CEPC data processing scheme

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On behalf of Installation and Alignment team

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Contents

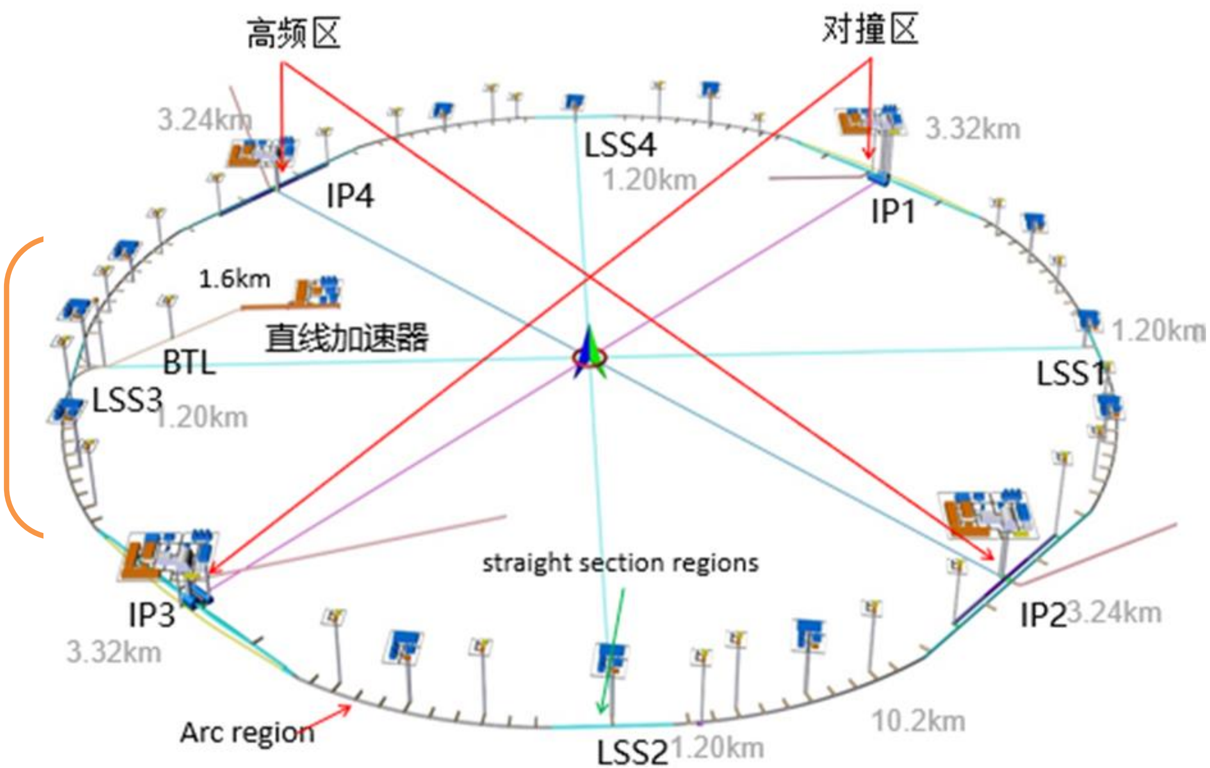
Review

- CDR work
  - Alignment control network design
  - Component fiducialization and pre-alignment design
  - Tunnel installation alignment design
  - Component smooth alignment design
  - Position monitoring system design
- TDR work
  - An overall component installation scheme was made based on 8 years construction period. Include work contents, manpower plan and installation progress schedule.
  - Vision instrument development to improve measurement efficiency. Four times photogrammetry experiments were carried out, million capacity coded target and five-face target were tested. The body of vision instrument manufacture was completed, system integration and software development is ongoing.
  - Today's report is about alignment data processing.

