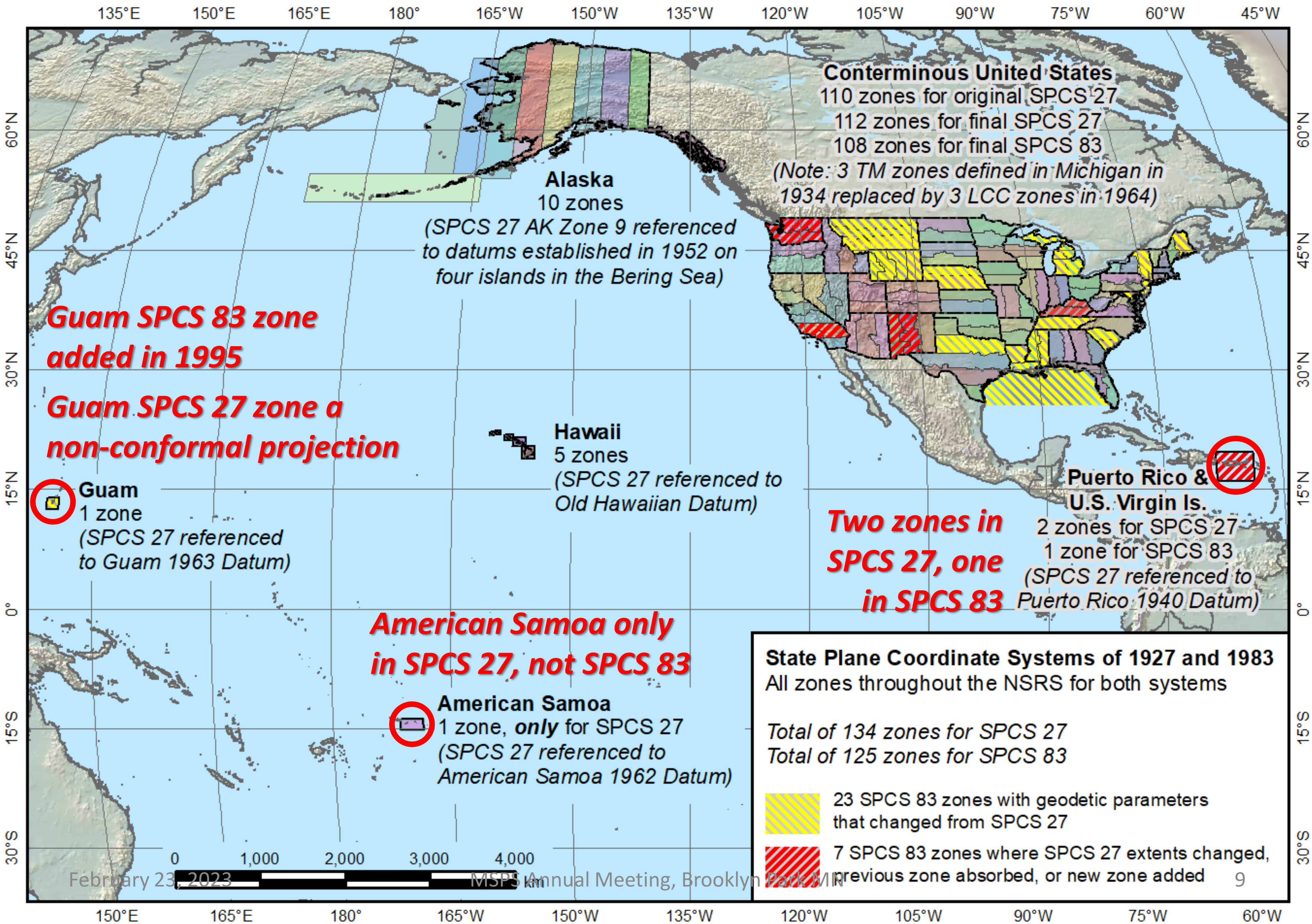
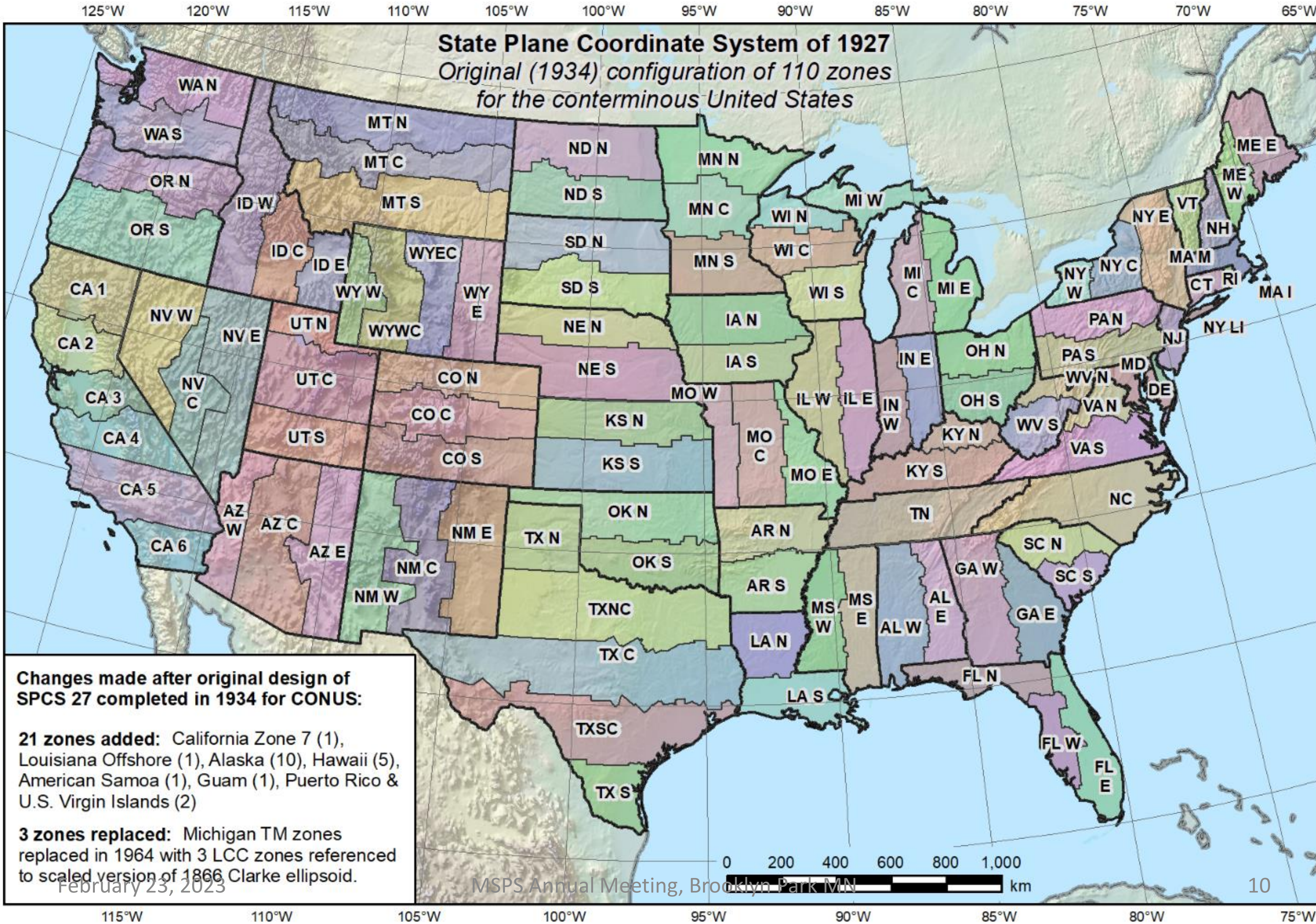
An interesting and varied history

- Initially created for North Carolina at customer request
  - Gave practical access to ***National Spatial Reference System*** (NSRS)
  - SPCS 27 started in 1933, completed in 1934(!)
- Changes from SPCS 27 to SPCS 83:
  - Multi-zone to single-zone for some states (SC, NE, MT)
  - Change in grid origin and units (US feet to meters)
  - American Samoa has no SPCS 83 zone
- Departures from policy and convention:
  - Guam used non-conformal projection for SPCS 27
  - Michigan used "scaled" ellipsoid for SPCS 27 (after 1963)
  - California added small Los Angeles County zone for SPCS 27
  - Kentucky has "layered" (overlapping) SPCS 83 zones
  - Montana single SPCS 83 zone greatly exceeds 1:10,000 scale error

State Plane Coordinate Systems of 1927 (134 zones) and 1983 (125 zones)



Original SPCS 27, as of 1934 (110 zones total)

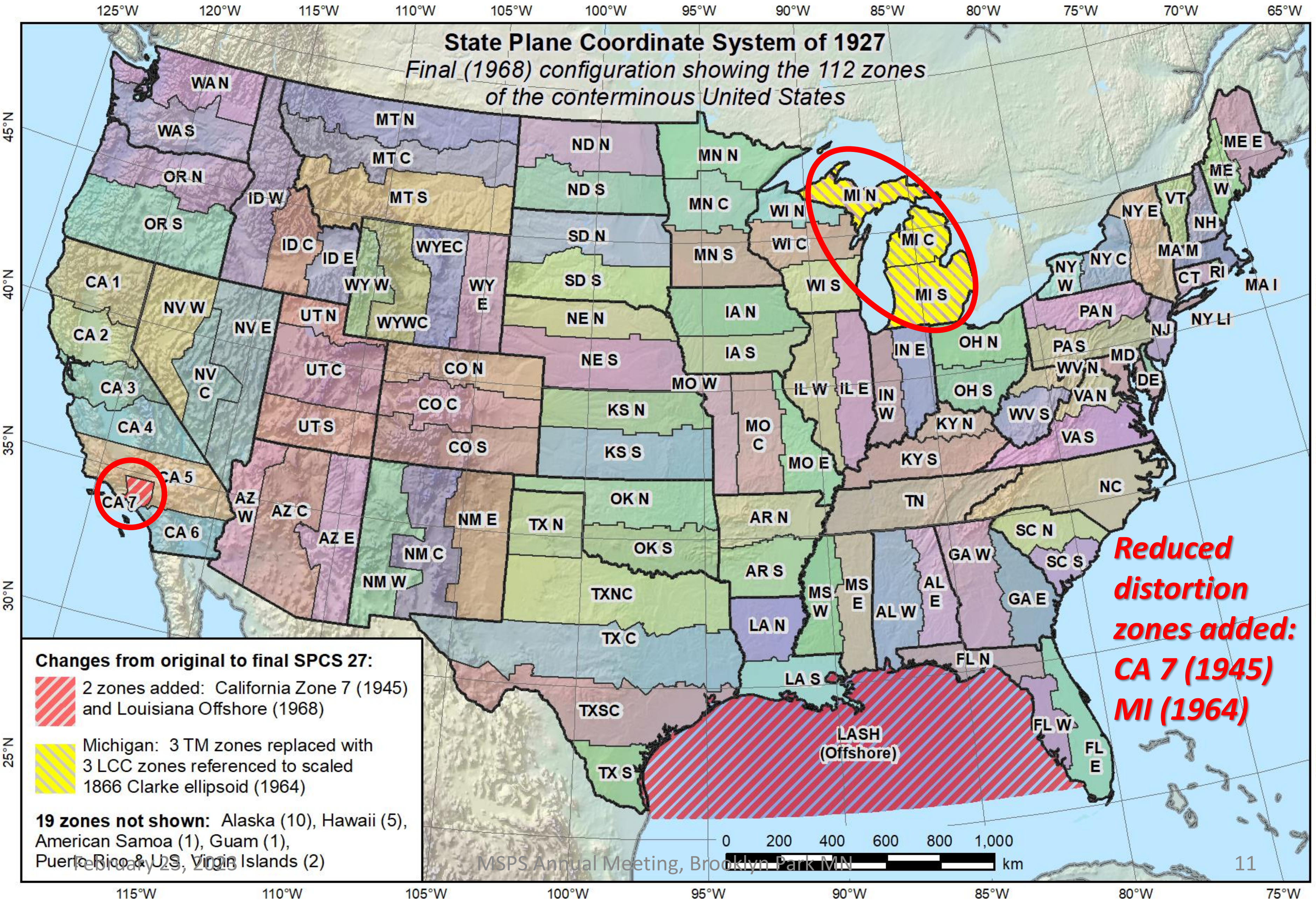


Changes made after original design of SPCS 27 completed in 1934 for CONUS:

21 zones added: California Zone 7 (1), Louisiana Offshore (1), Alaska (10), Hawaii (5), American Samoa (1), Guam (1), Puerto Rico & U.S. Virgin Islands (2)

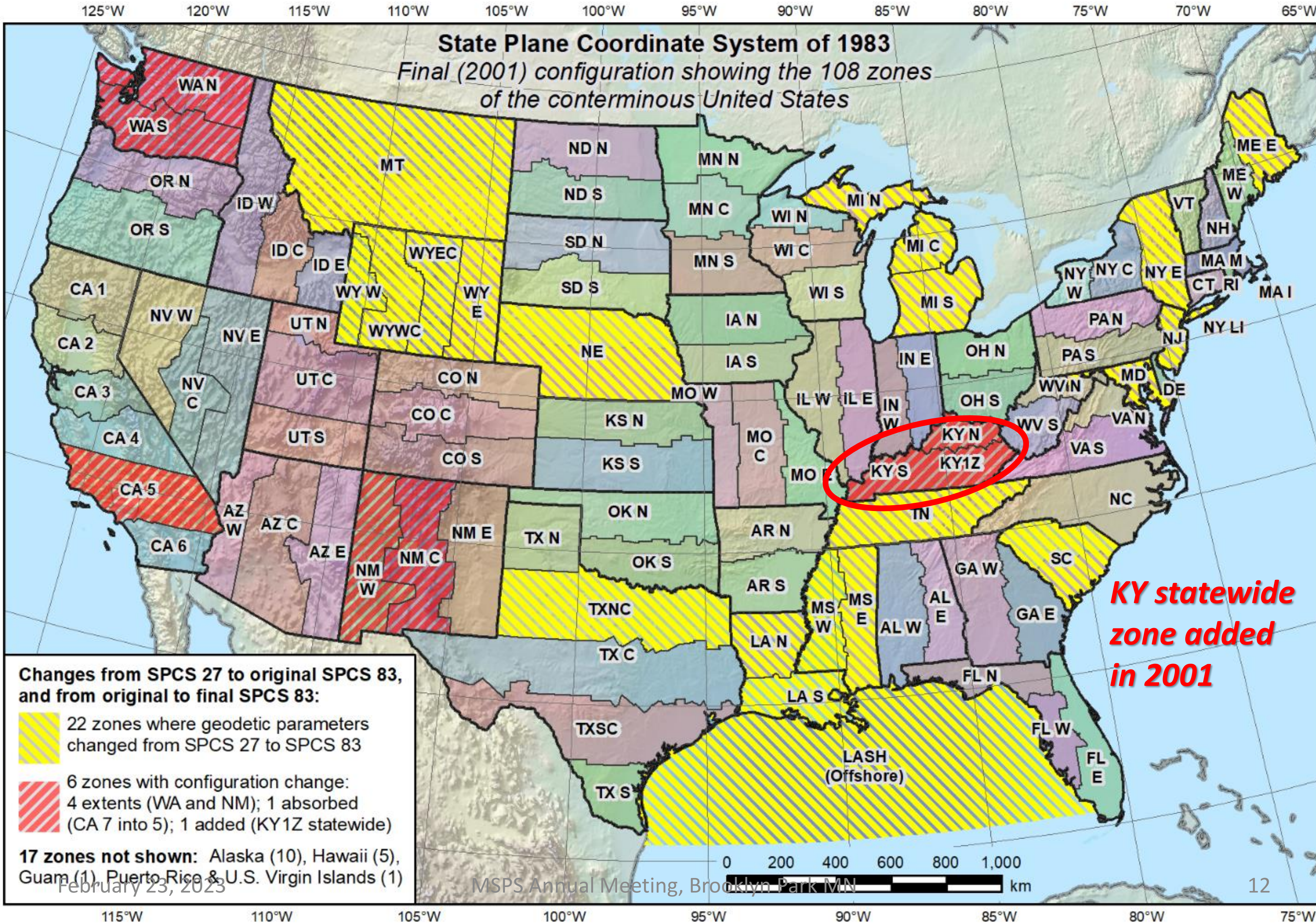
3 zones replaced: Michigan TM zones replaced in 1964 with 3 LCC zones referenced to scaled version of 1866 Clarke ellipsoid.

Final SPCS 27, as of 1968 (112 zones in CONUS, 131 zones total)

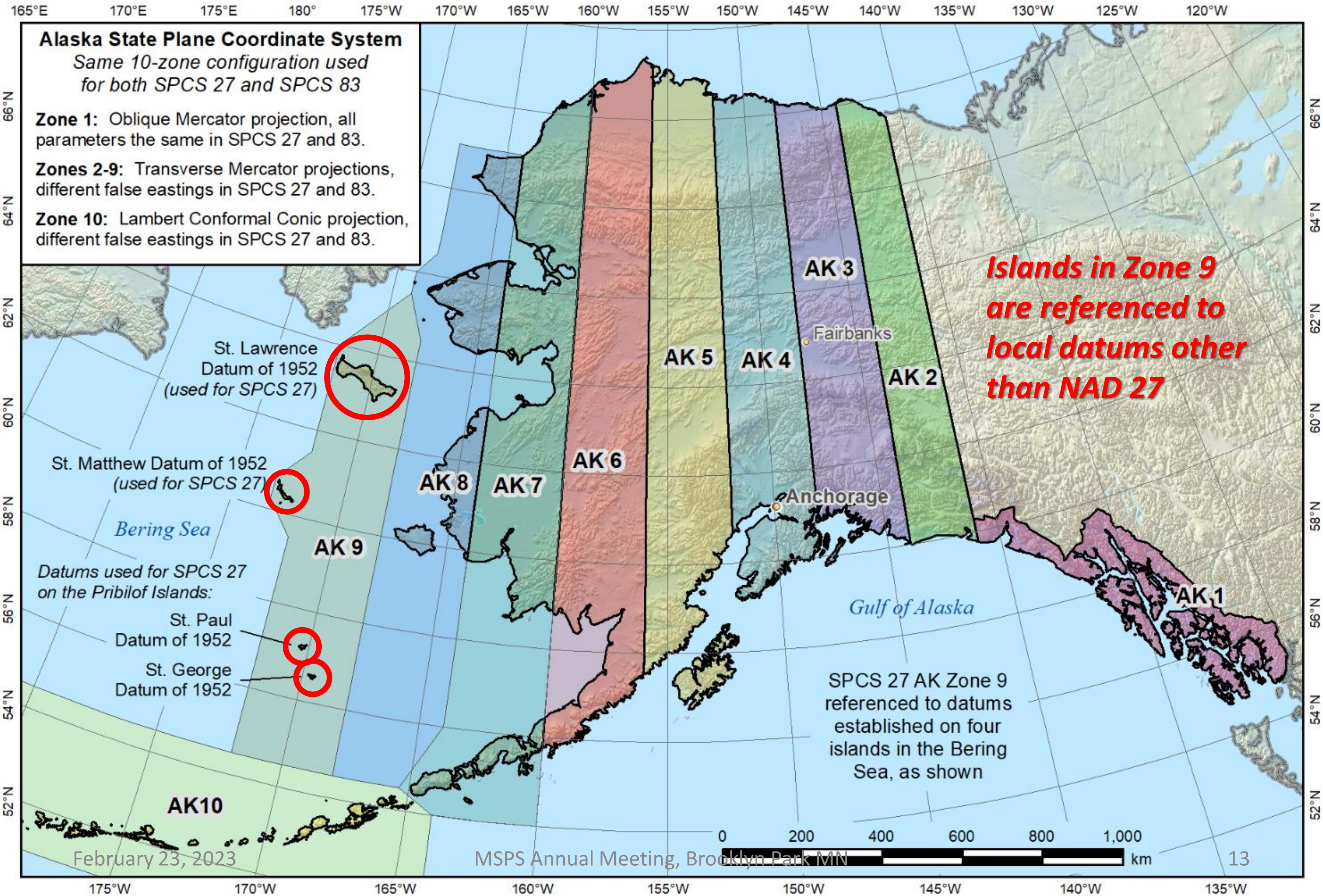


Reduced distortion zones added:
CA 7 (1945)
MI (1964)

