Technology and Application of Laser Tracker in Large Space Measurement

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主要内容

1 Introduction

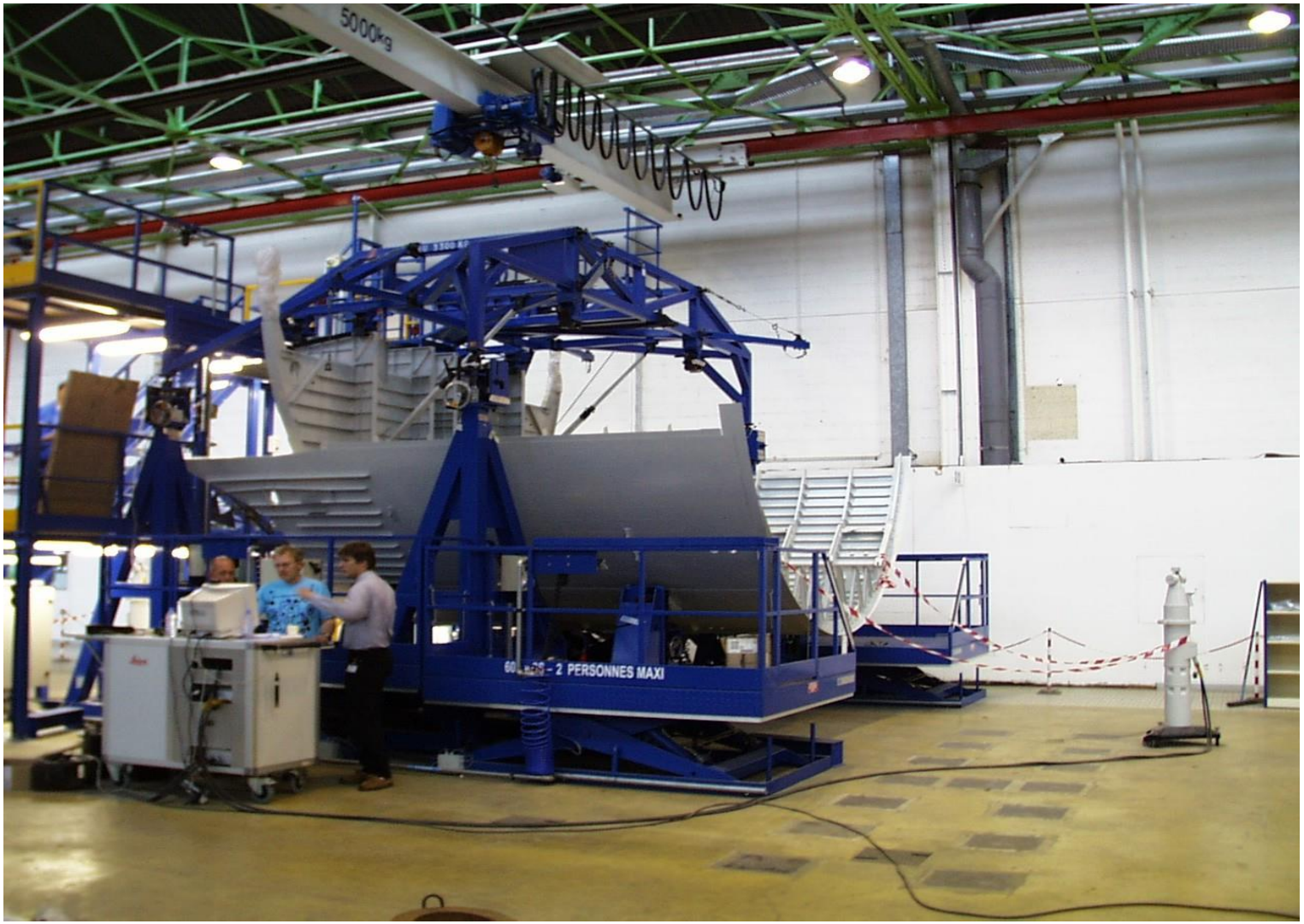
1 Introduction

In recent years, with the development of modern industry, especially the rapid development of manufacturing industry, the 3D precision measurements for all kinds of large-scale engineering or large pieces of the structures appeared, including measurements about position, attitude and shape detection etc.

The characteristics of this kind of works is large scale, high precision, on-site measurement, dynamic measurement and attitude measurement, the traditional CMM can not meet these requirements, so large scale coordinate measurement technology appeared.

At the same time, many new problems appeared in large scale measurements, and we need the knowledge of several disciplines to solve them, such as geodetic, engineering survey and instruments etc.

1 Introduction



1 Introduction

Fixture measuring

1 Introduction

Tailcone measuring of spacecraft

1 Introduction

Detection of car's body

1 Introduction

The above cases can be measured by single station of laser tracker.

Based on observation of distance and angles, we can:

1、 Calculate X, Y, and Z parameters of targets.

2、 Calculate attitude parameters.

3、 Reflect the space geometric information of the targets (relation between points, lines, and surfaces)

But some large scale projects, can not be measured by single station.

1 Introduction

Large hydropower station measuring

1 Introduction

Detection of production line

1 Introduction

Accelerator alignment

1 Introduction

To the large scale projects which can not be measured by single station, we can use the method of:

Free station and
Multi-station match (by common points)

So, we should find a method to transform the points' coordinates of each station to a unified coordinate system.

The method is three dimensional adjustment.