Geodetic problem of CEPC alignment

- CEPC structure
  - Collider ring circumference:100km
  - Ring diameter : 32km
  - Large dimension brings new challenges

*Linac: **1.2km***
*BT: **1.6km***
Circumference of ring tunnel:100km
*Collider: **100km***
Booster: 100km
Tunnel cross section: 6X5m



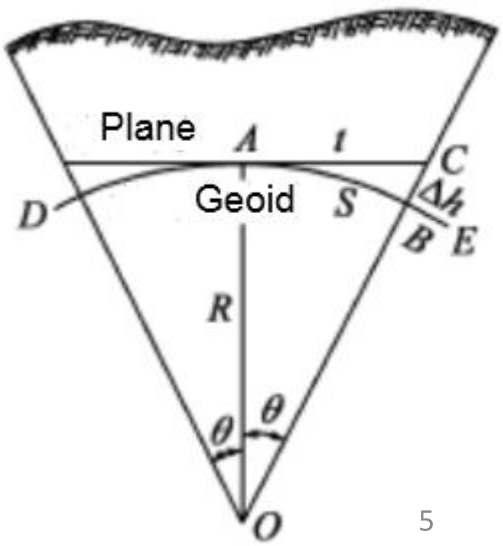
Ring tunnel

Geodetic problem of CEPC alignment

- Measurement reference datum: weight direction and geoid

- Traditional alignment measurement

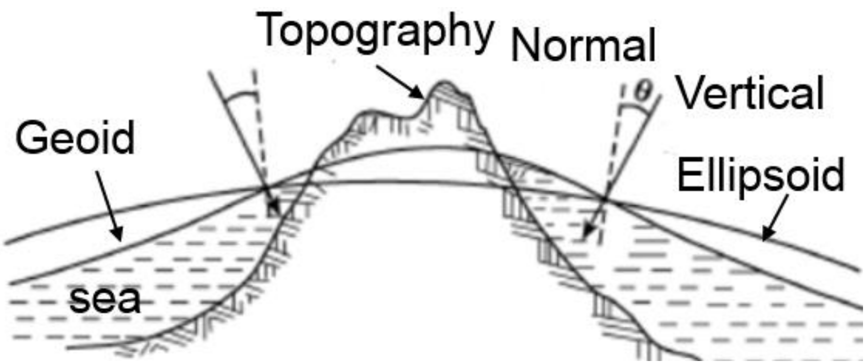
  - Accelerator dimensions: Tens of meters to several kilometers
  - Suppose the geoid is a plane or a sphere and weight direction is parallel with the normal.
  - Earth curvature has little effect in the horizontal direction but significant effect in the elevation direction.
  - Horizontal observations can be solved based on a plane and elevation observations can be solved based on a sphere.



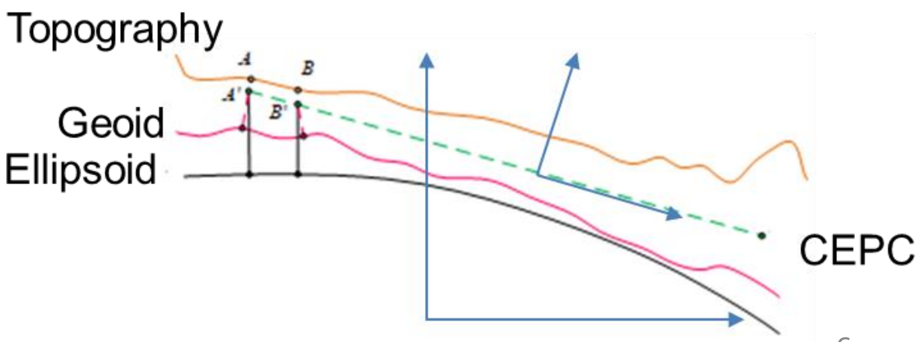
$$\Delta S = \frac{1}{3}\frac{S^3}{R^2} \qquad \Delta h = \frac{S^2}{2R} \qquad R=6371km$$

Geodetic problem of CEPC alignment

- Actual shape
  - Geoid and topography are irregular
  - Vertical change with the gravimetric equipotential surface

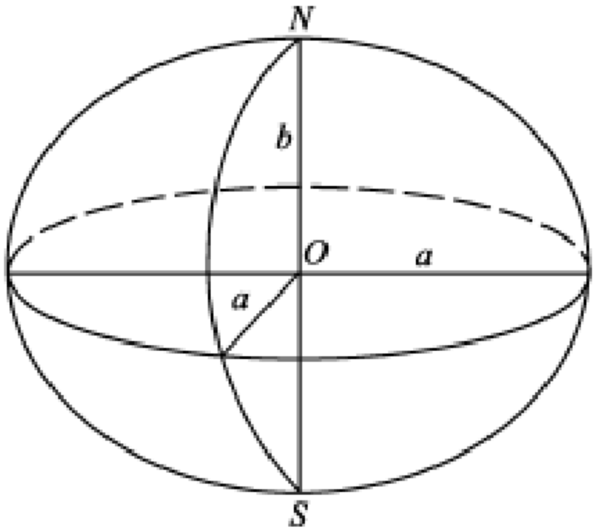


- CEPC measurement :Reference datum can not simply rely on standard geometry alone.
- Requirements for spatial position calculation
  1. datums
  2. Coordinate systems
  3. Data processing method