Final SPCS 83, as of 2001 (108 zones in CONUS, 125 zones total)



Alaska State Plane Coordinate Systems of 1927 and 1983 (10 zones)

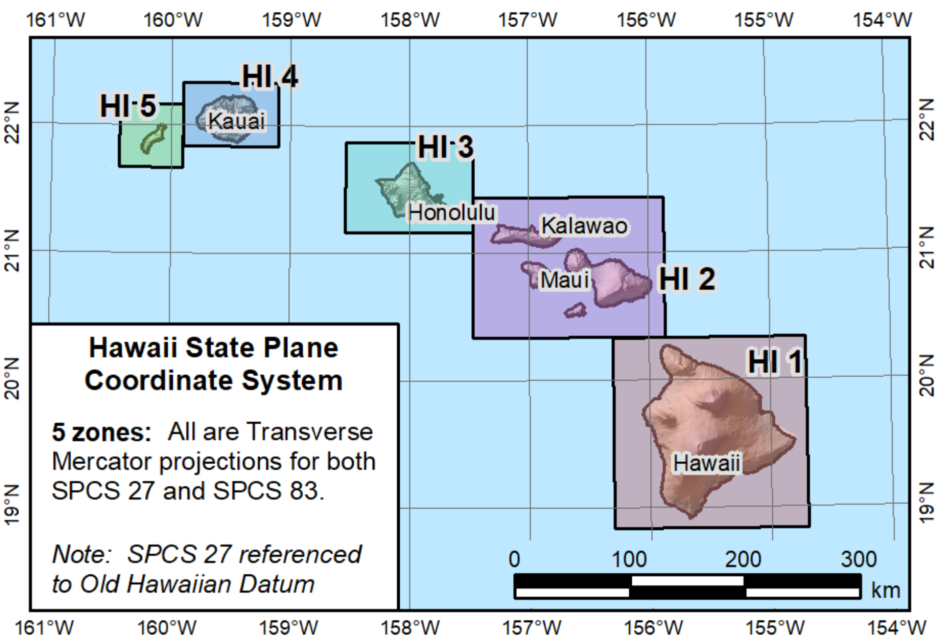


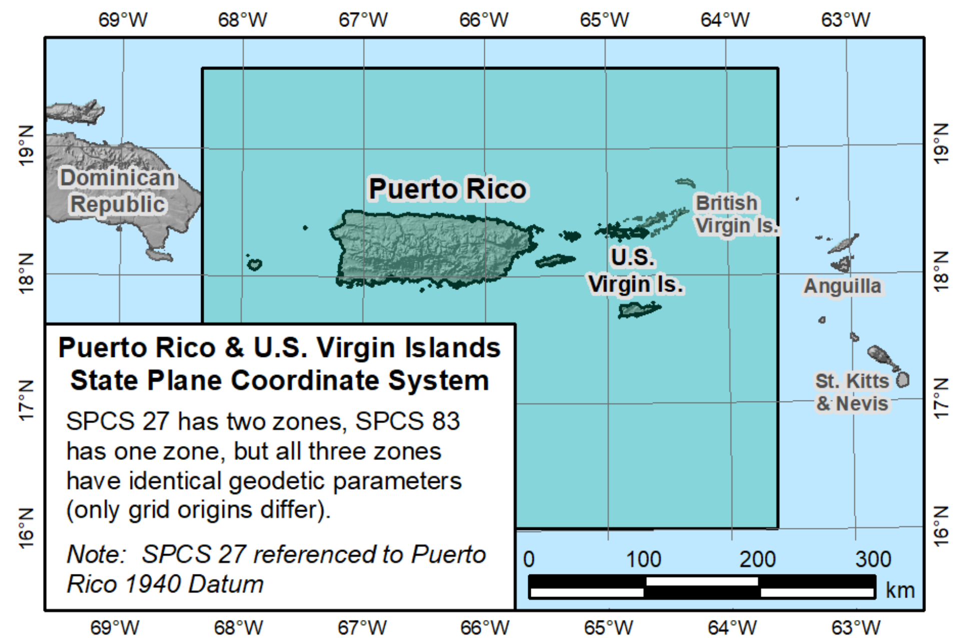
Hawaii State Plane Coordinate Systems of 1927 and 1983 (5 zones)

"SPCS 27" version referenced to Old Hawaiian Datum

Puerto Rico and U.S. Virgin Islands State Plane Coordinate Systems of 1927 (2 zones) and 1983 (1 zone)

"SPCS 27" version referenced to Puerto Rico 1940 Datum





Issues with SPCS 83

- Incomplete NGS documentation (until now)
- Inconsistent zone definitions
  - Highly variable linear distortion
  - "Layered" zones exist (Kentucky)
  - Inconsistent specification of grid origins
  - Scale explicitly defined for some zones, implicitly for others
  - Incomplete coverage of U.S. territories
- Note common usage of SPCS "at ground"
  - Many surveyors & engineers scale SPCS to topo surface
  - NGS used to give workshops on this methodology
  - Process incorporated in most surveying software
  - Shows desire to work "at ground"

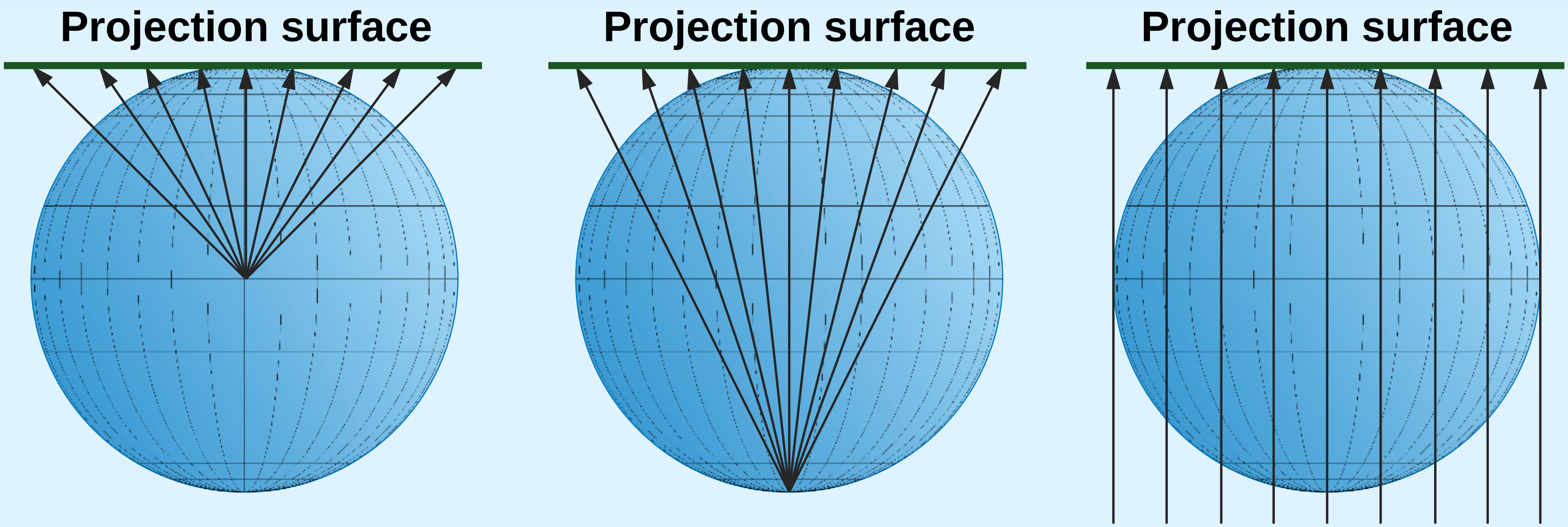
Map projection concepts

- Linear distortion ("scale error")
  - Amount map projection "grid" distance differs from true (curved) horizontal distance
    - Usually at topographic surface ("grid" vs. "ground" distance)
    - Can also be at ellipsoid surface ("grid" vs. ellipsoid distance)
- Conformal map projection
  - Linear distortion unique at a point (same in every direction)
  - Lines on Earth intersect at same angle on map
    - Meridians and parallels intersect at right angles on map
    - Shapes of areas on Earth are *locally* preserved on map
  - Simple relationship between grid and geodetic azimuth
  - SPCS2022 will only use conformal projections
    - Same for SPCS 83 and SPCS 27 (with one exception in Guam)

SPCS2022 characteristics *(draft)*

- Technical requirements
  - ***Linear distortion*** design criterion at topographic surface (*not* at ellipsoid surface)
    - Difference in distance between "grid" and "ground"
  - Use 1-parallel definition for LCC projections
- Other characteristics
  - Default designs (if no consensus stakeholder input)
  - "Layered" zones
  - Low-distortion projections (LDPs)
  - "Special purpose" zones

Can think of projection as "light rays" projecting onto surface



Ray source at center of Earth

Gnomonic projection *(non-conformal)*

Ray source at opposite side of Earth

Stereographic projection *(conformal)*

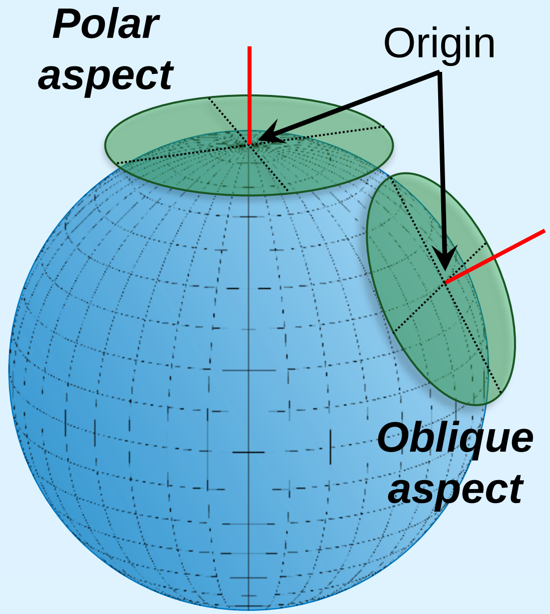
Ray source at infinity

Orthographic projection *(non-conformal)*

However, this only works for a few sphere-based projections

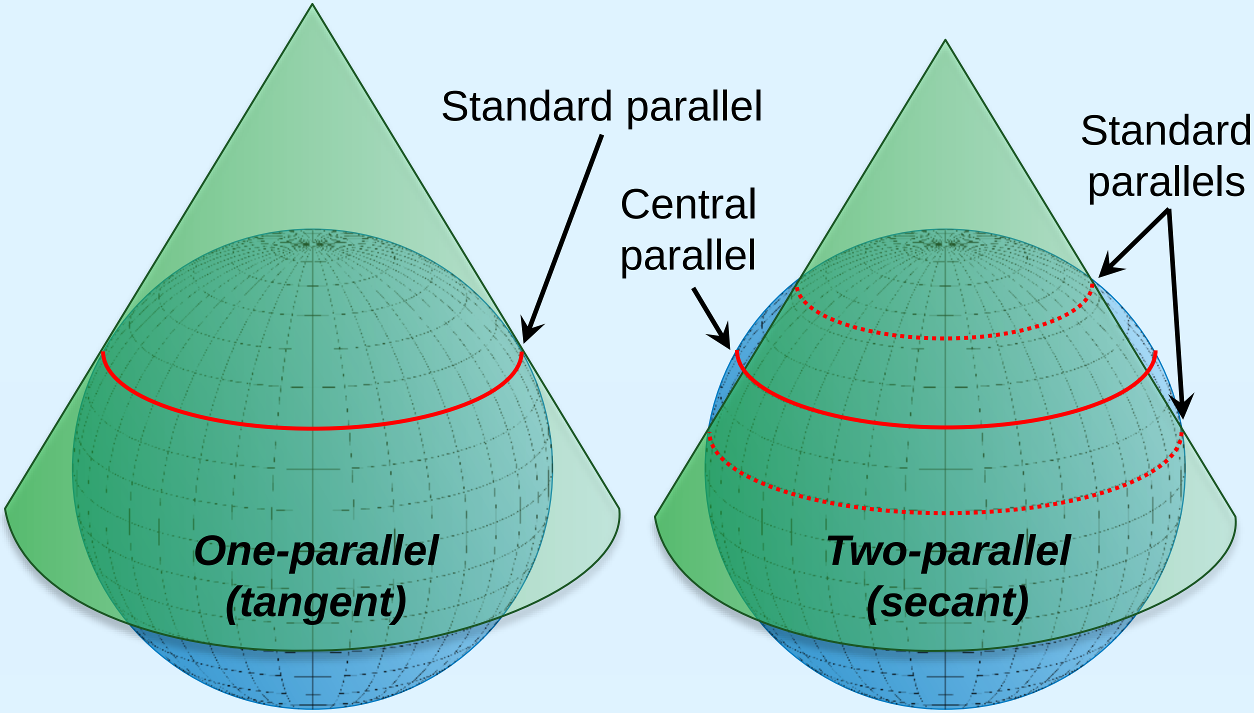
Developable surfaces: Planes and cones

Planar (azimuthal) projections



e.g., stereographic (*not* used for SPCS)

Conic projections

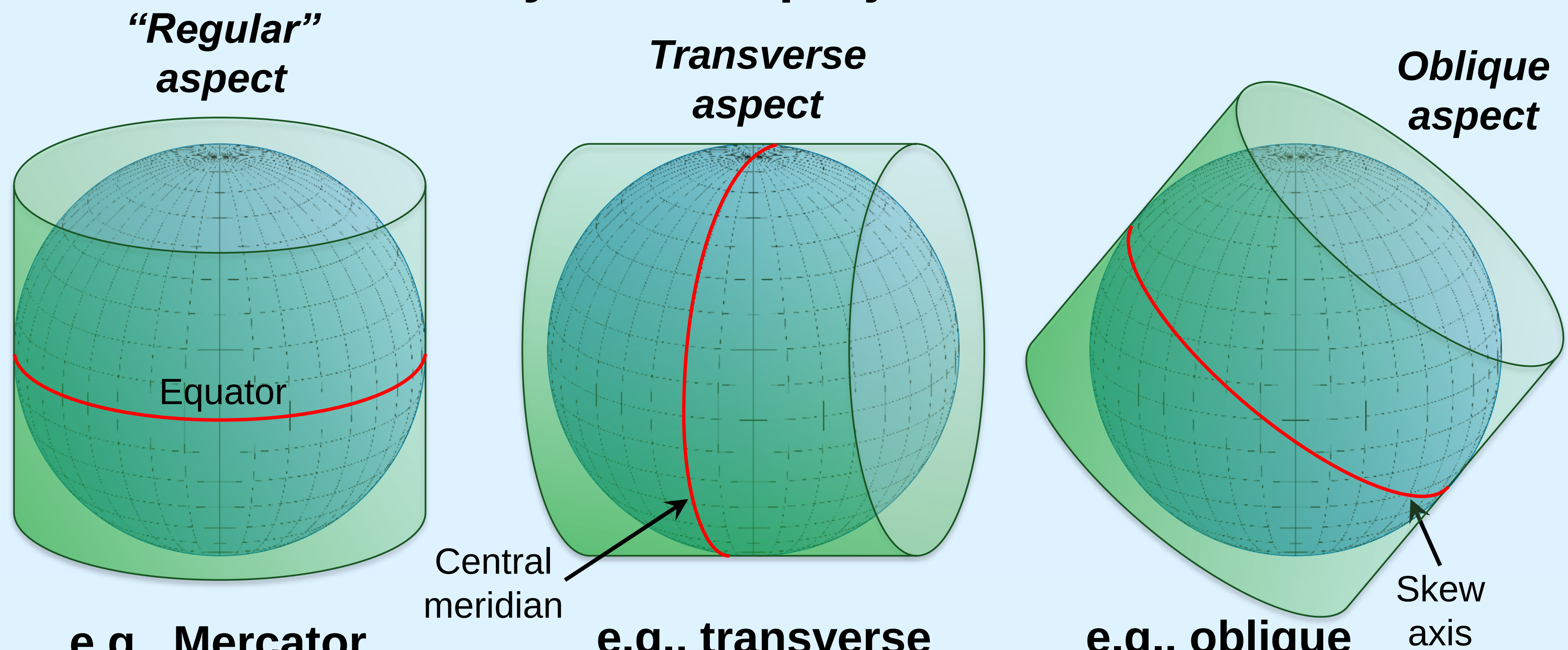


e.g., Lambert conformal conic (used for SPCS)

Examples given are CONFORMAL projections

Developable surfaces: Cylinders

Cylindrical projections



e.g., Mercator (*not* used for SPCS)

e.g., transverse Mercator (used for SPCS)

e.g., oblique Mercator (used for SPCS)

Examples given are CONFORMAL projections

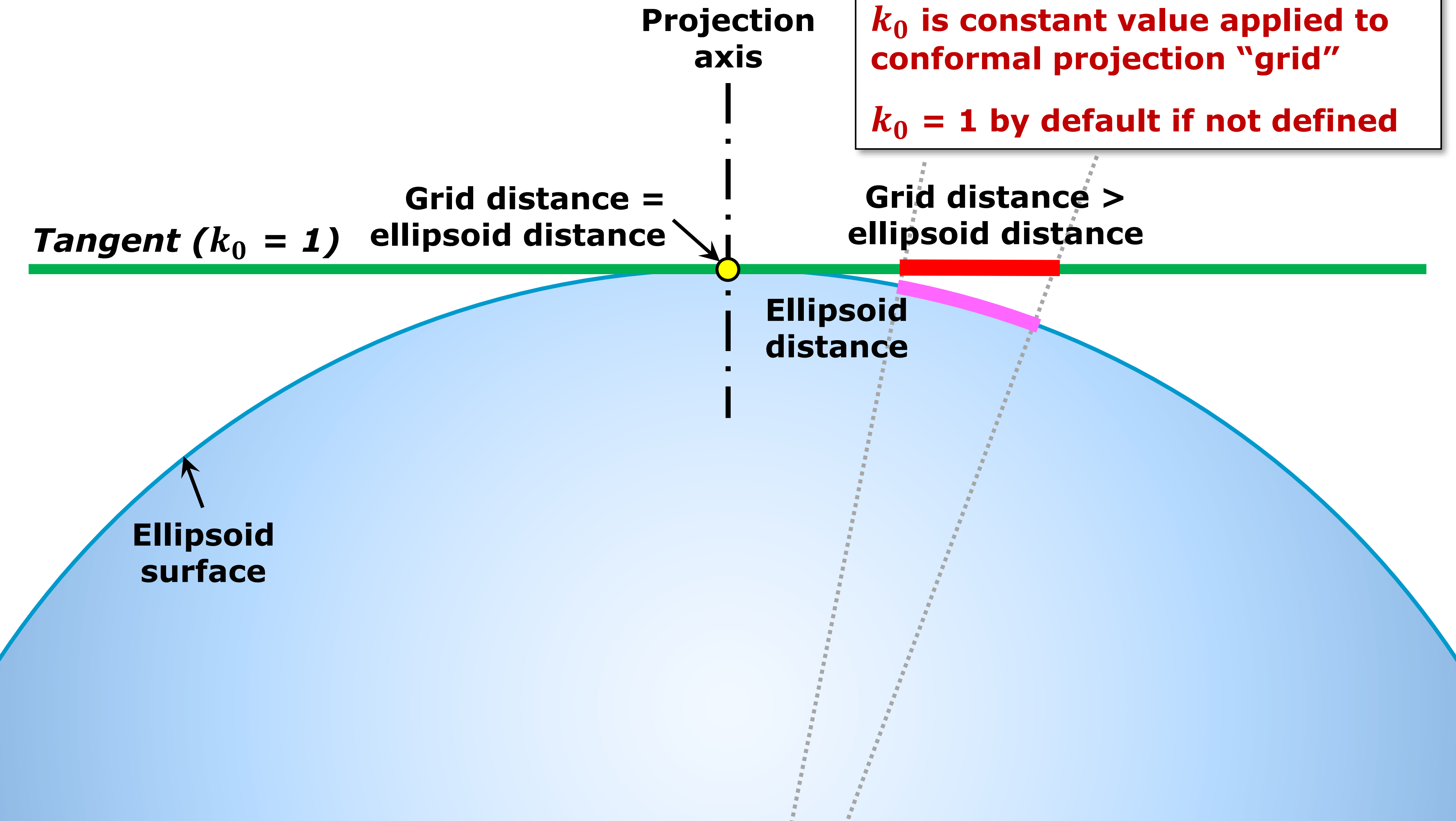
A map projection is a mathematical function

$$(northing, easting) = f(latitude, longitude) \times k_0$$

k_0 is projection axis scale factor

k_0 is constant value applied to conformal projection "grid"