2 Accuracy analysis of Laser Tracker

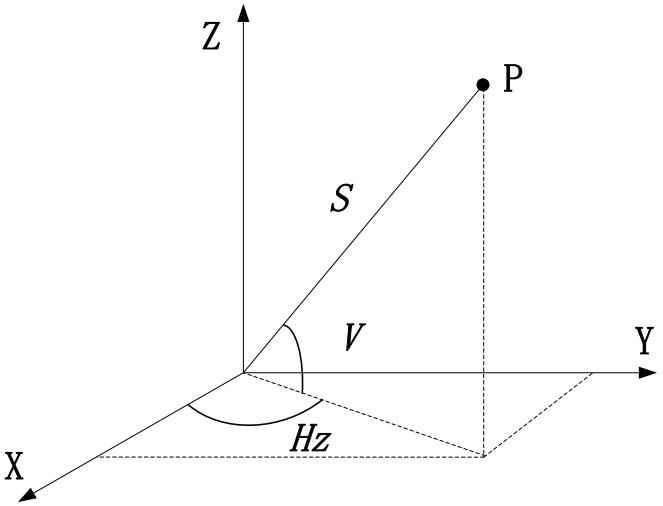
2 Accuracy analysis of Laser Tracker

Problem

The measuring errors of laser tracker is mainly including angle errors and distance error.

The purpose of accuracy analysis is :

- **Reflect the error source of laser tracker**
- **Provide theoretical evidence for the weight of observations in 3D adjustment**



2 Accuracy analysis of Laser Tracker

Problem

Leica AT901-B for example:

- **Angle accuracy:** $m_\alpha = \pm(15\mu\text{m}+6\mu\text{m/m})$
- **Distance accuracy:** $m_s = \pm 0.5\mu\text{m/m}, \quad s \le 20\text{m};$ $m_s = 10\mu\text{m}, \quad s \ge 20\text{m}$
- **Coordinate accuracy:** $m_p = \pm(15\mu\text{m}+6\mu\text{m/m})$
- **Range:** $S = 80\text{m}$

Two problems:

(1) What is relationship between the angle accuracy expression of μm and ″?

(2) Why is the angle accuracy equal to coordinate accuracy?

2 Accuracy analysis of Laser Tracker

1、Angle error

（1）theoretical accuracy

The equation from μm to ″

$$m_{\alpha}'' = \frac{m_{\alpha}}{S} \cdot \rho''$$

S （m）	1	5	10	20	30	40	50	60	70	80
error （″）	4.3	1.9	1.6	1.4	1.3	1.3	1.3	1.3	1.3	1.3

2 Accuracy analysis of Laser Tracker

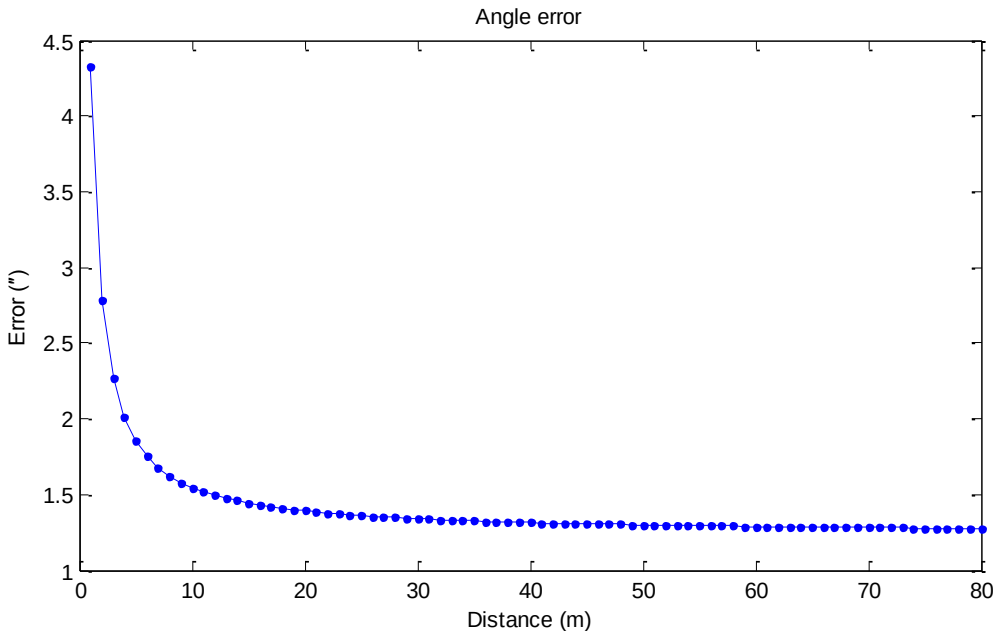
1、Angle error

（1）theoretical accuracy

The theoretical angle error of laser tracker, which is especially large in short distance, decreases while distance value increases.

When the distance is over 10 meters, $1.2'' < m_\alpha < 1.5''$ **,and it tends to be stable.**

$S > 10\text{m}, \qquad 1.2'' < m_\alpha < 1.5''$

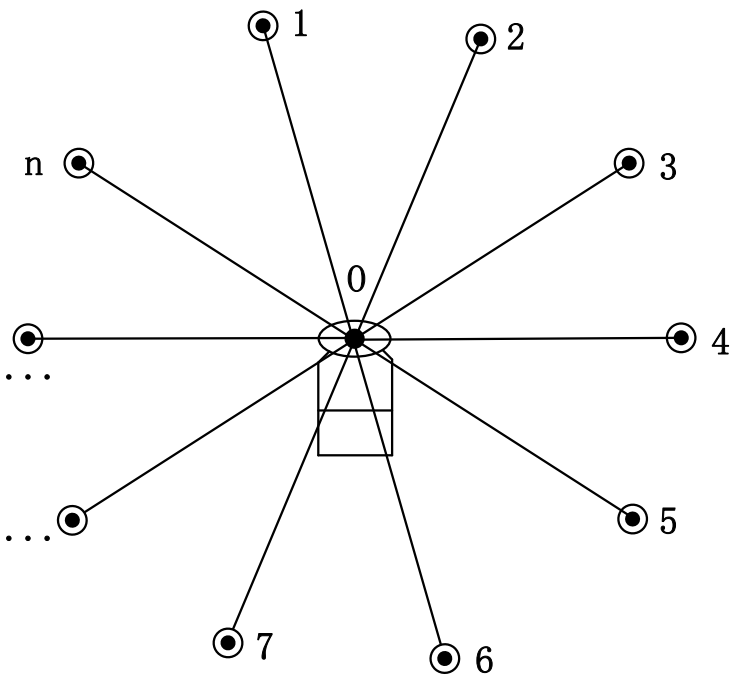


2 Accuracy analysis of Laser Tracker

1、Angle error

（2）actual error by experiment——horizontal angle

layout several points around laser tracker，cover 360° horizontal range，same height with LT to avoid vertical error.