CEPC geodetic datum

CEPC geodetic datum



1. Reference Ellipsoid

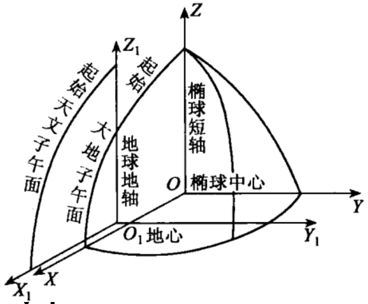
- Reference ellipsoid is the mathematical representation of the earth.
- Is the base to establish geodetic coordinate system, quasi-geoid model and vertical deflection model.
- Define reference ellipsoid includes: Determine ellipsoid parameters(Semi-major Axis, Flattening), ellipsoid location and ellipsoid directional
- Ellipsoid location:
    - Carry out Astro-Geodetic measurement on the surface control network points.
    - Multipoint location method (vertical deflection formula, General Laplace Equation) calculate the ellipsoid center position.

CEPC geodetic datum

- Make the ellipsoid best-fit with the local geoid in the CEPC area.

$\sum N^2 = \min$ N is the Height Anomaly

➢ Ellipsoid directional

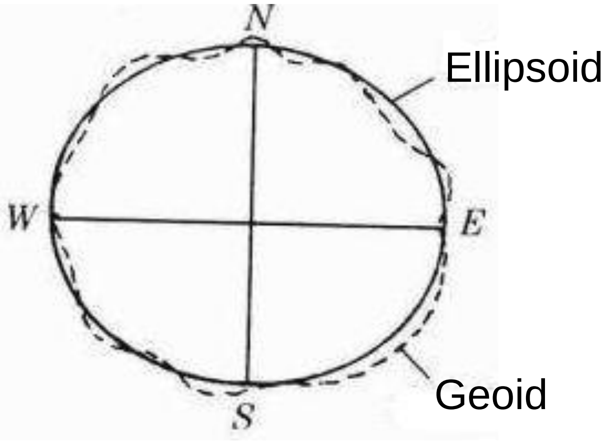


- Facilitate the conversion between geodetic coordinates and astronomical coordinates: Semi-minor Axis parallel with the Earth's rotation axis, geodetic prime meridian plane parallel with the prime astronomical meridian plane.

2. Quasi-Geoid

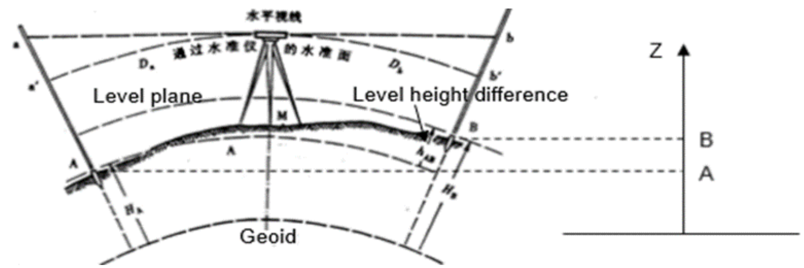
➢ Mathematic model, its shape is very close to the Geoid.

➢ Height datum for level measurement.