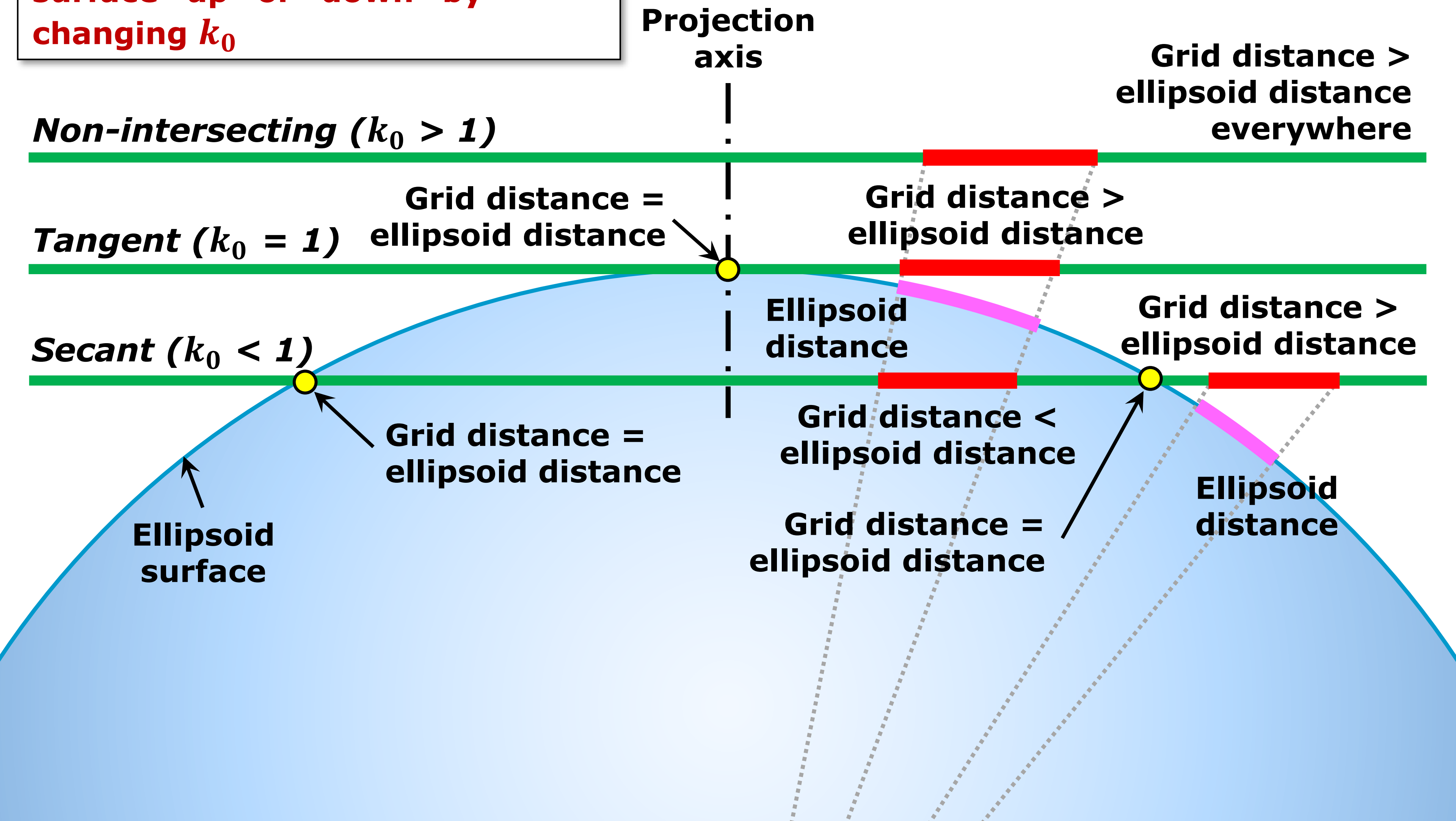
k_0 = 1 by default if not defined



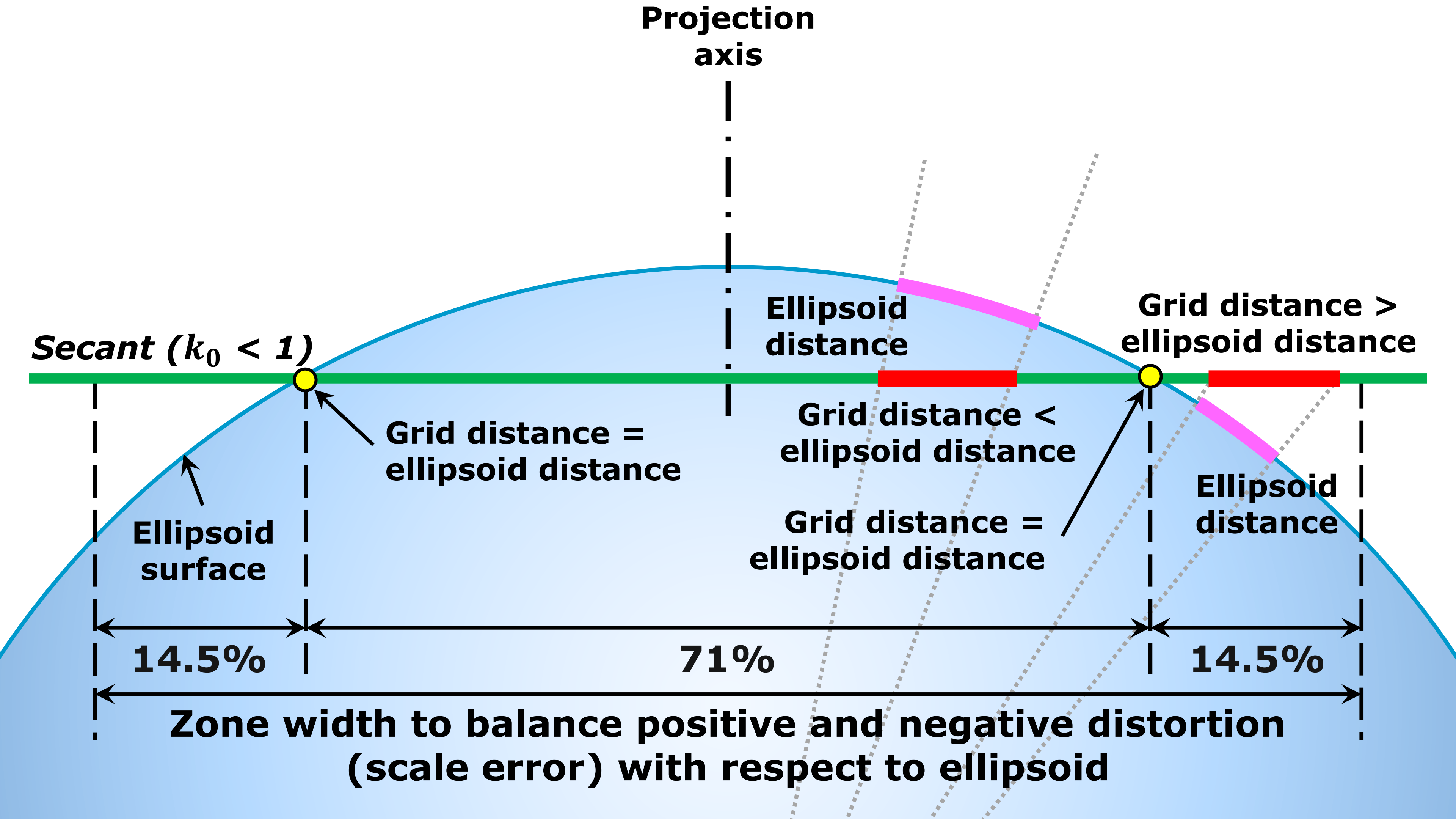
A map projection is a mathematical function

$$(northing, easting) = f(latitude, longitude) \times k_0$$

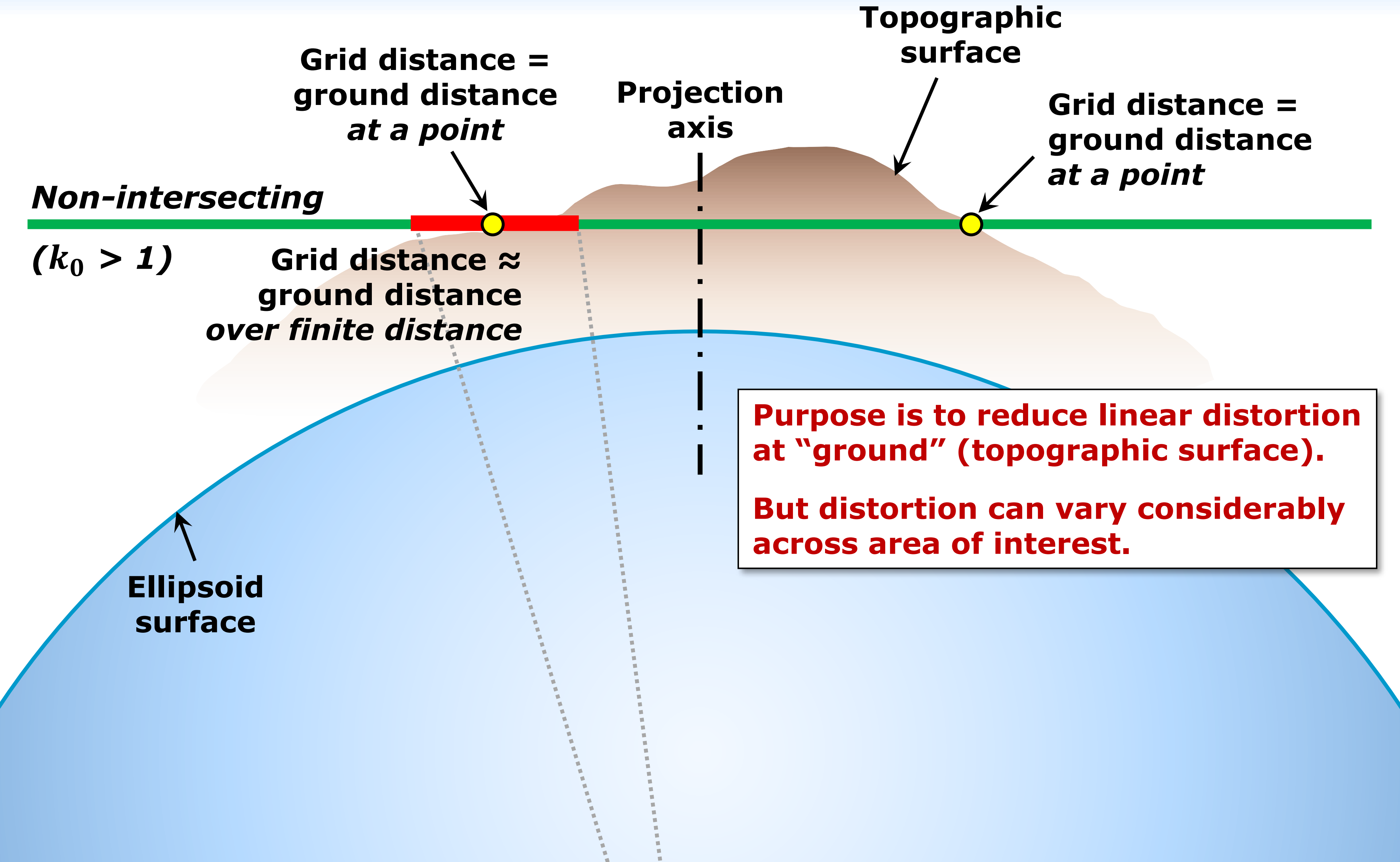
Can "move" conformal projection surface "up" or "down" by changing k_0



"Secant" conformal map projection



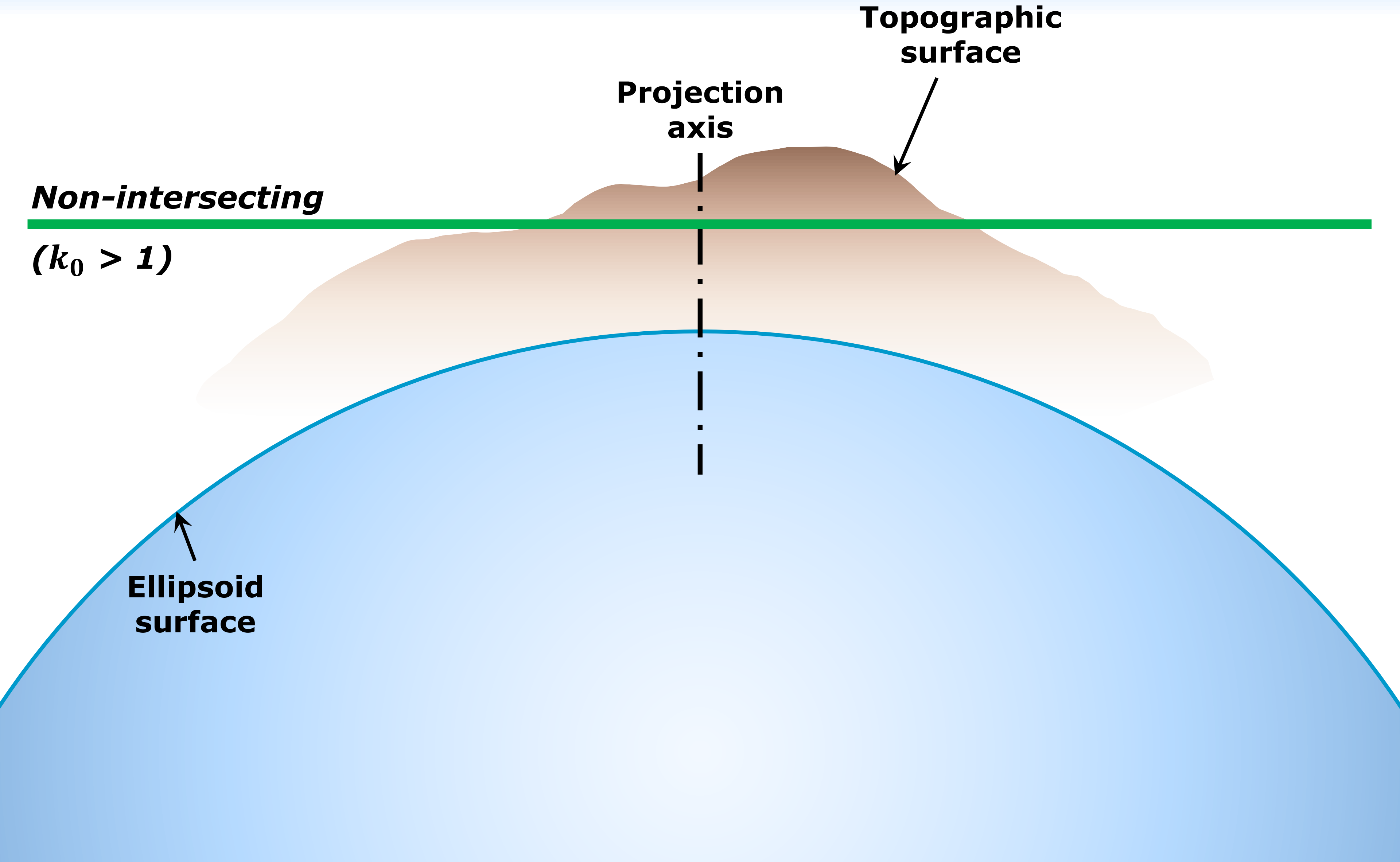
"Non-intersecting" conformal map projection



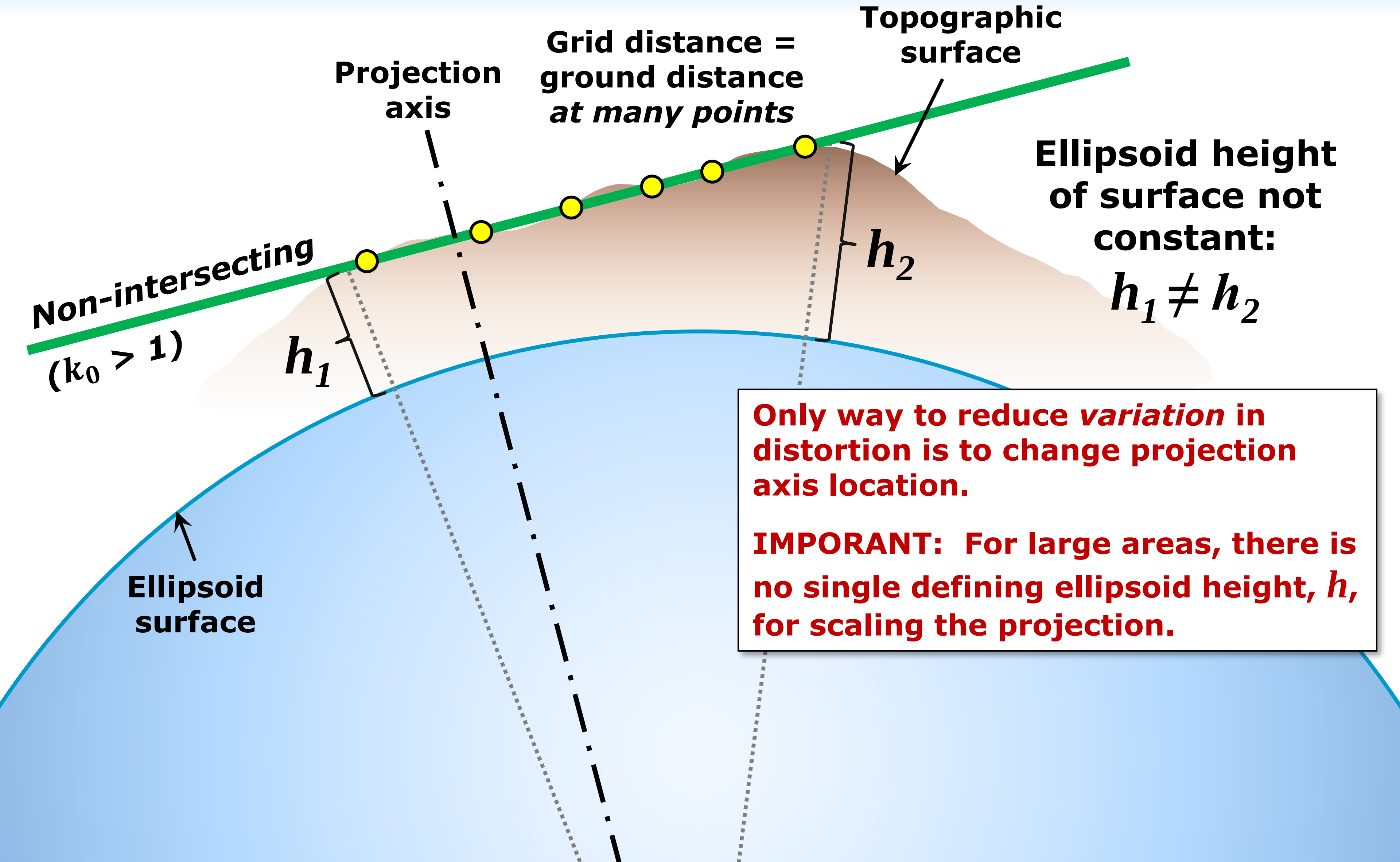
Purpose is to reduce linear distortion at "ground" (topographic surface).