$$\overline{M_j} = \frac{1}{m}\sum_{i=1}^{m} M_{ij}$$

$$m_\alpha = \frac{1.253}{\sqrt{(m-1)m}} \cdot \frac{\sum_{j=1}^{n}\sum_{i=1}^{m}\left|v_{ij}\right|}{n-1}$$

2 Accuracy analysis of Laser Tracker

1、Angle error

（2）actual error by experiment——horizontal angle

RMS	0.78(0.40)				
Horizontal error of each point	P1	P2	P3	P4	P5
	0.53(0.30)	0.62(0.41)	0.46(0.34)	0.67(0.42)	0.53(0.70)
	P6	P7	P8	P9	P10
	0.44(0.23)	0.69(0.63)	0.69(0.24)	0.64(0.77)	0.61(0.18)
Single face error	Face I			0.92(0.47)	
	Face Ⅱ			0.77(0.59)	

1）The distance from points to LT is 3.6m ~ 6.9m， in this range the theoretical error is 1.7″~ 2.1″， so the actual error is lower than theoretical .

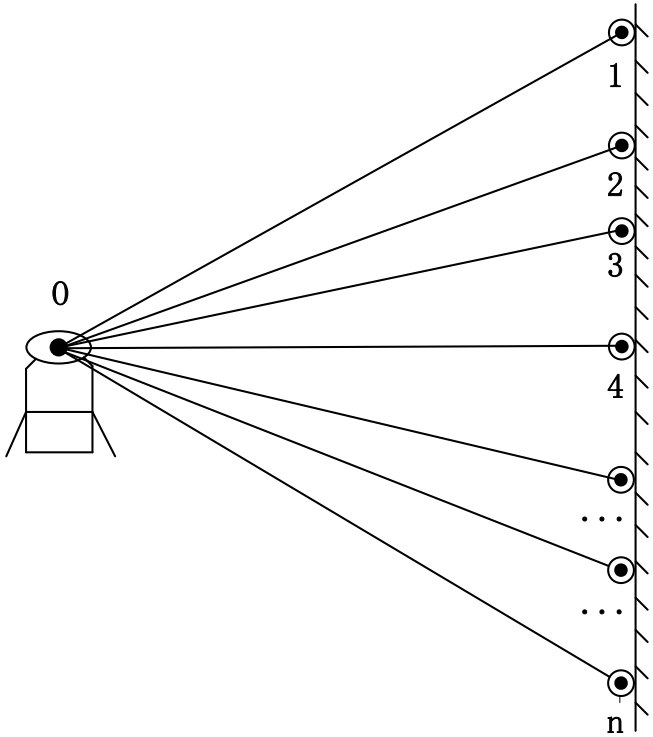
2）The two-face error is 0.59″（leveling 0.43″）， lower than face I 0.92″（0.47″）and face II 0.77″（0.59″）.

2 Accuracy analysis of Laser Tracker

1、Angle error

（2） actual error by experiment——vertical angle

layout several points in front of laser tracker in a vertical line on the wall，cover ±45° vertical range.



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2 Accuracy analysis of Laser Tracker

1、Angle error

（2） actual error by experiment——vertical angle

	theoretical (″)	Actual error (″, unleveling/leveling))	Single face error (″, unleveling/leveling))	
			I面	Ⅱ面
1（48m）	1.3	0.67(0.59)	0.80(0.90)	0.84(0.74)
2（38m）	1.3	0.53(0.57)	0.76(0.57)	0.72(0.78)
3（28m）	1.3	0.47(0.55)	0.57(0.56)	0.54(0.77)
4（18m）	1.4	0.53(0.41)	0.64(0.54)	0.67(0.55)
5（10m）	1.5	0.50(0.42)	0.73(0.54)	0.64(0.54)

1）The two-face vertical error is 0.52″， while single face error is 0.67″（I）and 0.68″（Ⅱ）. Both are lower than theoretical value and two-face error is lower than single face.