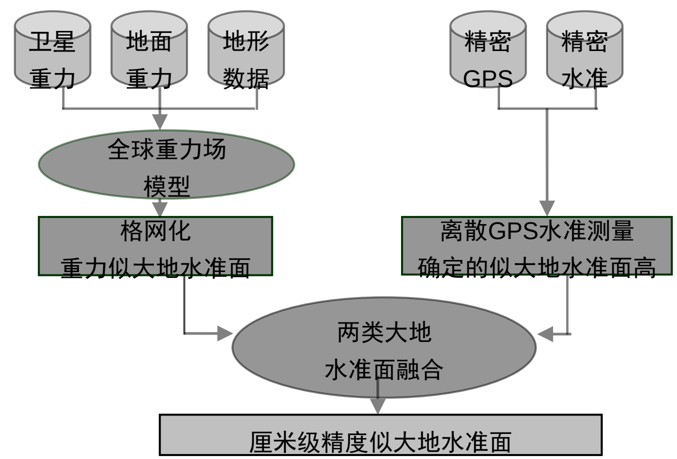


CEPC geodetic datum

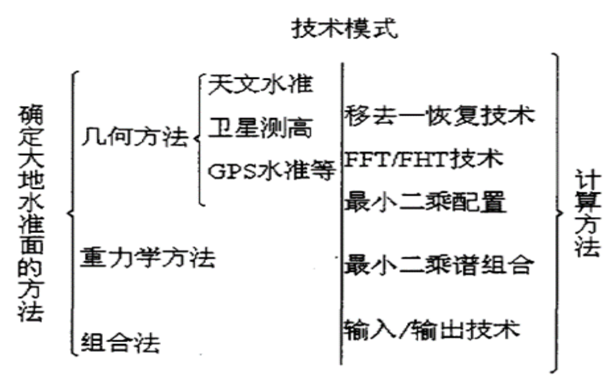
- Function: Provide the global height datum, converse the level observations to the height coordinates in the CEPC coordinate system.



- Observation values:
  - Satellite Gravity
  - Ground Gravity
  - Topographic Data,
  - Precise GPS data
  - Precise Leveling data

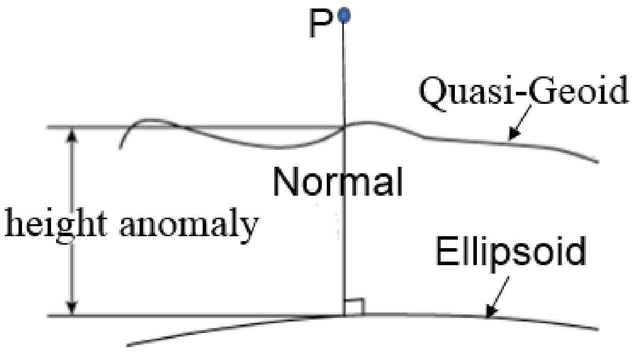


- Calculation methods:
  - Geometric method
  - Gravity method
  - Combined method



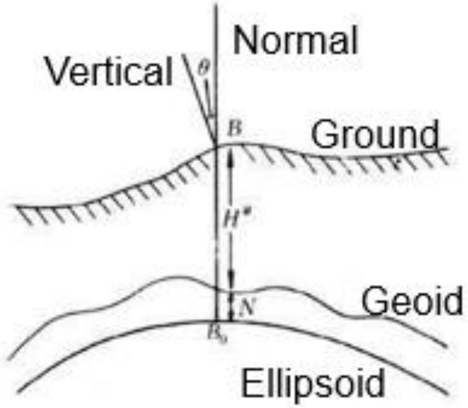
CEPC geodetic datum

- Get the Quasi-Geoid model in the CEPC geodetic coordinate system. It is a spherical cap harmonic function, use it can calculate the height anomaly of any point in the CEPC area.



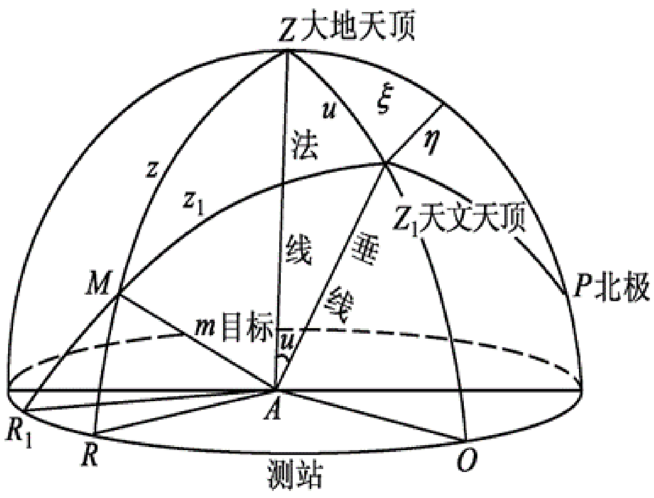
3. Vertical deflection model

- For a point: its normal and vertical is not parallel, the angle between them is named vertical deflection.
- Function: Provide a global datum to realize the height axis of the instrument coordinate system directional in the CEPC coordinate system.