But distortion can vary considerably across area of interest.

“Non-intersecting” conformal map projection



Changing projection axis to reduce distortion variation



Linear distortion magnitudes

ppm = parts per million (mm/km)

- **±20 ppm** = 2 cm/km = 0.1 ft/mile = 1 : 50,000
  Often used as "low distortion" design criterion (***at ground***)
- **±50 ppm** = 5 cm/km = 0.3 ft/mile = 1 : 20,000
  Minimum design criterion for SPCS2022 designs by NGS (***at ground***)
- **±100 ppm** = 10 cm/km = 0.5 ft/mile = 1 : 10,000
  "Nominal" maximum State Plane value (***on ellipsoid***)
  Can be much greater at topo surface
- **±400 ppm** = 40 cm/km = 2.1 ft/mile = 1 : 2,500
  Maximum design criterion for SPCS2022 zones (***at ground***)
  Maximum UTM value (***on ellipsoid***)

Nominal distortion criterion (on ellipsoid) for SPCS 27 and 83 zones (although greatly exceeded for some zones in SPCS 83).

Linear distortion magnitudes

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- **±400 ppm** = 40 cm/km = 2.1 ft/mile = 1 : 2,500
  Maximum design criterion for SPCS2022 zones (***at ground***)
  Maximum UTM value (***on ellipsoid***)

Distortion range (at ground) for zones designed by NGS, as proposed in draft SPCS2022 policy and procedures.

Linear distortion magnitudes

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- **±100 ppm** = 10 cm/km = 0.5 ft/mile = 1 : 10,000
  "Nominal" maximum State Plane value (***on ellipsoid***)
  Can be much greater at topo surface

- **±400 ppm** = 40 cm/km = 2.1 ft/mile = 1 : 2,500
  Maximum design criterion for SPCS2022 zones (***at ground***)
  Maximum UTM value (***on ellipsoid***)

Distortion criterion (at ground) often used for "low distortion projection" (LDPs); designed by others for SPCS2022 (not by NGS)

SPCS2022 characteristics *(draft)*

- Technical requirements
  - ***Linear distortion*** design criterion at topographic surface (*not* at ellipsoid surface)
    - Difference in distance between "grid" and "ground"
  - Use 1-parallel definition for LCC projections
- Other characteristics
  - Default designs (if no consensus stakeholder input)
  - "Layered" zones
  - Low-distortion projections (LDPs)
  - "Special purpose" zones

Lambert Conformal Conic projection

- Conical developable surface
- Used for many State Plane zones
- Can define scale two different ways:
  - Define scale ***explicitly*** on central standard parallel
  - Compute scale ***implicitly***
    - From separation between two "standard" parallels
    - Scale (at ellipsoid) is exactly 1 for standard parallels
- The two types are mathematically identical!
  - "Projection axis" for both is central standard parallel

Why only a 1-parallel LCC?

- Consistency
  - Explicitly define projection scale (same as TM and OM)
  - Can use same number of parameters as TM
  - Applicable to both “secant” and “non-intersecting” cases
- Simplicity
  - Easier to design with respect to topography
  - Scale due to separation of 2 standard parallels not obvious
  - Can more readily use “clean” values for parallels
- Mathematically identical to 2-parallel
  - ***Any 2-parallel LCC can be recast as 1-parallel that behaves exactly the same***

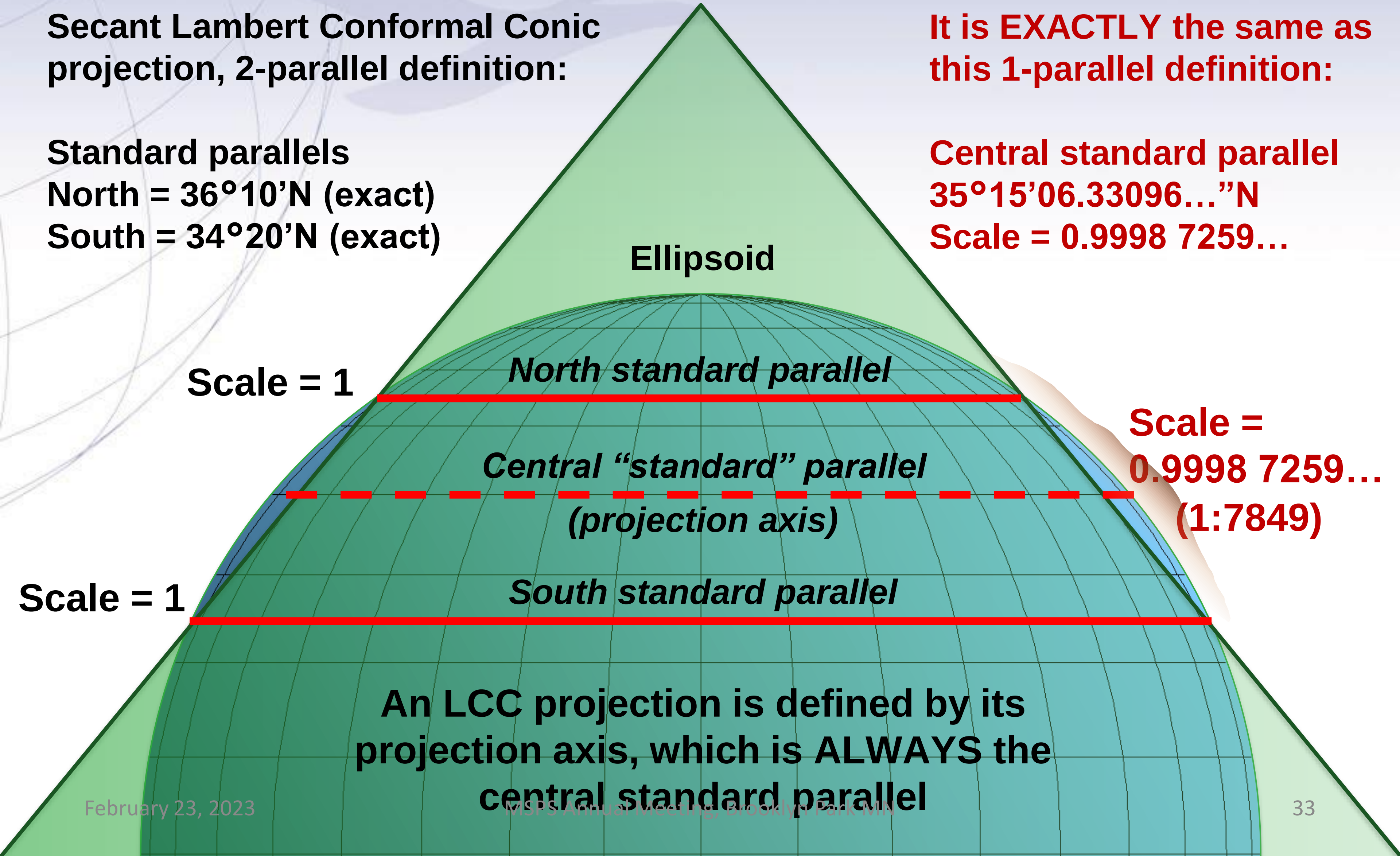
Consider North Carolina SPCS 83 Zone

Secant Lambert Conformal Conic projection, 2-parallel definition:

Standard parallels
North = 36°10'N (exact)
South = 34°20'N (exact)

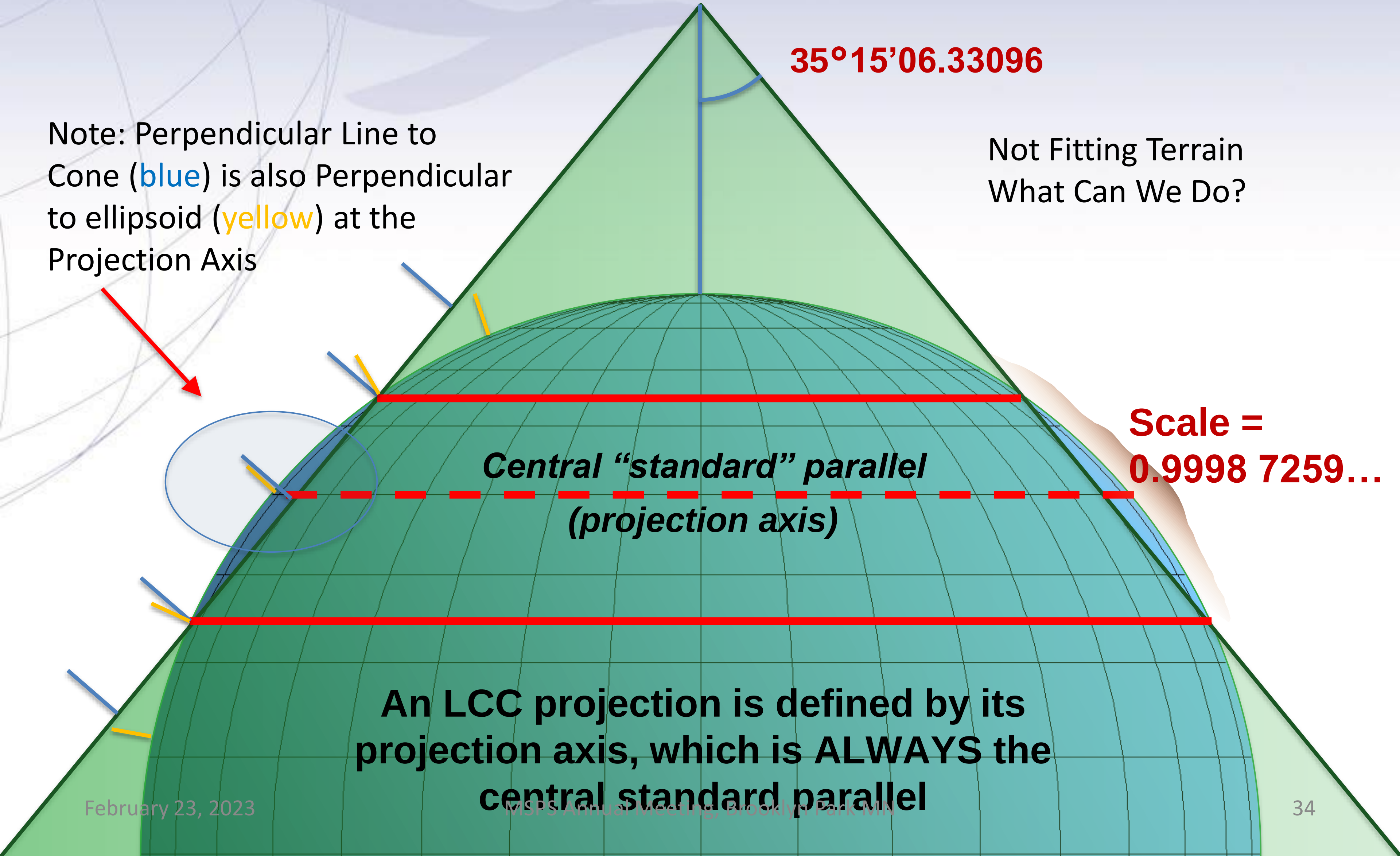
It is EXACTLY the same as this 1-parallel definition:

Central standard parallel 35°15'06.33096…"N
Scale = 0.9998 7259…

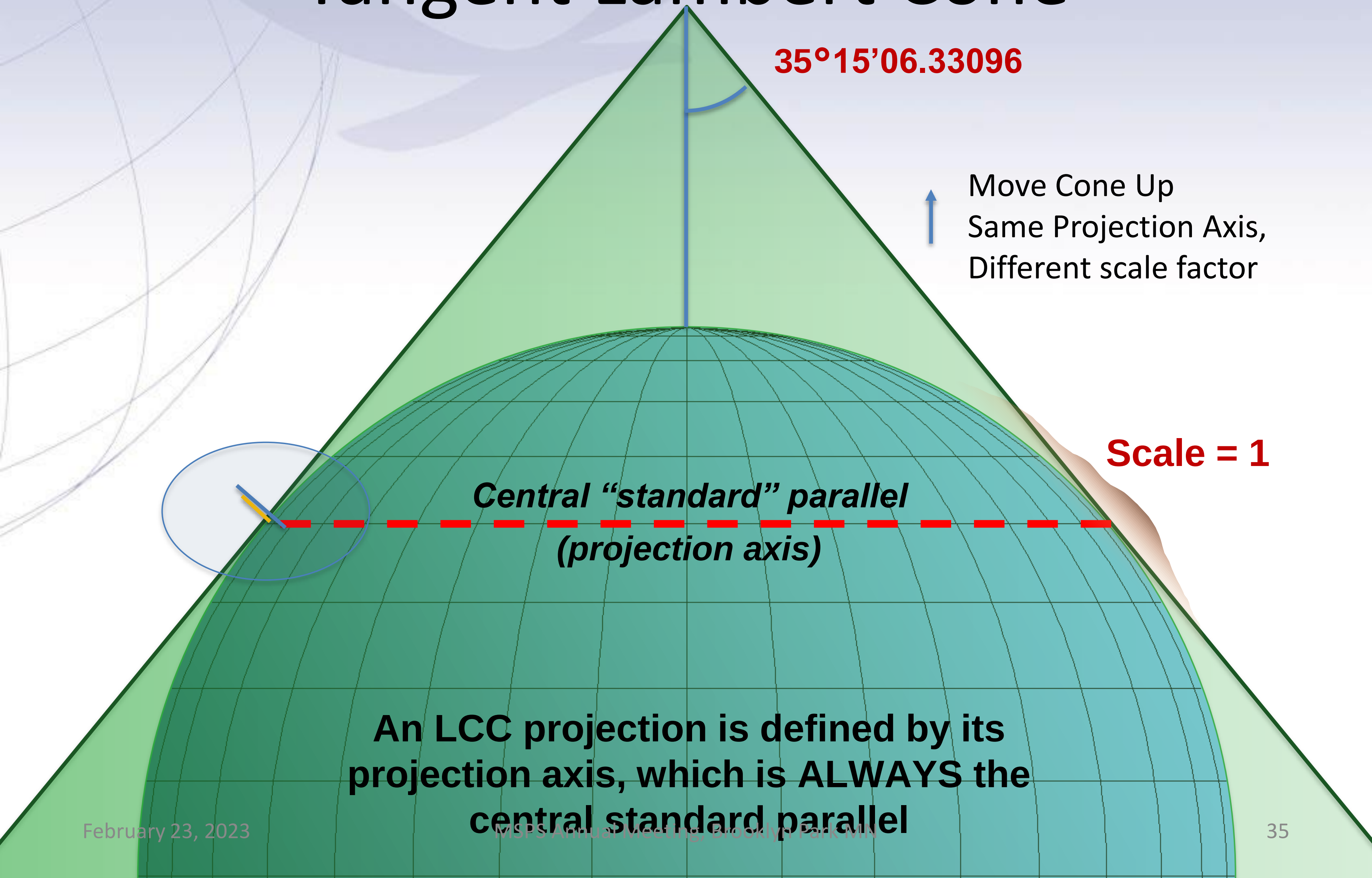


An LCC projection is defined by its projection axis, which is ALWAYS the central standard parallel