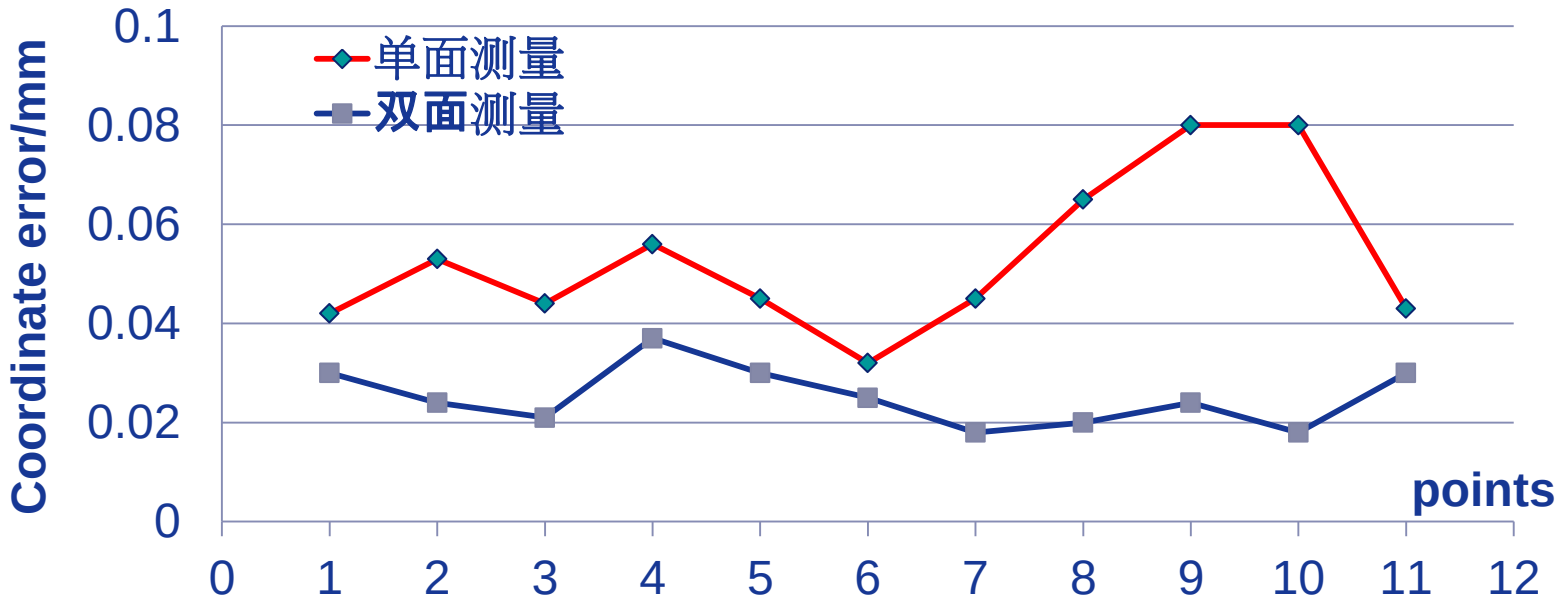
2）its nearly the same accuracy between face I and face II.

2 Accuracy analysis of Laser Tracker

1、Angle error

（3） actual error by experiment——coordinates

in space(7m×5m×3m), layout 11 points, two stations of AT901: observations from single face I and II.



2 Accuracy analysis of Laser Tracker

2、distance error

- **Distance accuracy of AT901：**

$$m_s = \pm 0.5\mu\text{m/m}, \quad s \le 20\text{m};$$
$$m_s = 10\mu\text{m}, \quad s \ge 20\text{m}$$

distance(m)	1	5	10	20	30	40	50
angle error(μm)	21	45	75	135	195	255	315
distance error(μm)	0.5	2.5	5	10	10	10	10

2 Accuracy analysis of Laser Tracker

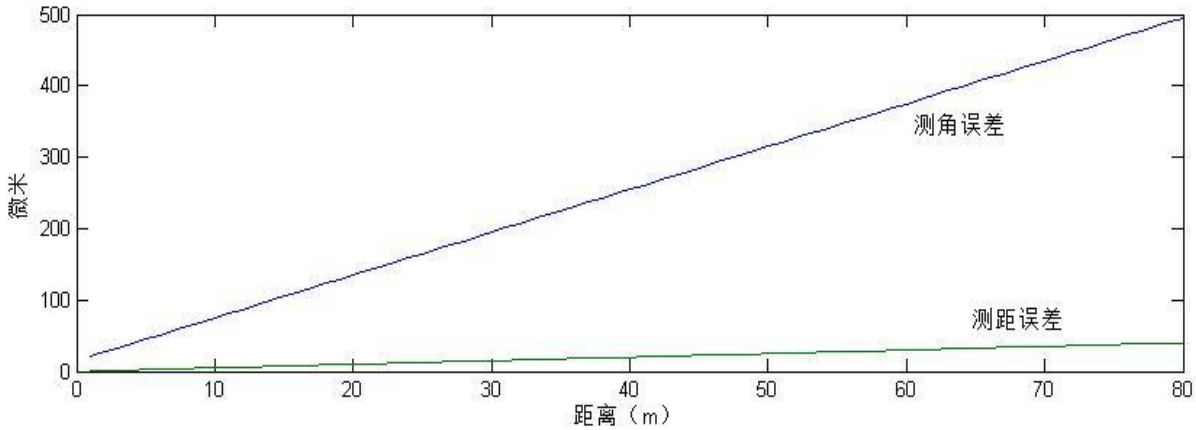
2、distance error

conclusion：

Based on the comparison of angle error and distance error, we can get the conclusion that:

the angle error is the main part of LT measuring errors, and it can be reduced by two-face observation.