CEPC geodetic datum

- Establish methods:
  - Astro-Geodetic measurement
  - Gravity measurement
  - Astro-Gravity measurement
  - EGM2008 model calculation
  - GNSS measurement



- Grid mathematic model, through interpolation can get the deflection components in the meridian circle and the prime vertical of any point.
- Function relationship:

$$\xi = \varphi - B$$

$$\eta = (\lambda - L)\cos\varphi$$

Vertical Deflection component:

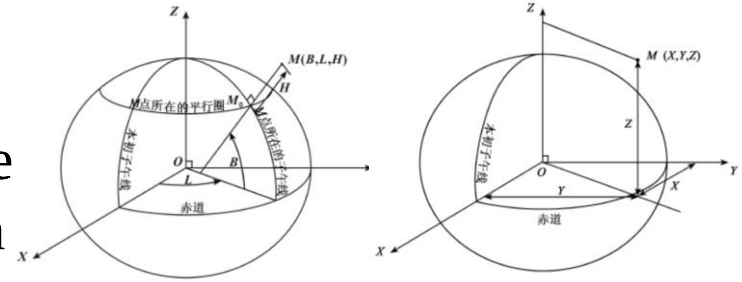
$\xi \quad \eta$

Geodetic Coordinate:
B—latitude; L--longitude

Astronomical Coordinate:
φ—latitude; λ--longitude

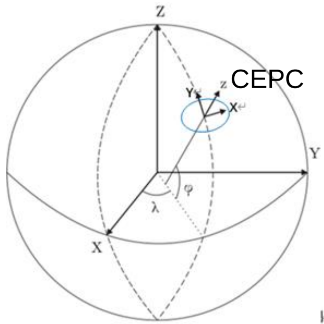
CEPC coordinate system

CEPC coordinate system



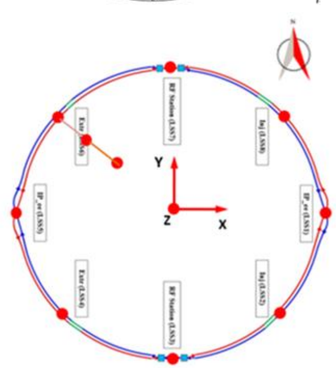
1. CEPC Geodetic Coordinate System

➢ Origin :ellipsoid center, Z points to the north pole, X points to the intersection point of the prime meridian and the equator.



2. CEPC Coordinate System

➢ Origin in the center of the main ring, XY plane parallel with the best-fit plane of the intersection points of the quasi-geoid and the ellipsoid normal at the surface control network points. The purpose is to make the XY plane normal as consistent as possible with the vertical in the CEPC area. Z perpendicular to XY plane, points to the up. Y points to the north.



CEPC coordinate system

CEPC coordinate system

- Establish method

  ① The civil construction company shall build some civil reference points in the construction area and establish a civil coordinate system.

  ② In the civil coordinate system design the positions of the ring center and the surface network control points and build them.

  ③ Carry out GNSS and level measurement, get the surface network control points' coordinates in CGCS2000 coordinate system and level heights.

  ④ Do coordinate system transformation: best-fit the control points' coordinates to their corresponding level height values. After this, the height direction of the transformed coordinate system is what we need.

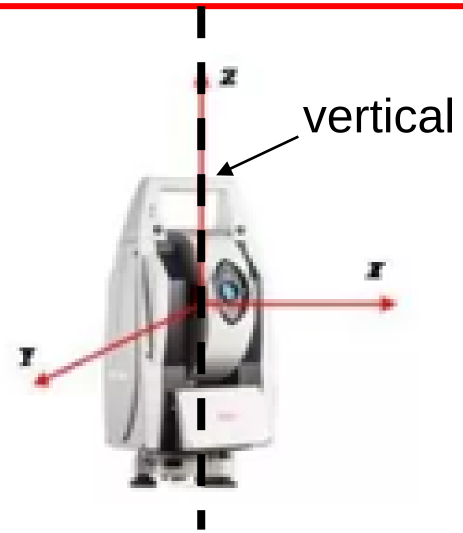
  ⑤ In the transformed coordinate system establish CEPC coordinate system: origin is the ring center, Z is the height direction, Y points to the north.