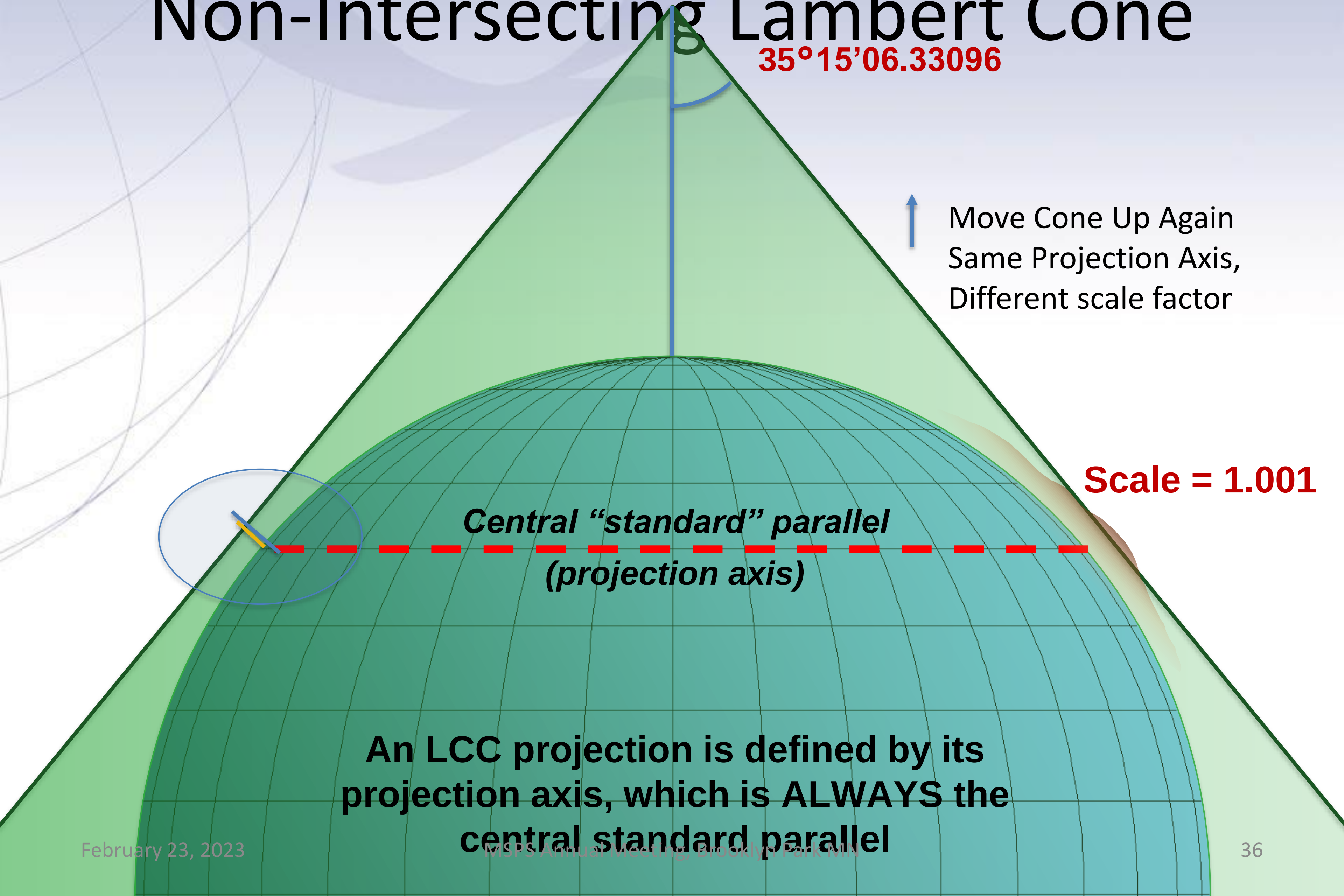
Secant Lambert Cone



Tangent Lambert Cone

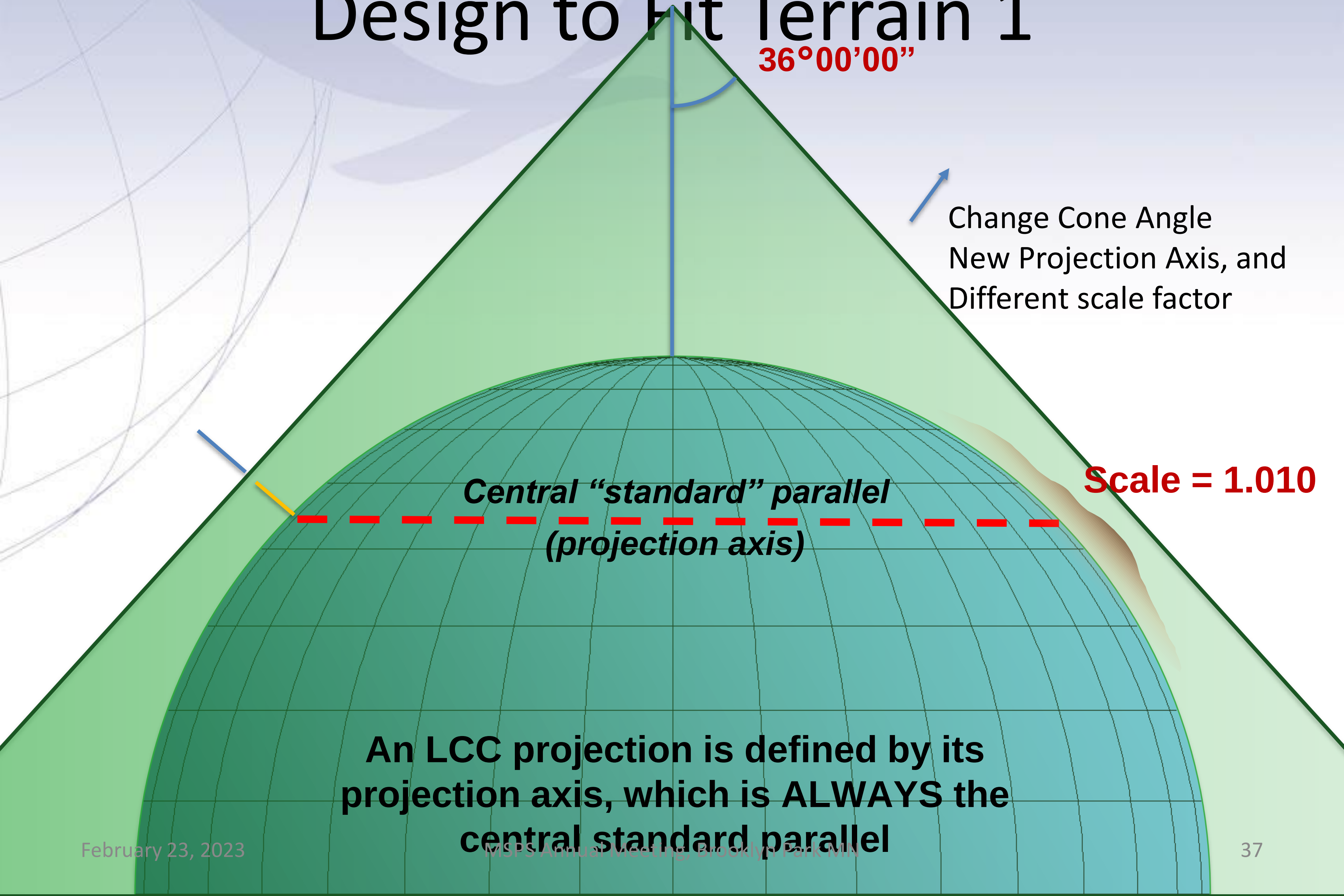


Non-Intersecting Lambert Cone

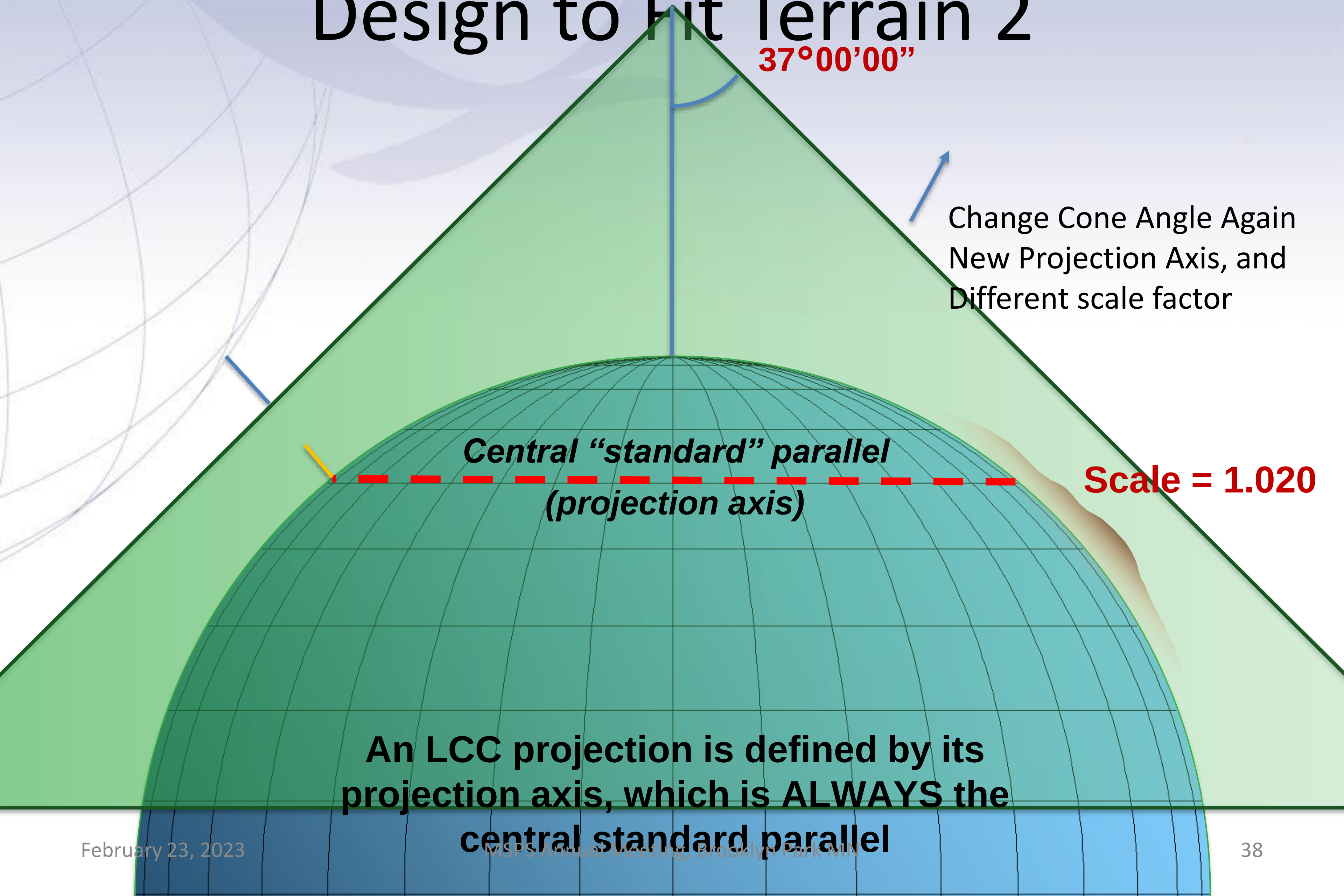


An LCC projection is defined by its projection axis, which is ALWAYS the central standard parallel

Design to Fit Terrain 1

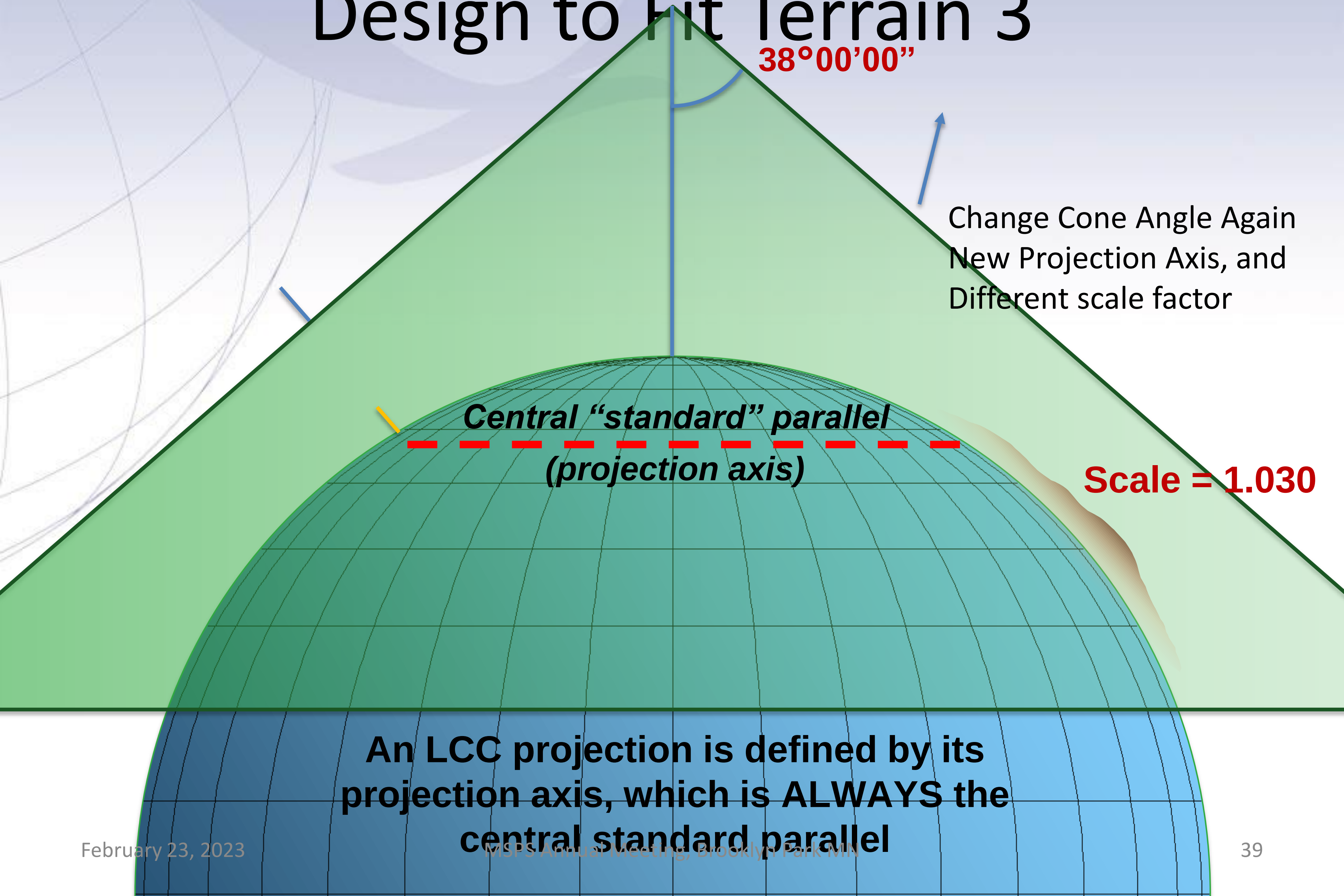


Design to Fit Terrain 2



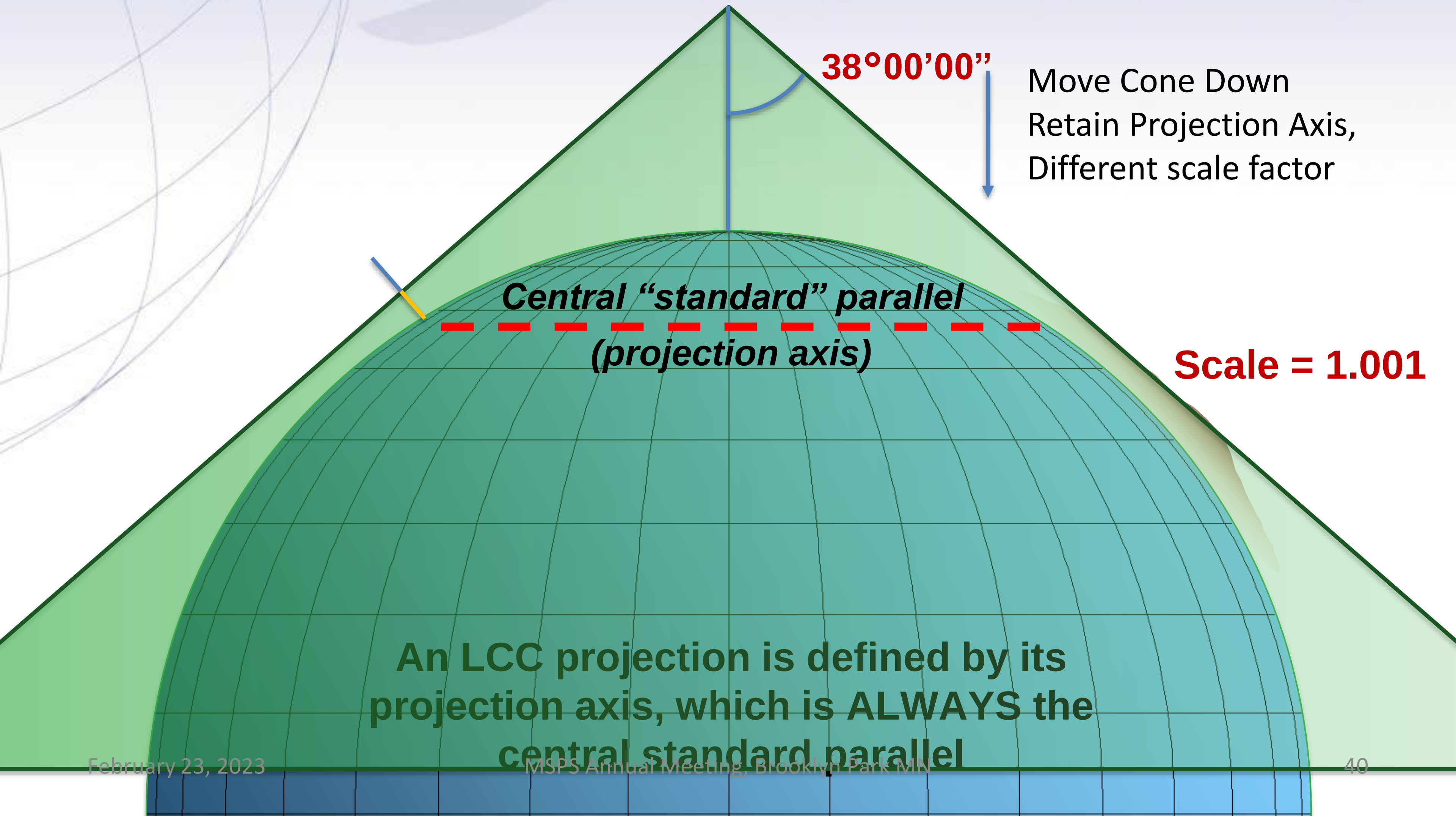
An LCC projection is defined by its projection axis, which is ALWAYS the central standard parallel

Design to Fit Terrain 3



An LCC projection is defined by its projection axis, which is ALWAYS the central standard parallel

Design to Fit Terrain 4



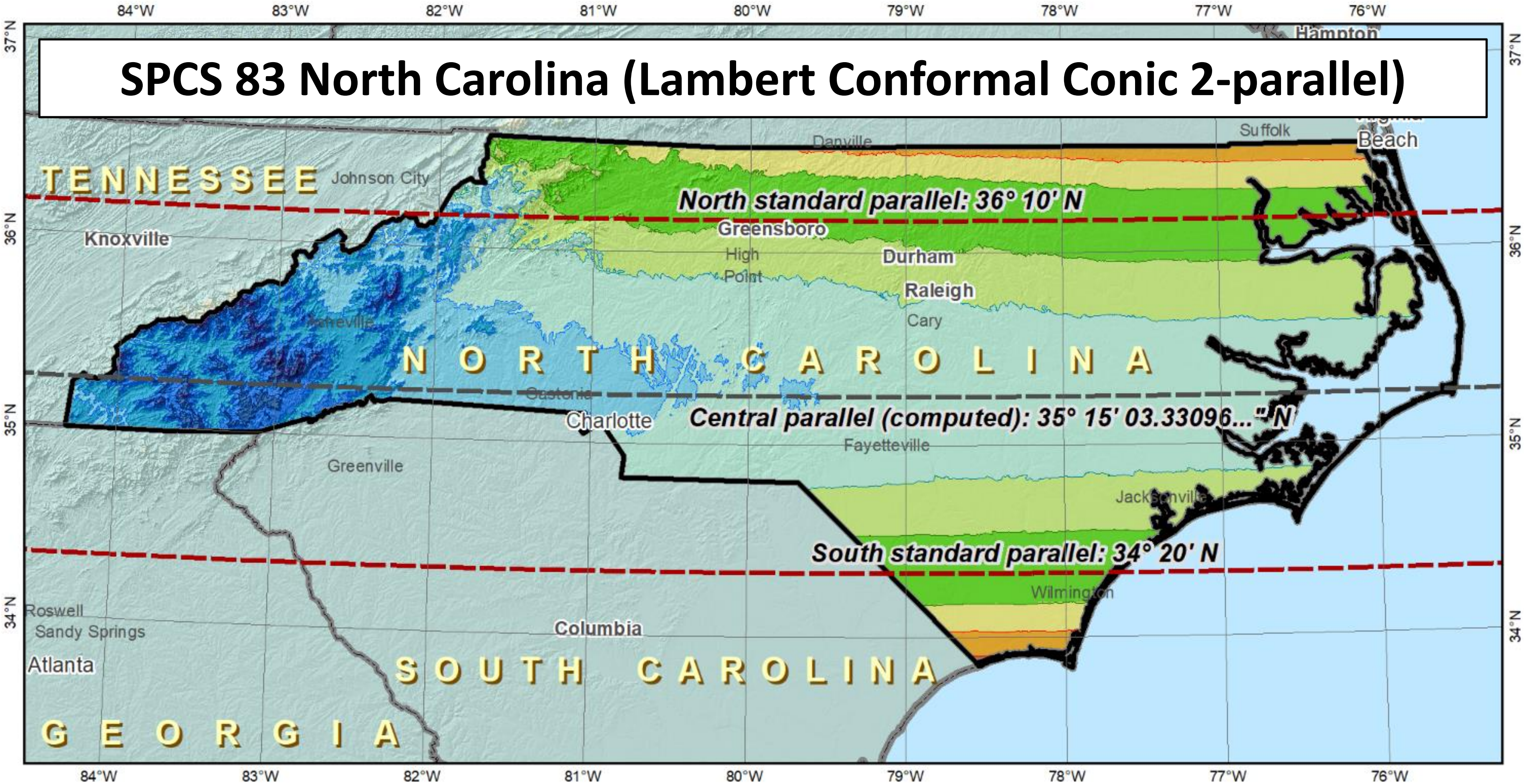
SPCS2022 characteristics ***(draft)***

- Technical requirements
  - ***Linear distortion*** design criterion at topographic surface (*not* at ellipsoid surface)
    - Difference in distance between "grid" and "ground"
  - Use 1-parallel definition for LCC projections
- Other characteristics
  - Default designs (if no consensus stakeholder input)
  - "Layered" zones
  - Low-distortion projections (LDPs)
  - "Special purpose" zones