So it explains the equation $m_\alpha = m_P = \pm(15\mu\text{m}+6\mu\text{m/m})$



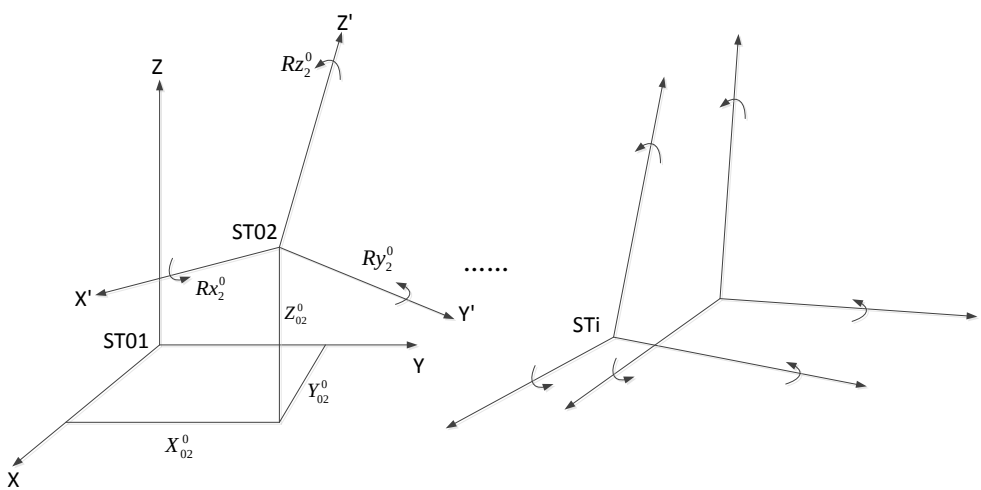
3 Three dimensional adjustment

3 Three dimensional adjustment

1、Modeling

each single coordinate system transform to unified coordinate system：

$$\begin{pmatrix} X_{ij} \\ Y_{ij} \\ Z_{ij} \end{pmatrix} = \begin{pmatrix} a_{i1} & b_{i1} & c_{i1} \\ a_{i2} & b_{i2} & c_{i2} \\ a_{i3} & b_{i3} & c_{i3} \end{pmatrix} \cdot \begin{pmatrix} X_j - X_{0i} \\ Y_j - Y_{0i} \\ Z_j - Z_{0i} \end{pmatrix}$$



$$a_{i1} = \cos Ry_i \cdot \cos Rz_i$$

$$a_{i2} = -\cos Ry_i \cdot \sin Rz_i$$

$$a_{i3} = \sin Ry_i$$

$$b_{i1} = \sin Rx_i \cdot \sin Ry_i \cdot \cos Rz_i + \cos Rx_i \cdot \sin Rz_i$$

$$b_{i2} = -\sin Rx_i \cdot \sin Ry_i \cdot \sin Rz_i + \cos Rx_i \cdot \cos Rz_i$$

$$b_{i3} = -\sin Rx_i \cdot \cos Ry_i$$

$$c_{i1} = -\cos Rx_i \cdot \sin Ry_i \cdot \cos Rz_i + \sin Rx_i \cdot \sin Rz_i$$

$$c_{i2} = \cos Rx_i \cdot \sin Ry_i \cdot \sin Rz_i + \sin Rx_i \cdot \cos Rz_i$$

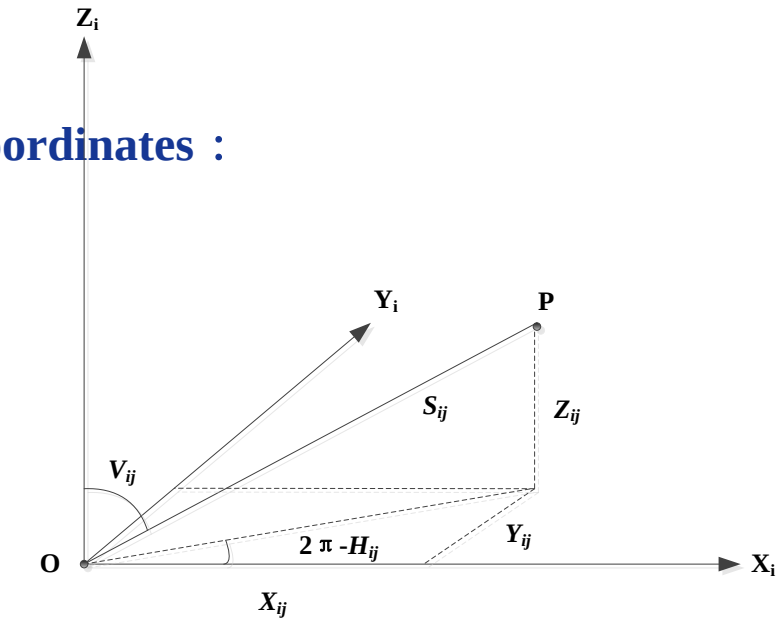
$$c_{i3} = \cos Rx_i \cdot \cos Ry_i$$

3 Three dimensional adjustment

1、Modeling

the relationship between observations and coordinates：

$$\begin{cases} Hz_{ij} = 2\pi - \arctan\dfrac{Y_{ij}}{X_{ij}} \\ V_{ij} = \dfrac{\pi}{2} - \arctan\dfrac{Z_{ij}}{\sqrt{X_{ij}^2 + Y_{ij}^2}} \\ S_{ij} = \sqrt{\left(X_i - X_j\right) + \left(Y_i - Y_j\right) + \left(Z_i - Z_j\right)} \end{cases}$$



$$V = A \cdot \delta x - l$$

$$V^T P V = \min$$

$$\delta x = N^{-1} A^T P l$$

$$V = (v_{11}^S, v_{11}^{Hz}, v_{11}^V, \cdots, v_{1n_1}^S, v_{1n_1}^{Hz}, v_{1n_1}^V, \cdots, v_{mn_m}^S, v_{mn_m}^{Hz}, v_{mn_m}^V)^T$$

$$l = \left(l_{11}^S, l_{11}^{Hz}, l_{11}^V \cdots, {}_{1n_m}^S, l_{1n_m}^{Hz}, l_{1n_m}^V, \cdots, l_{mn_m}^S, l_{mn_m}^{Hz}, l_{mn_m}^V\right)^T$$

$$\delta X = \left(\delta X_1, \delta Y_1, \delta Z_1, \delta Rx_1, \delta Ry_1, \delta Rz_1, \cdots\cdots\right)^T$$

3 Three dimensional adjustment

2、parameters estimation

Based on the coordinate transformation:

$$\delta X = \left(\delta X_1, \delta Y_1, \delta Z_1, \delta Rx_1, \delta Ry_1, \delta Rz_1, \cdots\cdots\right)^T$$

3、observations' weight decision

1）experiential methods

$$P_{Hz} = \frac{m_0^2}{m_{Hz}^2}、P_V = \frac{m_0^2}{m_V^2}、P_S = \frac{m_0^2}{m_S^2}$$