- Calculate the transformation parameters from CEPC geoid coordinate system to the CEPC coordinate system :ΔX ΔY ΔZ Rx Ry Rz.

CEPC coordinate system

3. Station coordinate system

- Is an instrument coordinate system, be used to carry out measurement.
- Origin in the center of the instrument, Z is parallel with the vertical.



Data processing method

Data processing method

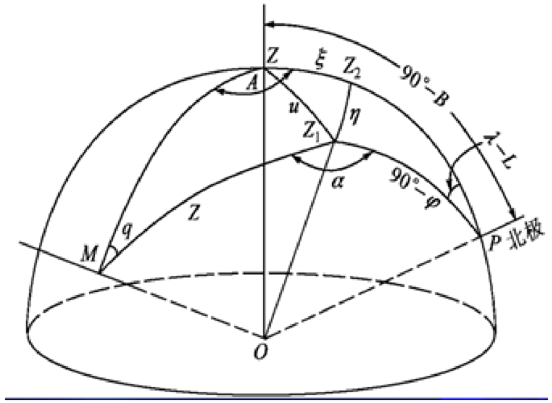
1. Calculate approximate coordinates

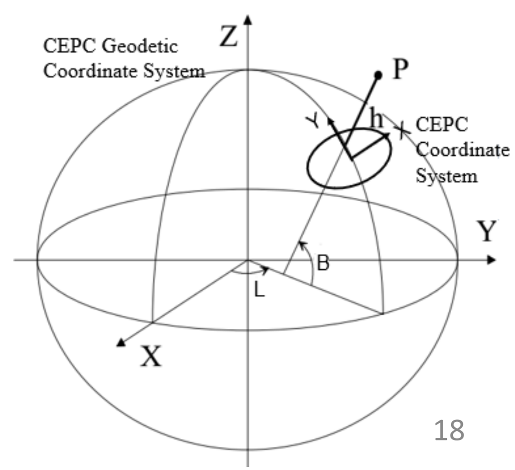
- Use the surface network control points' coordinates as the known data, according to the observation values of each station, can calculate the approximate coordinates of all the control points in CEPC coordinate system.

2. Calculate the vertical direction in CEPC coordinate system

- Vertical deflection model can give the deflection components of a point in the CEPC geodetic coordinate system.

- approximate coordinates (CEPC coordinate system) ➡ approximate L and B in CEPC geodetic coordinate system.

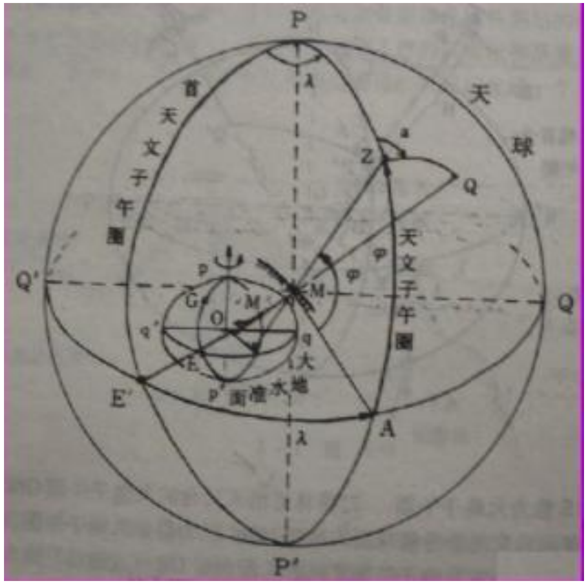




Data processing method

- According to formula calculate astronomical coordinate $\lambda \quad \varphi$

$$\begin{cases} \lambda = L + \eta \sec \varphi \\ \varphi = B + \xi \end{cases}$$



- The unite vector $S\left(X_{DS} \quad Y_{DS} \quad Z_{DS}\right)$ parallel with the vertical in this point in CEPC geodetic coordinate system:

$$\begin{cases} X_{DS} = \cos\varphi \cdot \cos\lambda \\ Y_{DS} = \cos\varphi \cdot \sin\lambda \\ Z_{DS} = \sin\varphi \end{cases}$$