Default SPCS2022 designs *(draft)*

- Default needed in absence of stakeholder input
- Same projections and zones for most SPCS 83 zones
- Performance and coverage very similar to SPCS 83
- Characteristics that differ from SPCS 83:
  - Projection scale modified to minimize distortion at ground
  - Lambert Conformal Conic converted to one-parallel type
  - Most geodetic origins with arc-minutes evenly divisible by 3
  - A few zones with different projection & zone extents

SPCS 83 North Carolina (Lambert Conformal Conic 2-parallel)



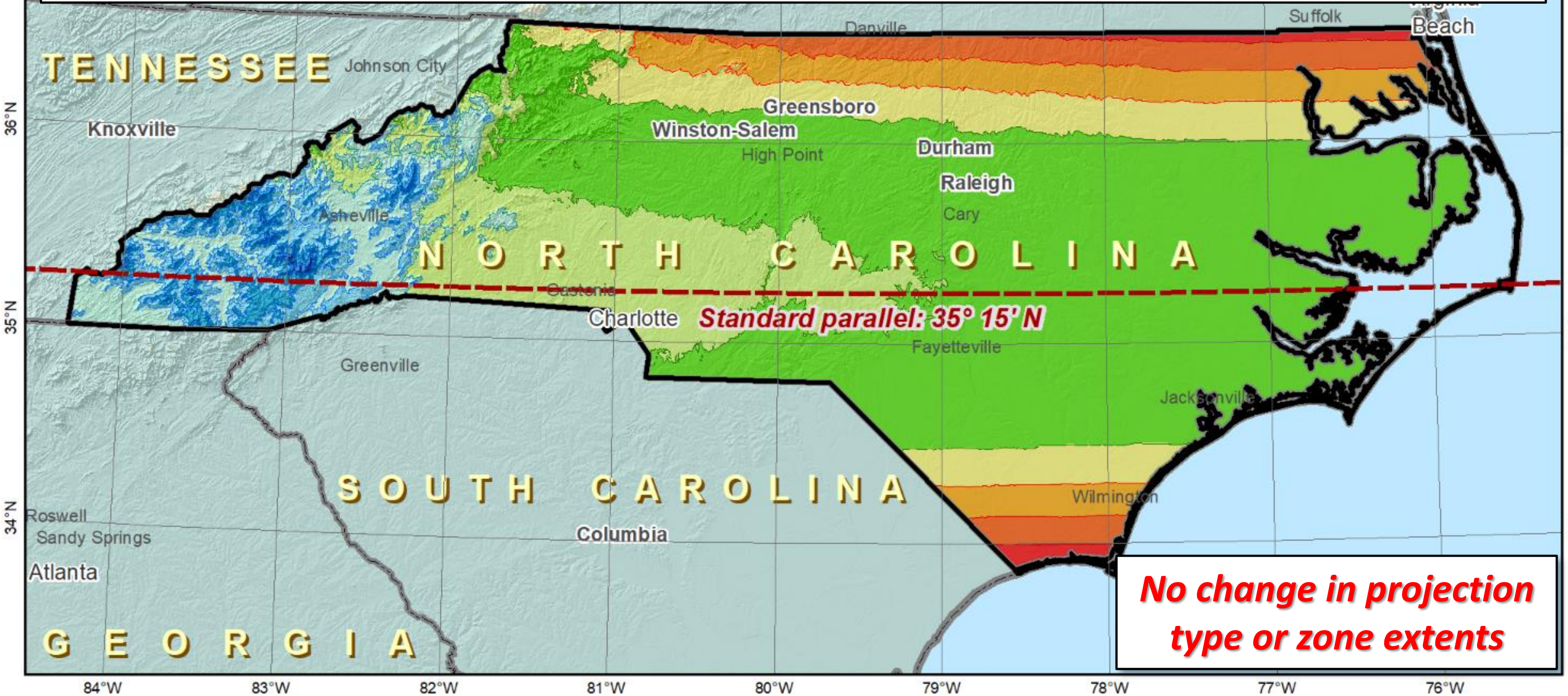
Linear distortion (parts per million)

< -400	to -200	to +150
to -400	to -150	to +200
to -350	to -100	to +250
to -300	±50	to +300
to -250	to +100	> +300

0 50 100 150 200 250 km

		SPCS 83 NC
Central parallel		35°15'06.33…"N
Cen parallel scale		0.9998 7259…
	Height (m)	Distortion (ppm)
Min	-41	-413
Max	1939	+176
Mean	197	-93

SPCS2022 “default” NC (Lambert Conformal Conic 1-parallel)

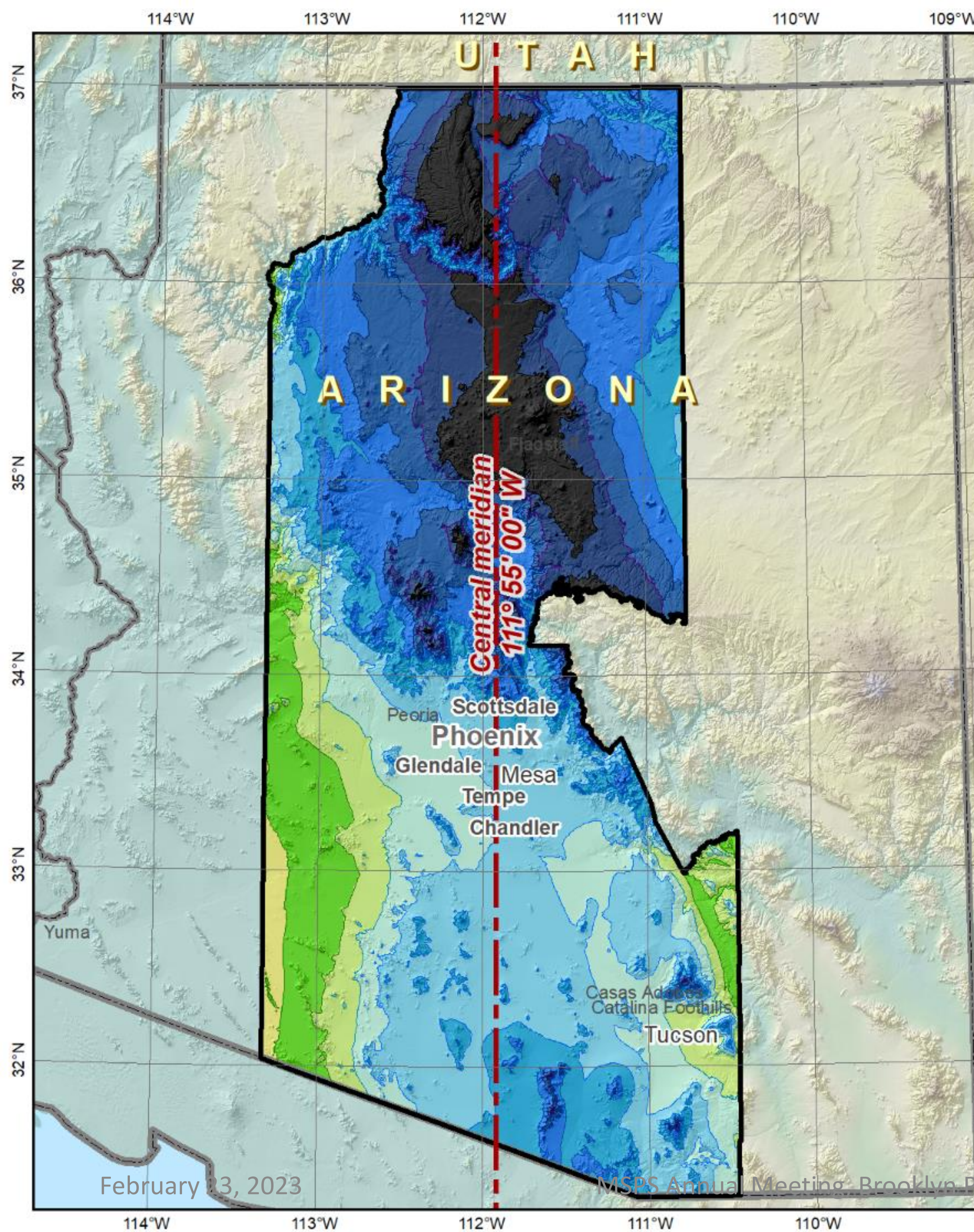


Linear distortion (parts per million)

< -400	to -200	to +150
to -400	to -150	to +200
to -350	to -100	to +250
to -300	±50	to +300
to -250	to +100	> +300

0 50 100 150 200 250 km

	Height (m)	SPCS 83 NC	SPCS2022
Central parallel		35°15’06.33…”N	35°15’N
Cen parallel scale		0.9998 7259…	0.99996
	Height (m)	**Distortion (ppm)**	
Min	-41	-413	-325
Max	1939	+176	+263
Mean	197	-93	-5

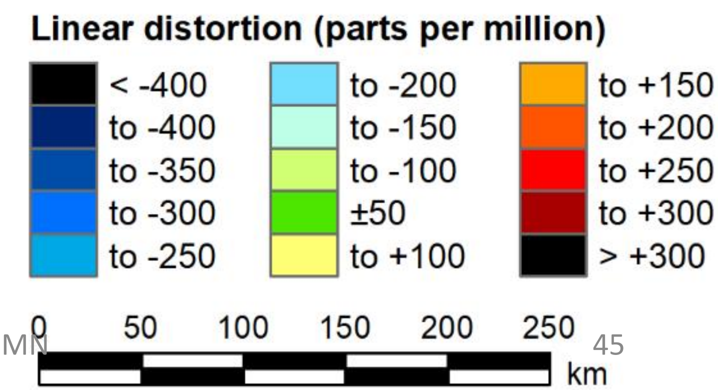


SPCS 83
Arizona Central Zone
(Transverse Mercator)

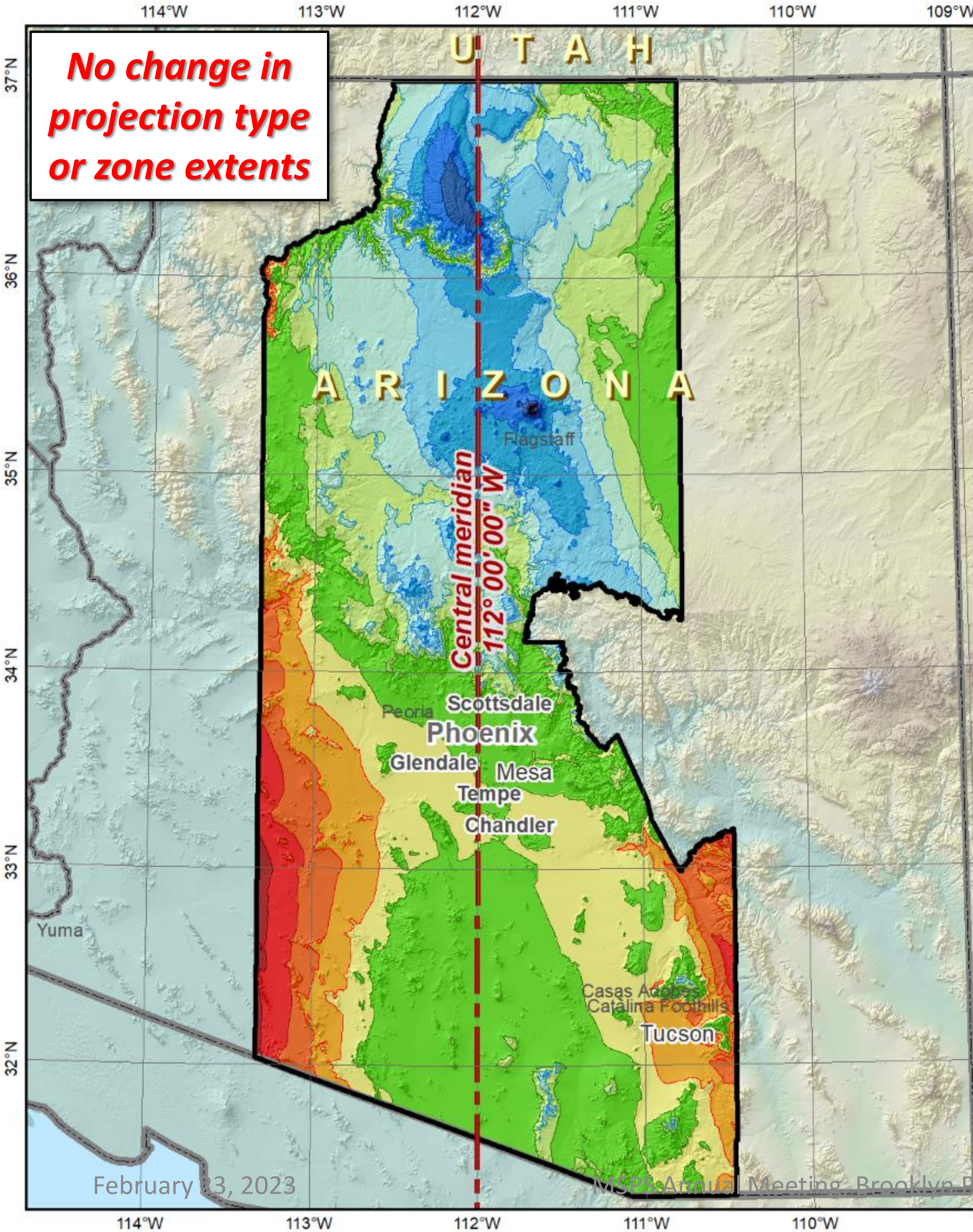
Height (m)	
Min	96
Max	3607
Mean	1177

SPCS 83 AZ C

C.M.	111°55'W
Scale	0.9999
Distortion (ppm)	
Min	-660
Max	+102
Mean	-224

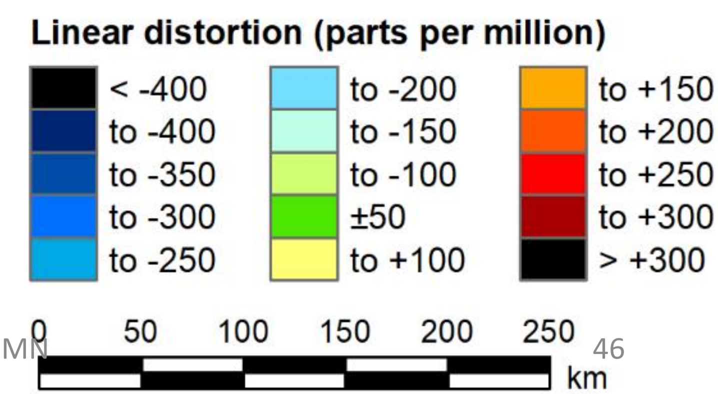


SPCS2022 "default" Arizona Central Zone (Transverse Mercator)



	Height (m)
Min	96
Max	3607
Mean	1177

	SPCS 83 AZ C	SPCS2022
C.M.	111°55'W	112°W
Scale	0.9999	1.0001
	Distortion (ppm)	
Min	-660	-455
Max	+102	+277
Mean	-224	-24



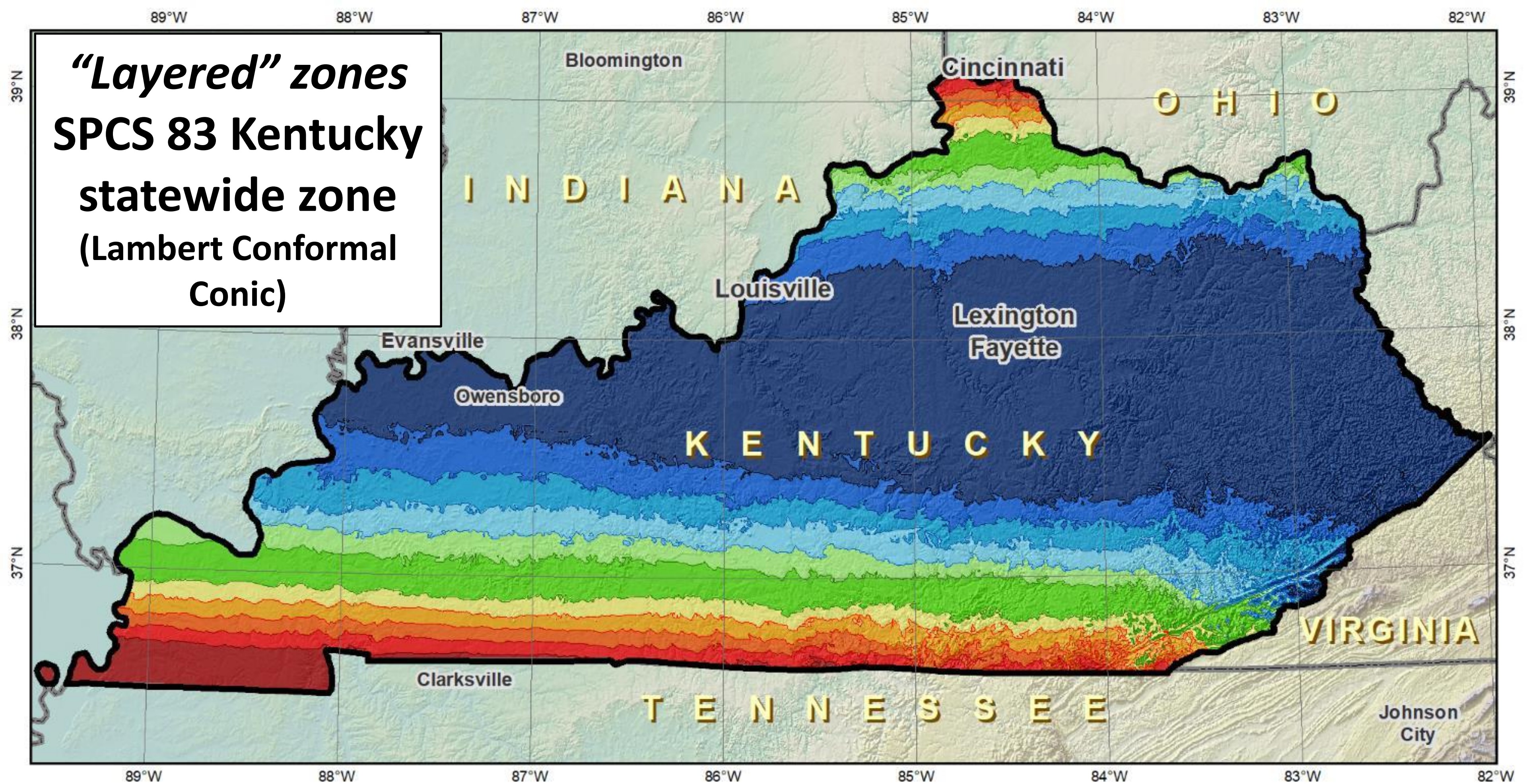
"Layered" zones ***(draft)***

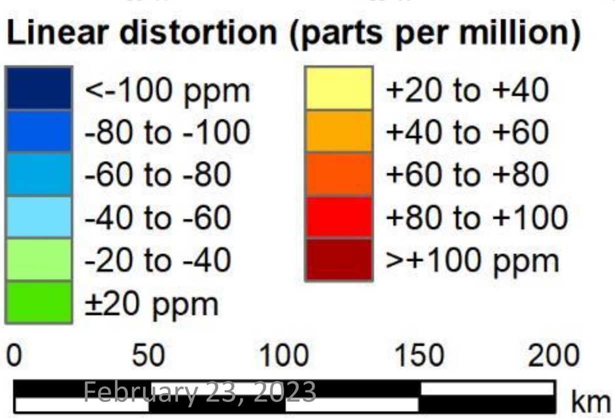
- Limitations
  - Max of ***TWO*** layers: Statewide and sub-zones
  - If two layers, one ***MUST*** be statewide
  - Minimum sub-zone dimension > 50 km