2）component of variance model

Calculate equations: $\sigma_0^2 = S^{-1} W_\sigma$

$$P_i = \frac{\sigma_{00}^2}{\sigma_{0i}^2 (P_i^0)^{-1}}$$

Terminate condition of iteration: $\max\left|\hat{\sigma}_{0i}^{2(r)} - \hat{\sigma}_{0i}^{2(r-1)}\right| < \varepsilon, (i = 1,2,3)$

4 Example and application

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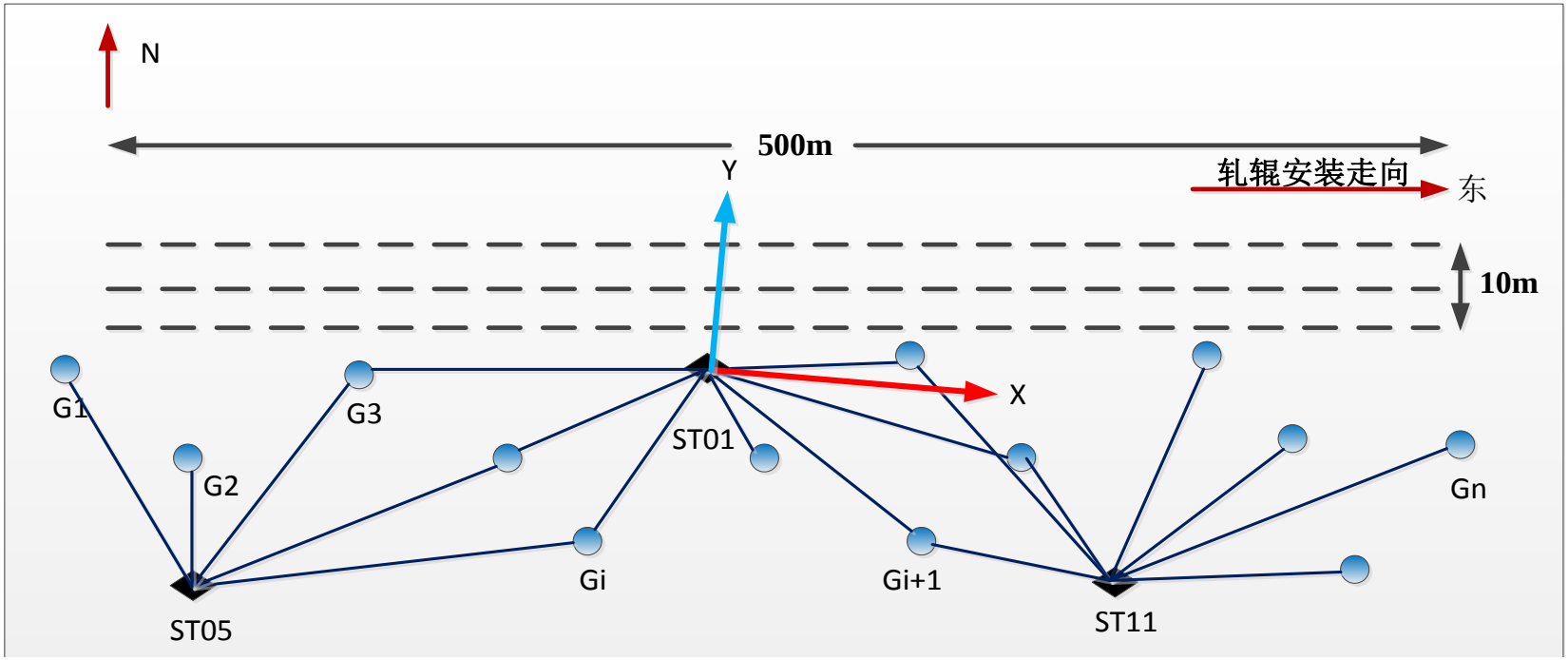
1、Application

The total length of a new production line in BAOSTEEL is more than 500 m, about 10m wide, and in order to install production equipment, it is necessary to establish high control network.