- Unite vector in CEPC coordinate system $S\left(X_{CS} \quad Y_{CS} \quad Z_{CS}\right)$

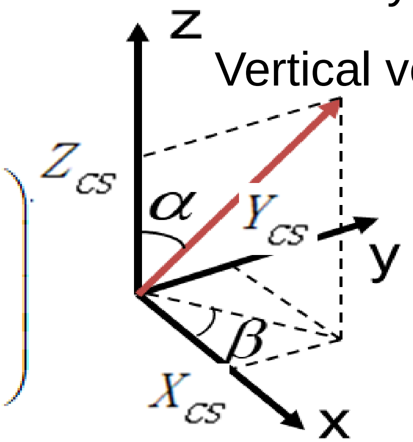
$$\begin{bmatrix} X_{CS} \\ Y_{CS} \\ Z_{CS} \end{bmatrix} = M \cdot \begin{bmatrix} X_{DS} \\ Y_{DS} \\ Z_{DS} \end{bmatrix}$$

- M: rotation transformation matrix, from CEPC geodetic coordinate system to CEPC coordinate system

Data processing method

- α: the angle between the vertical and the Z.

  β :the angle between projective vector and the X.



$$\alpha = \arccos(Z_{cs}) \quad \beta = \arccos\left(\frac{X_{cs}}{\sqrt{X_{cs}^2 + Y_{cs}^2}}\right)$$

3. Calculate the height coordinates of the control points in CEPC coordinate system.

- Level measurement can get the distance h between the control point and the Quasi-Geoid

- Calculate the projective point of control point on the Quasi-Geoid

  - Control point: (x_1, y_1, z_1) , Level height : h
  - Projective point:

$$\begin{cases} x_2 = x_1 + h \cdot \sin\alpha \cdot \cos\beta \\ y_2 = y_1 + h \cdot \sin\alpha \cdot \sin\beta \end{cases}$$

Data processing method

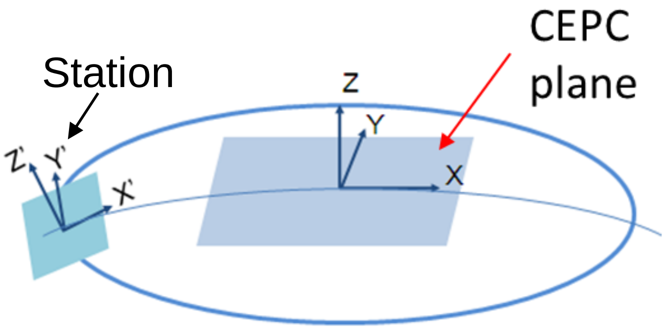
- According to the Quasi-Geoid model, use x2,y2, can calculate the projective point's height coordinate z2 in CEPC coordinate system.
- The accurate height coordinate Z1 of the control point in CEPC coordinate system: $z_1 = h \cdot \cos\alpha + z_2$

4. Observation values adjust calculation

- To get the control points' coordinates in CEPC coordinate system need to do adjust calculation use the observation values.
- Traditional adjust calculation of accelerator , the height observations and the horizontal observations are calculated separately.
- According to this way, we need to divide the original observations into the height observations and the horizontal observations in CEPC coordinate system.

Data processing method

- Directions of the coordinate axis in station coordinate system and CEPC coordinate system are not same. Need to calculate the rotation matrix R to get the height observations and the horizontal observations in CEPC coordinate system



- R can be calculated by best-fit the coordinates of control points in station coordinate system to the corresponding height coordinates in CEPC coordinate system.