But not a 3rd Layer

- States often want statewide ***and*** small zones
  - *Statewide:* Single geometry required for state GIS
  - *Sub-zones:* Lower distortion for surveying/engineering
- Accommodates state needs, but with restrictions
  - Prevent poor design choices for statewide zones
  - One already exists in SPCS 83…

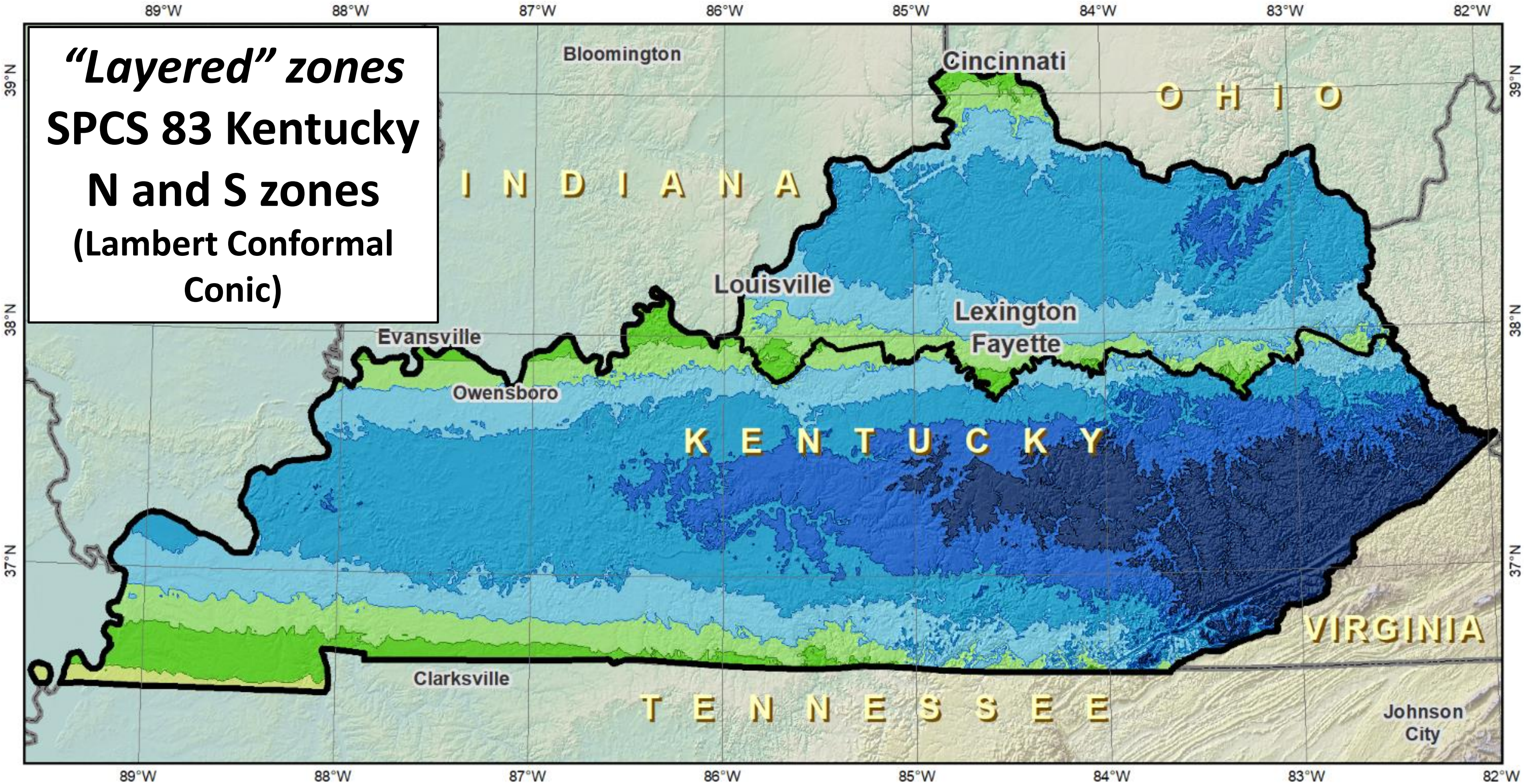
"Layered" zones SPCS 83 Kentucky statewide zone (Lambert Conformal Conic)

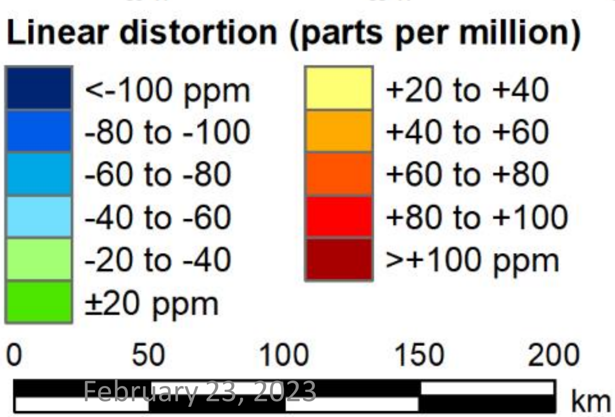




	North	South	Statewide
N parallel	38°58'N	37°56'N	38°40'N
S parallel	37°58'N	36°44'N	37°05'N
	Distortion (ppm)		
Min	-93	-211	-166
Max	+17	+42	+181
Mean	-56	-67	-58

“Layered” zones SPCS 83 Kentucky N and S zones
(Lambert Conformal Conic)



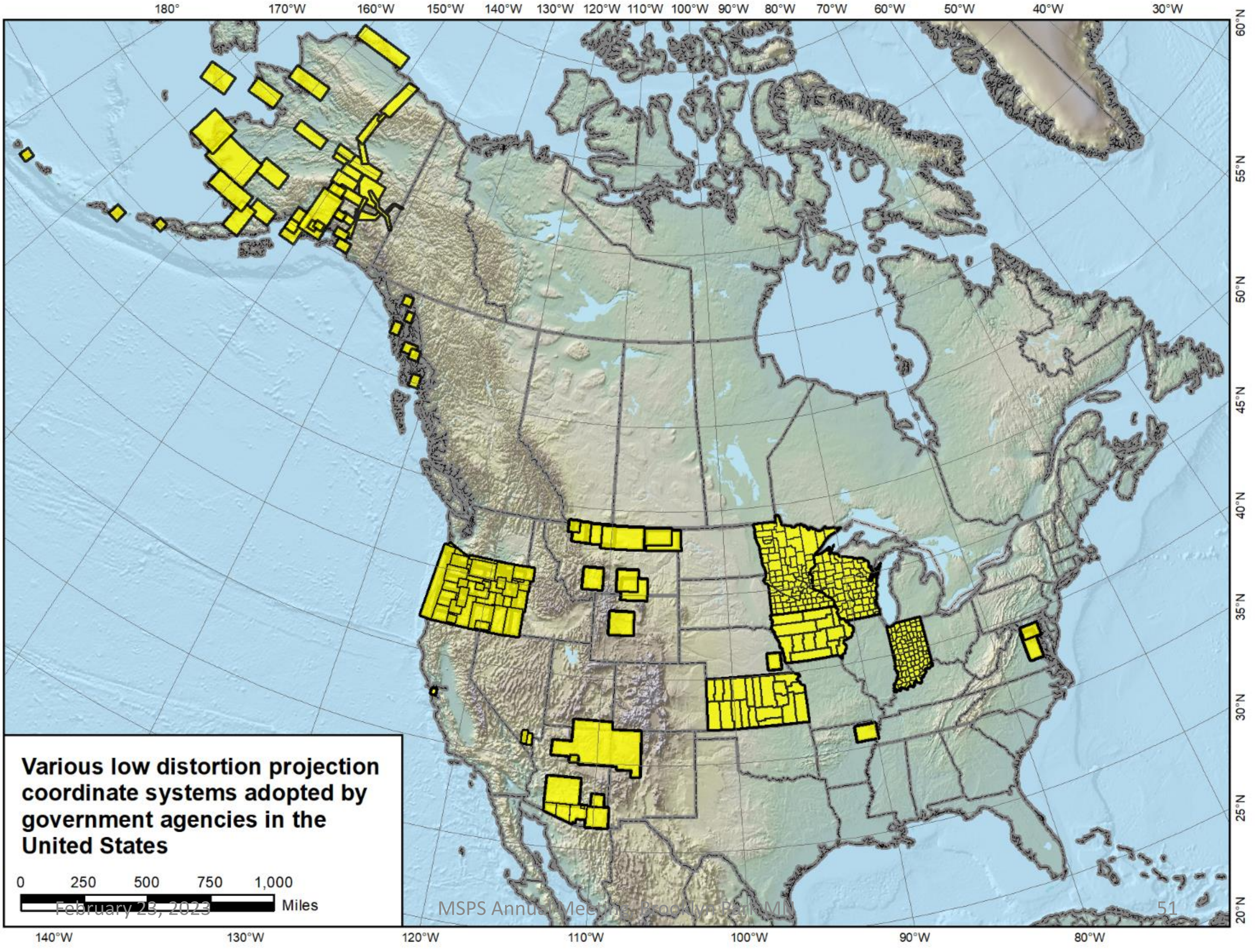


	North	South
N parallel	38°58’N	37°56’N
S parallel	37°58’N	36°44’N
	Distortion (ppm)	
Min	-93	-211
Max	+17	+42
Mean	-56	-67

Linear distortion design criteria ***(draft)***

- NGS design of zones requested by stakeholders
  - Limited to zones with 50-400 ppm distortion criterion
    - **50 ppm** = 5 cm/km = 0.3 ft/mi = 1:20,000
    - **400 ppm** = 40 cm/km = 2.1 ft/mi = 1:2,500
- Design criterion < 50 ppm ("low distortion")
  - Min criterion **20 ppm** = 2 cm/km = 0.1 ft/mi = 1:50,000
  - Must be designed by others (not by NGS)
  - Proposed and final design reviewed by NGS

What is the current situation with "low distortion" projected coordinate systems?


Various low distortion projection coordinate systems adopted by government agencies in the United States
0 250 500 750 1,000
Miles
180°
170°W
160°W
150°W
140°W
130°W
120°W
110°W
100°W
90°W
80°W
70°W
60°W
50°W
40°W
30°W
140°W
130°W
120°W
110°W
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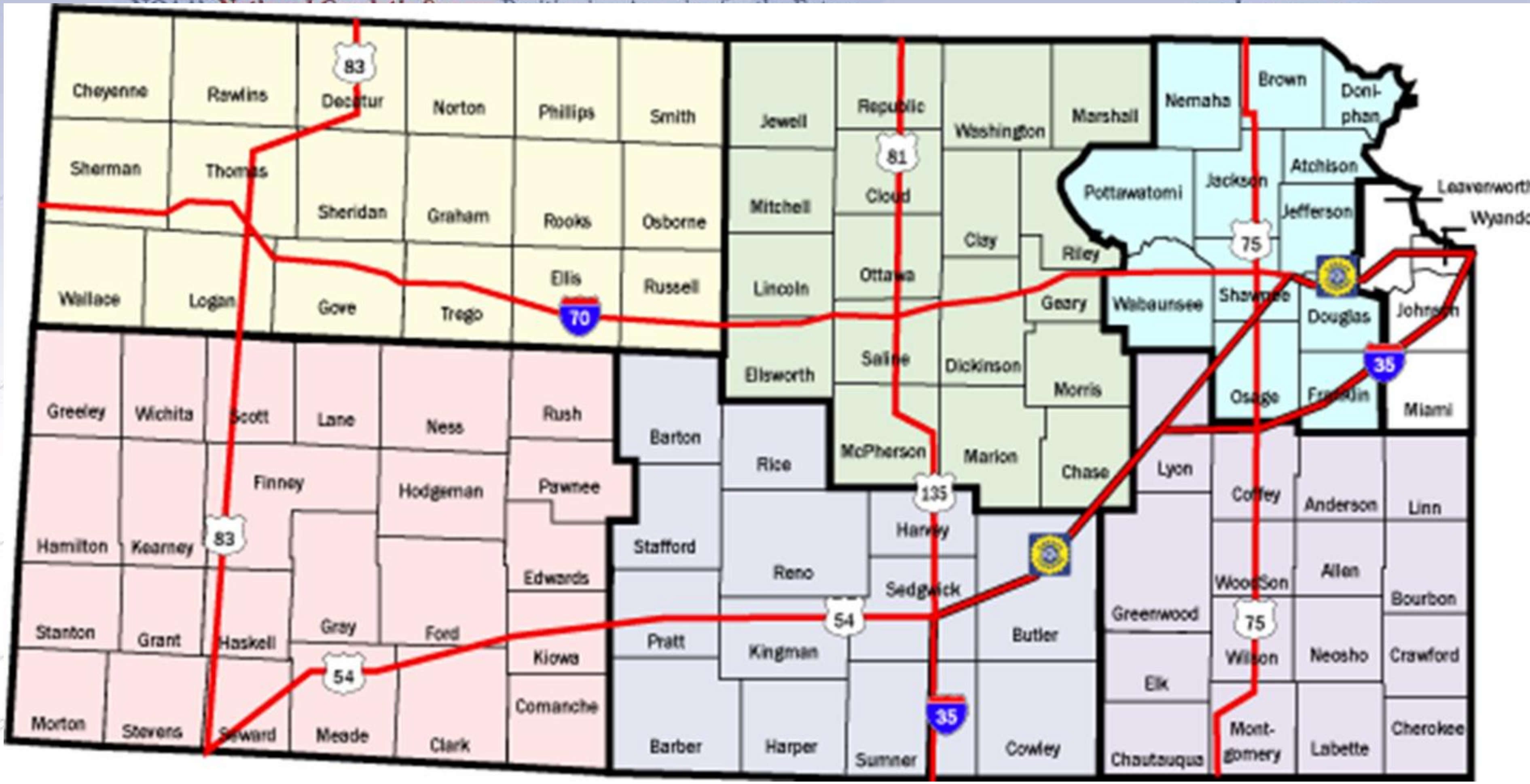
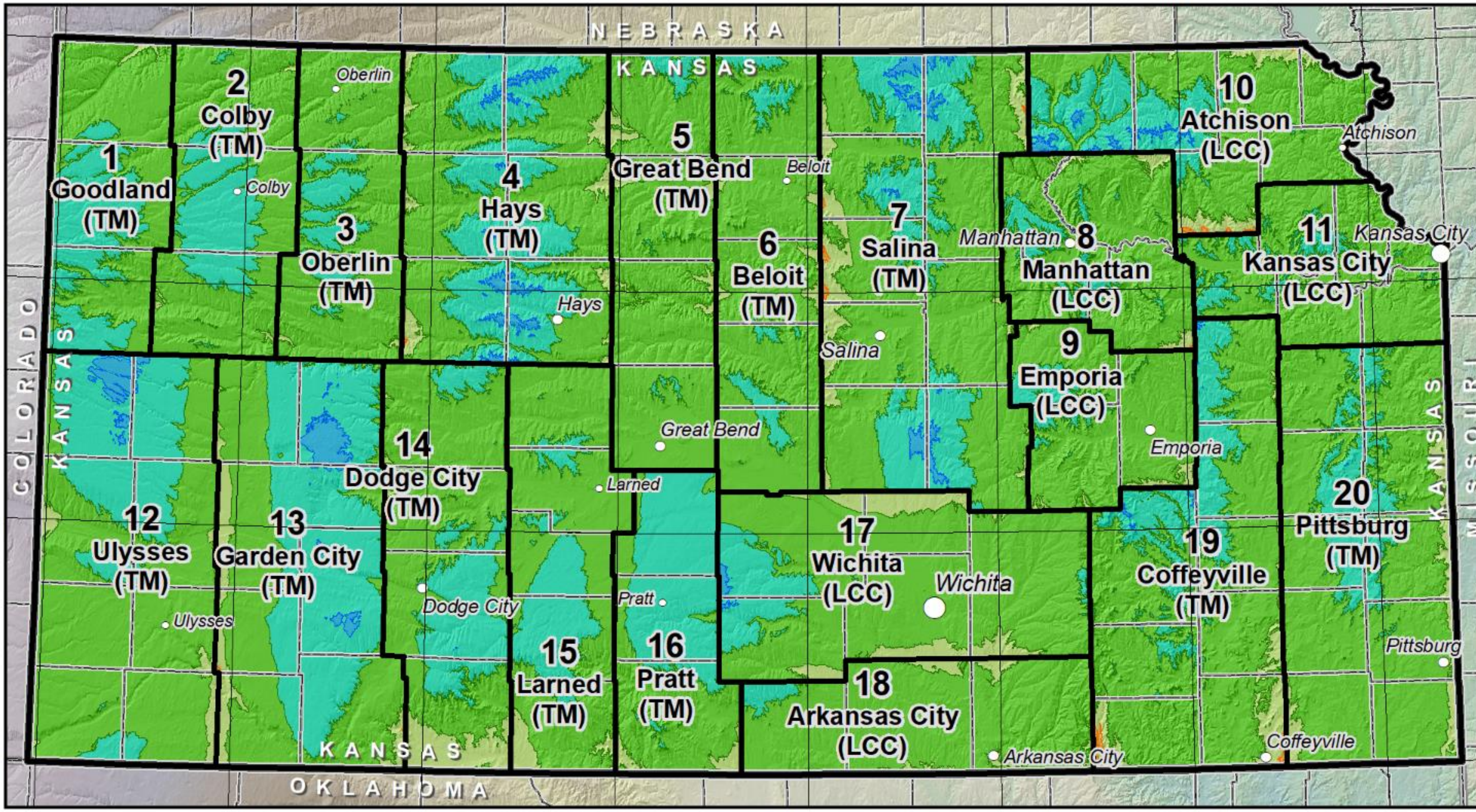
30°N
25°N
20°N



Kansas Map

Note county lines

https://www.kansas.gov/khp-crashlogs/search/index



Kansas Regional Coordinate System (KRCS)

All zones referenced to the North American Datum of 1983

Statewide Distortion Statistics

Minimum:	-26.9 ppm	*Area of the state that is:*
Maximum:	+26.0 ppm	within ±10 ppm = 68.330%
Mean:	-4.0 ppm	within ±20 ppm = 98.802%
Std dev:	+8.2 ppm	within ±25 ppm = 99.998%

Linear Distortion (parts per million)

- <-25 ppm (0.16 ft/mile)
- -20 to -25 ppm
- -10 to -20 ppm
- ±10 ppm (0.05 ft/mile)
- +10 to +20 ppm
- +20 to +25 ppm
- >+25 ppm (0.13 ft/mile)