4 Example and application

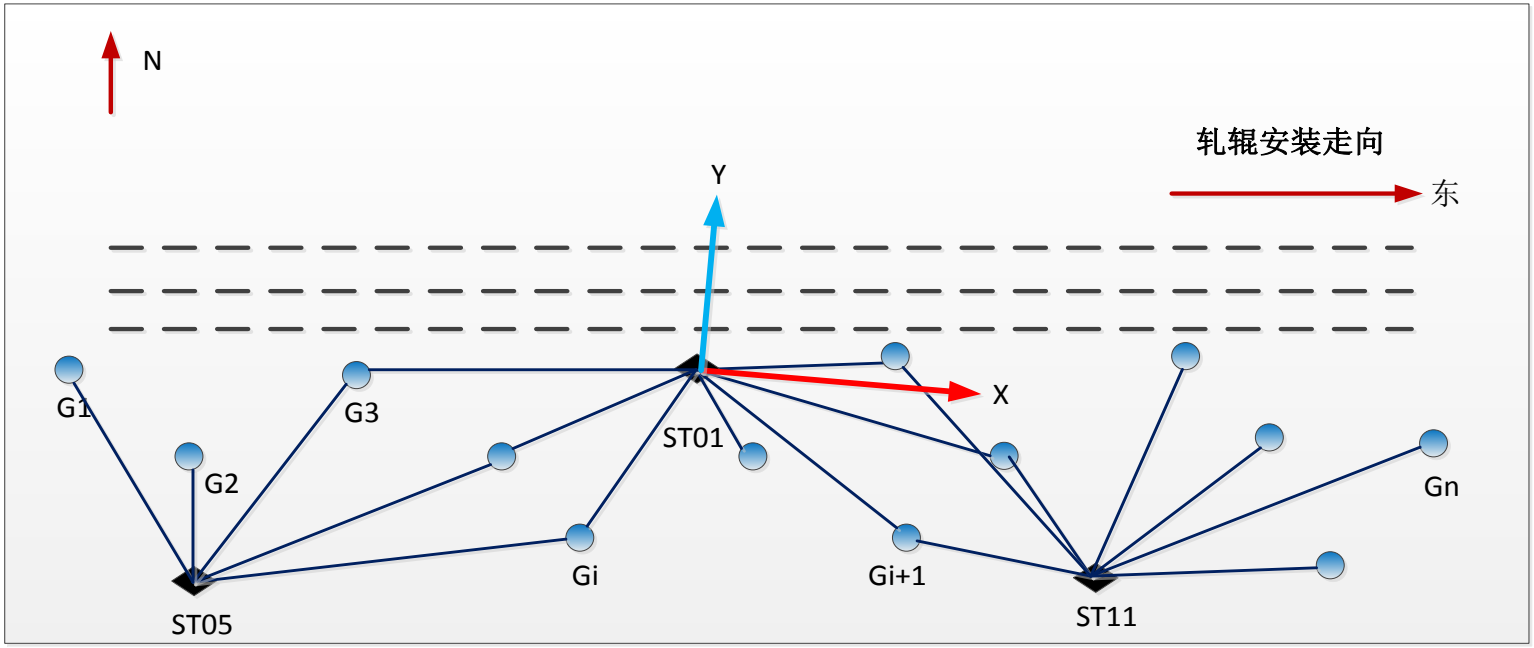
Measuring on site

4 Example and application

Control network survey

（1） Instrument: Leica AT901-B， CCR1.5″ reflector， 72 control points(G1~G72).

（2） In order to control the error accumulation of multi-station method, the measuring began from middle to both sides, and the coordinate system of first station was suggested for unified system after adjustment。