$p_{zi}\left(x_{zi} \quad y_{zi} \quad z_{zi}\right)$: coordinate of a control point in station coordinate system

$p_{ci}\left(x_{ci} \quad y_{ci} \quad z_{ci}\right)$:the corresponding coordinate in CEPC coordinate system

$$\begin{bmatrix} x_{si} \\ y_{si} \\ z_{si} \end{bmatrix} = R \begin{bmatrix} x_{zi} \\ y_{zi} \\ z_{zi} \end{bmatrix}$$

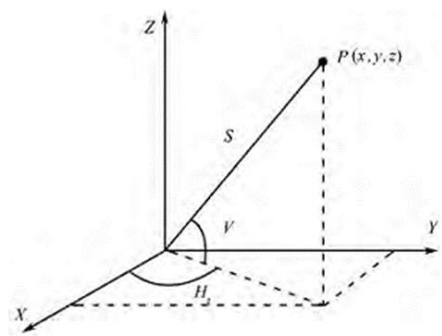
$$s.t. \sum \left(\Delta z_{si} - \Delta z_{ci}\right)^2 = \min$$

Constraint condition
least square method

Data processing method

5. 3D directional adjust

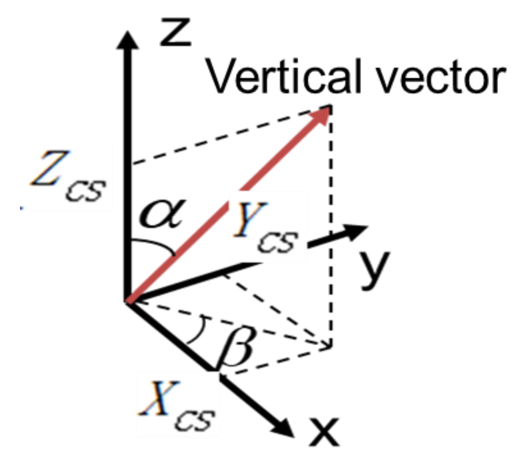
$$\begin{pmatrix} X_{ij} \\ Y_{ij} \\ Z_{ij} \end{pmatrix} = M \cdot \begin{pmatrix} X_j - X_{0i} \\ Y_j - Y_{0i} \\ Z_j - Z_{0i} \end{pmatrix}$$



$$\begin{bmatrix} V_{H_i} \\ V_{V_i} \\ V_{S_i} \end{bmatrix} = B \begin{bmatrix} x_i \\ y_i \\ \hat{z}_i \end{bmatrix} - \begin{bmatrix} H_i - arctg\left(\dfrac{Y_i^0}{X_i^0}\right) \\ V_i - arctg\left(\dfrac{Z_i^0}{\sqrt{X_i^{02} + Y_i^{02}}}\right) \\ S_i - \sqrt{X_i^{02} + Y_i^{02} + Z_i^{02}} \end{bmatrix}$$

$$V = Bx - l \;\rightarrow\; V^T PV = \min \;\rightarrow\; x = \left(B^T PB\right)^{-1} B^T Pl$$

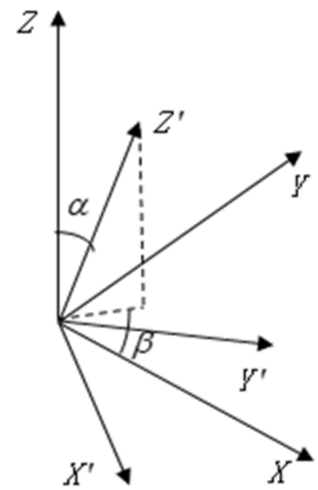
- The key point is to determine the rotation angel parameters.
- Suppose the angles between the vertical at the station and the axis of CEPC coordinate system are α β ,as what mentioned before



Data processing method

- The rotation transformation process from CEPC coordinate system to the station coordinate system are: rotate about CEPC z axis by β R_z^β, rotate about y axis by α R_y^α, rotate about z axis by γ R_z^γ

$$\begin{bmatrix} x_{zi} \\ y_{zi} \\ z_{zi} \end{bmatrix} = R_Z^\gamma R_Y^\alpha R_Z^\beta \begin{bmatrix} x_{ci} \\ y_{ci} \\ z_{ci} \end{bmatrix}$$



- γ Is the unknown parameter can be solved by 3D adjust calculation.
- For α and β are known data, 3D directional adjust can avoid the result distortion.

Summary

- CEPC measurement range is very large, the undulation of geoid and vertical need to be considered in doing the data processing.
- Three mathematical models: ellipsoid, Quasi-Geoid, vertical deflection will be used as datum in measurement and data processing.
- The transformation between local observations and global observations will be realized reference to three coordinate systems.
- A data processing method based on Quasi-Geoid model and vertical deflection model is proposed.

Thank You !