Projection Types

TM = Transverse Mercator

LCC = Lambert Conformal Conic

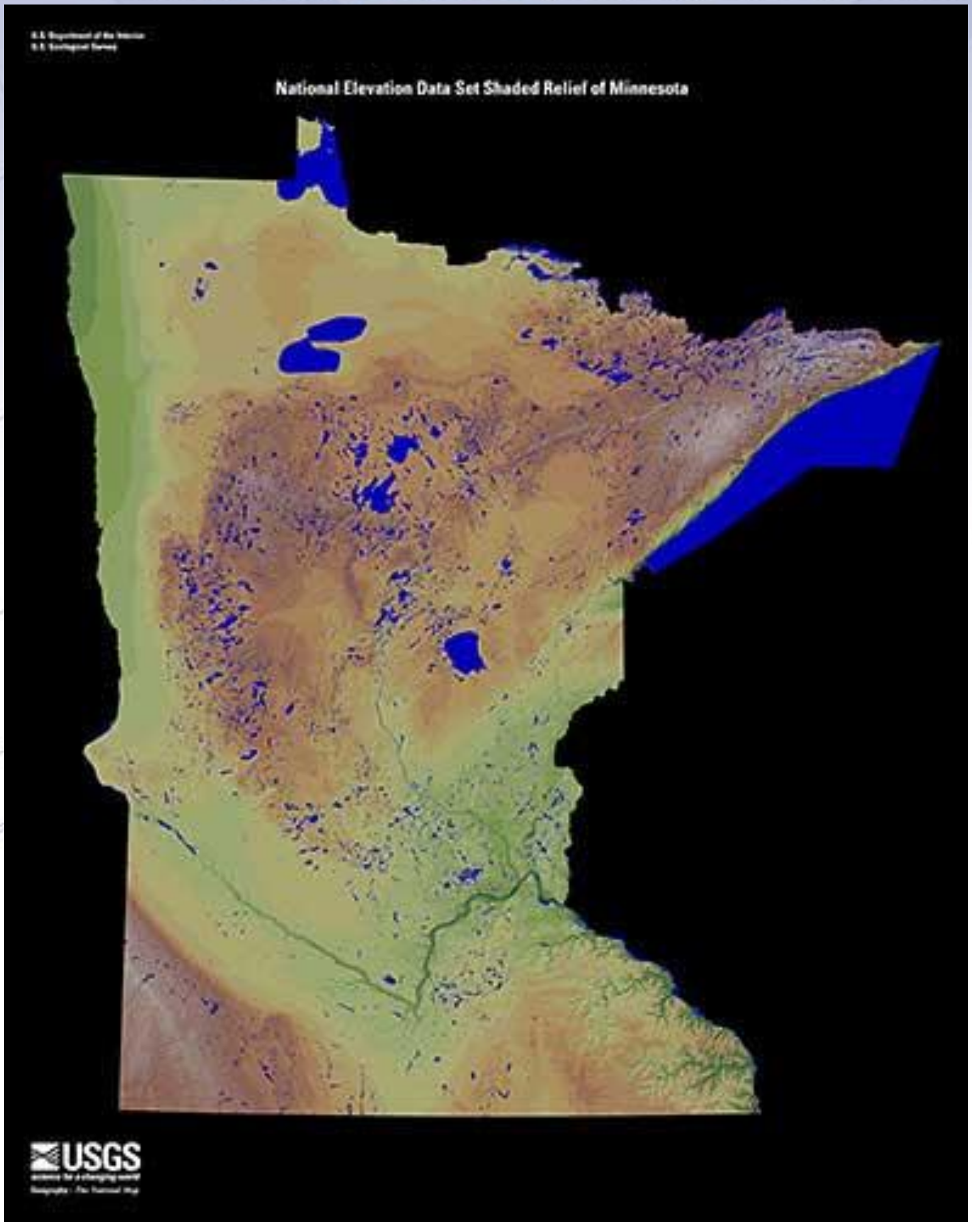
0 25 50 75 100 Miles

"Special purpose" zones *(FRN)*

- For areas with inadequate SPCS zone coverage
  - Usually areas that are in more than one zone
- Categories:
  - Major urban areas (e.g., New York, Chicago, St. Louis)
  - Large Indian reservations (e.g., Navajo Nation)
  - Federal applications covering large areas (e.g., coastal mapping of Atlantic Coast; Grand Canyon)
- Permitted for metro areas in 1977 policy (but never used)
- Only in FRN, ***not*** in draft policy & procedures
  - Intent is to get input on concept first

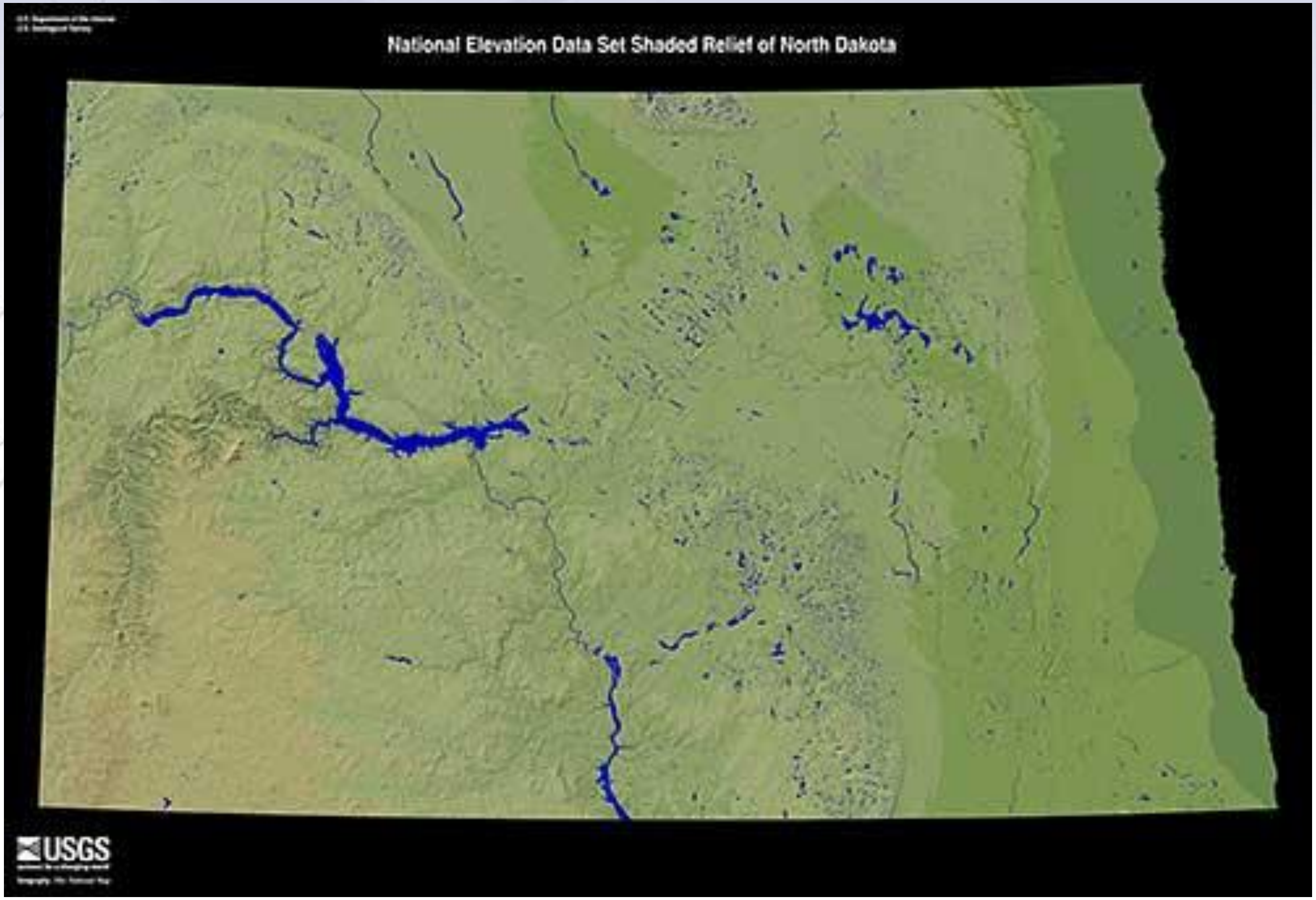
Twin Cities "Metro" Zone?

Minnesota Shaded Relief



https://eros.usgs.gov/sites/all/files/external/imagegallery/2523.jpg

North Dakota Shaded Relief



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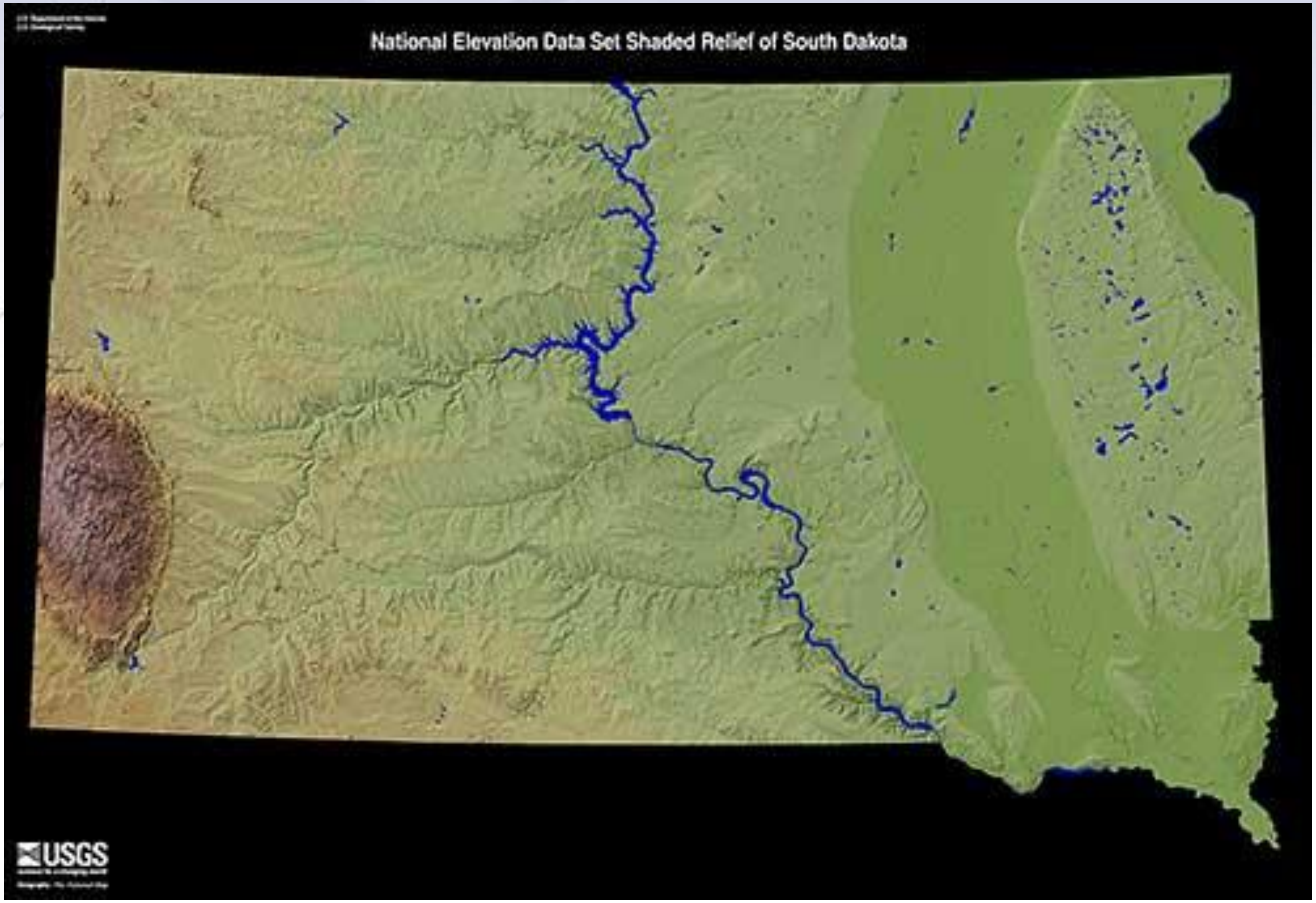
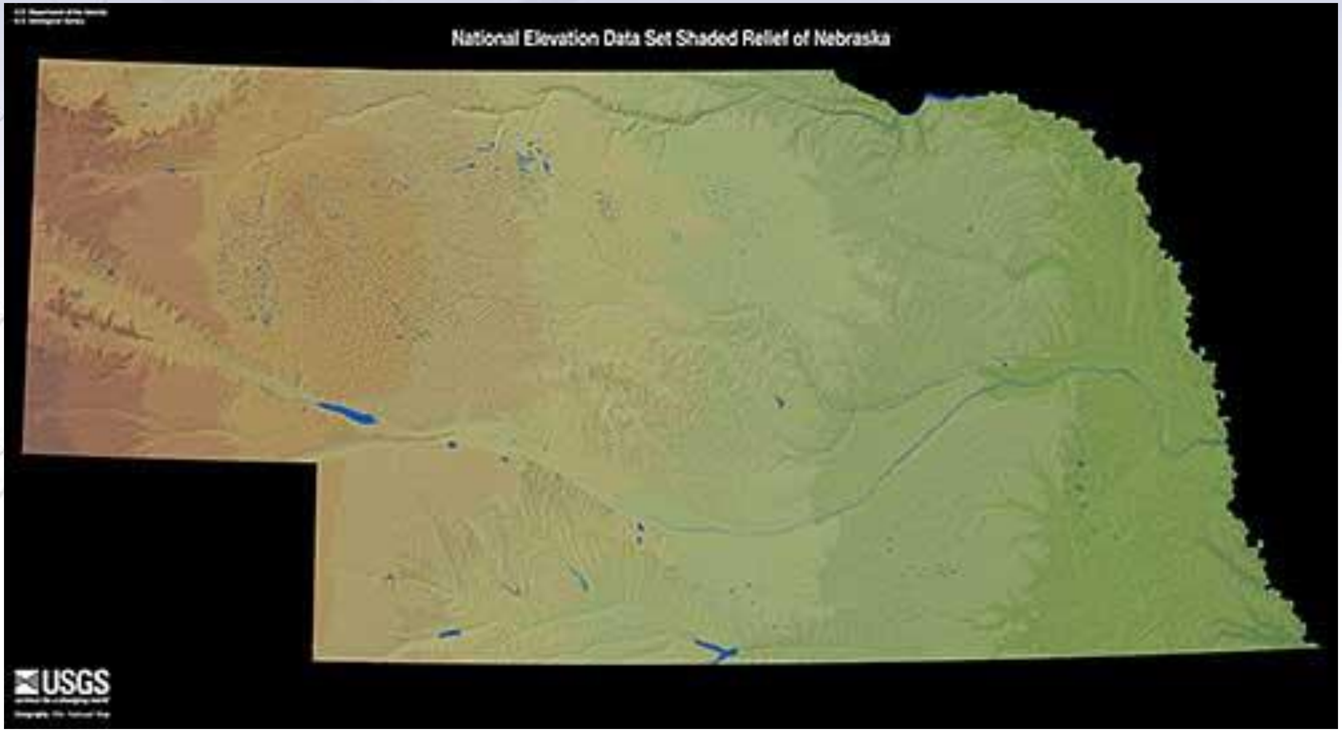
South Dakota Shaded Relief



https://eros.usgs.gov/imagegallery/states-ned-shaded-relief#https://eros.usgs.gov/sites/all/files/external/imagegallery/2542

Nebraska Shaded Relief



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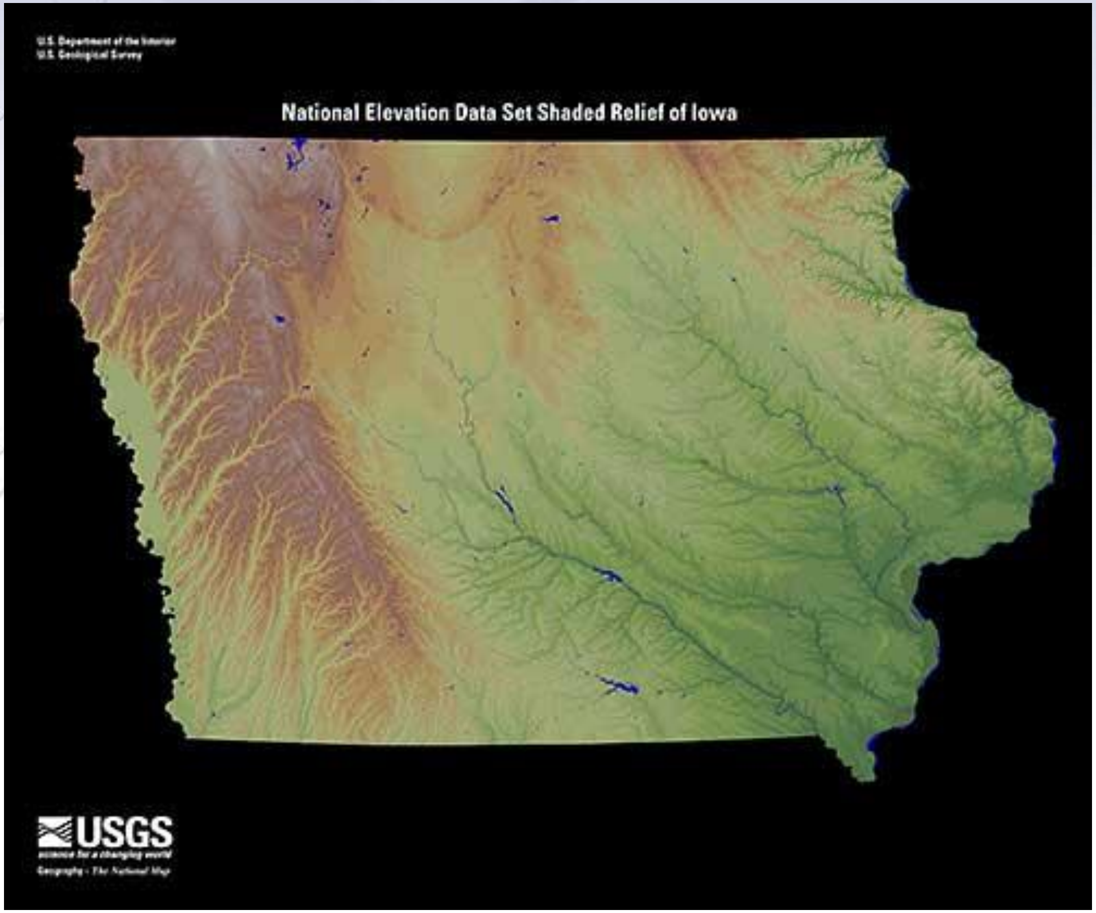
Iowa Shaded Relief



https://eros.usgs.gov/imagegallery/states-ned-shaded-relief#https://eros.usgs.gov/sites/all/files/external/imagegallery/2516

Wrap-up

- State Plane has a long and varied history
- Main characteristics of SPCS2022 ***(draft)***
  - Designed with respect to "ground"
  - Use 1-parallel definitions for LCCs
  - Default designs similar to existing State Plane
  - Can include a statewide zone plus a sub-zone layer
  - LDPs can be used but must be designed by others
- Stakeholder input on zones for their states
- **Next State Plane webinar on April 12 – register at:**

https://geodesy.noaa.gov/web/science_edu/webinar_series/Webinars.shtml

NOTE: SPCS2022 policy, procedures, and FRN currently in review
Approved version may differ from what is presented here but should be finalized before April 12 webinar