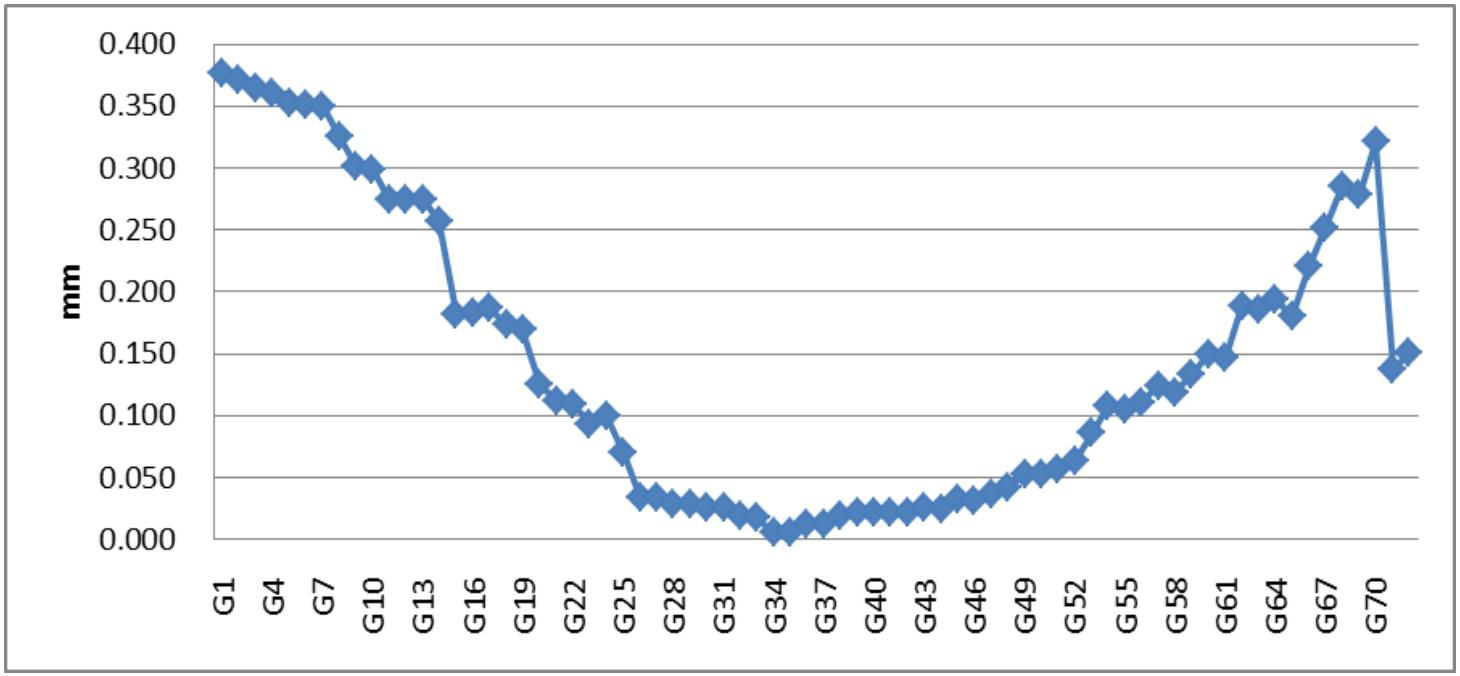


4 Example and application

2、 data processing

- **Coordinate error**

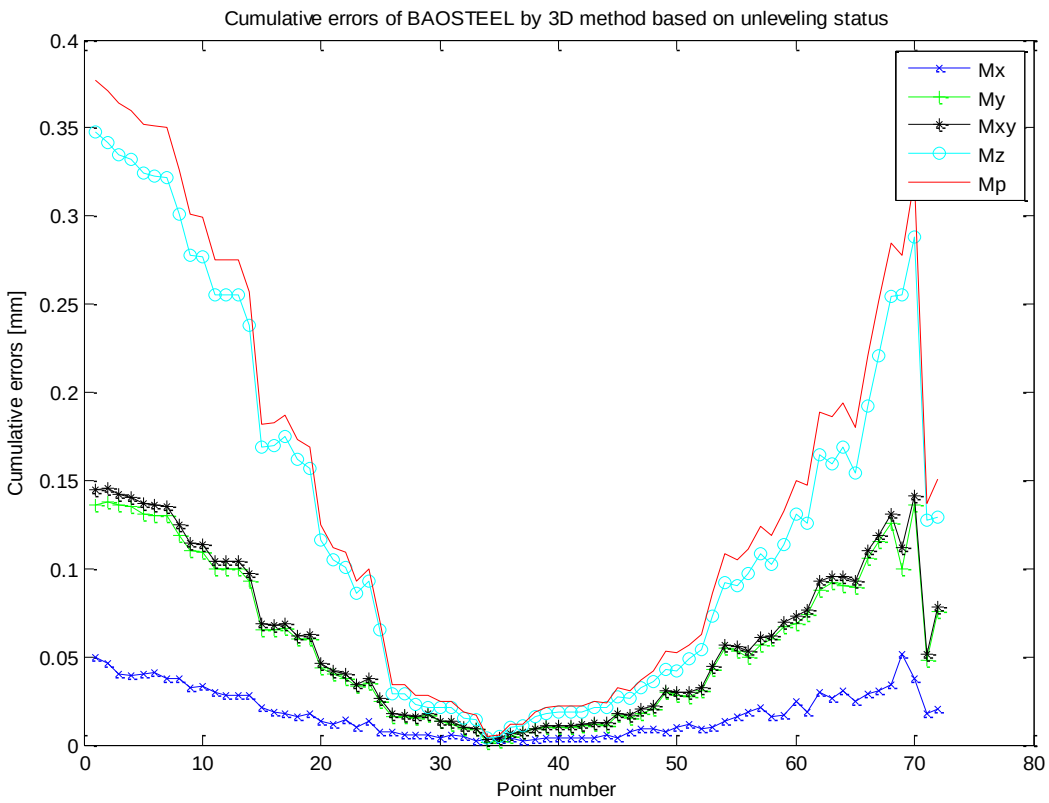
After 3D adjustment, according to the calculation, the length of production line was 488m, and there were 72 control points which were used for adjustment. The RMS of point coordinate is 0.185mm, and the maximum is 0.377mm.



4 Example and application

2、data processing

- **Axis errors**

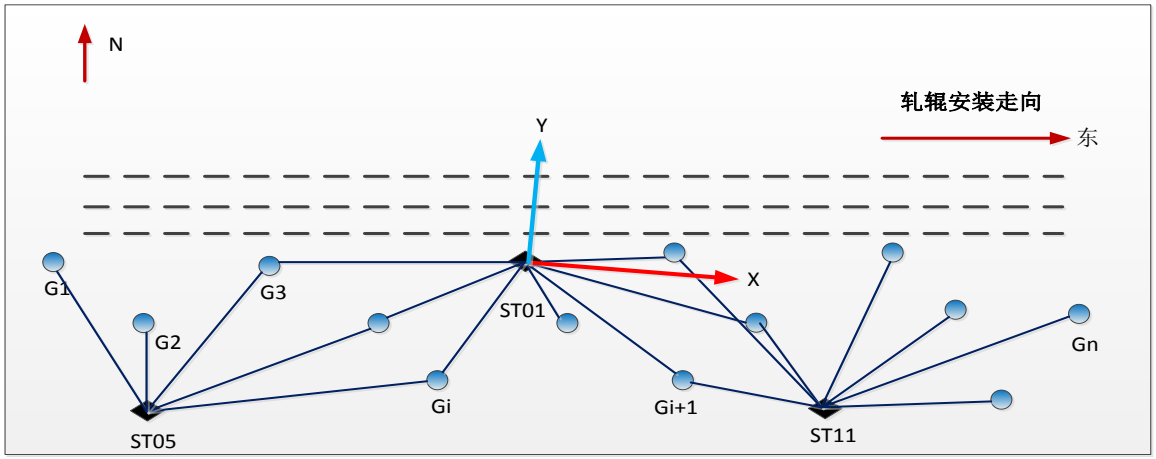


(1)The error of each axis is gradually accumulated from center to sides.
(2) The accuracy of XY plane is 0.076mm,while the accuracy of Z axis is 0.167mm,so the error of Z axis is higher than X axis and Y axis apparently.
(3)The deviation between each axis is enlarging sharply with the increasing of stations and length.

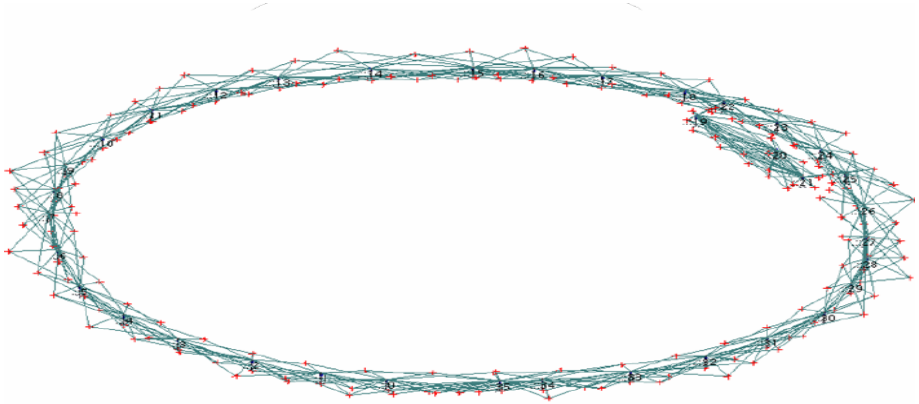
5 Summary

5 Summary

1、 The error of X axis is lower than Y axis, because the network is too narrow in Y axis ,so that the stability of network in X axis is better than Y.



Method: Add length constraints in Y direction to improve accuracy



5 Summary

2、The accumulated error in Z axis is larger than X axis and Y axis, because of the influence of vertical error. So leveling data can be considered for adjustment in the 3D model together for restraining accumulated errors in Z axis.

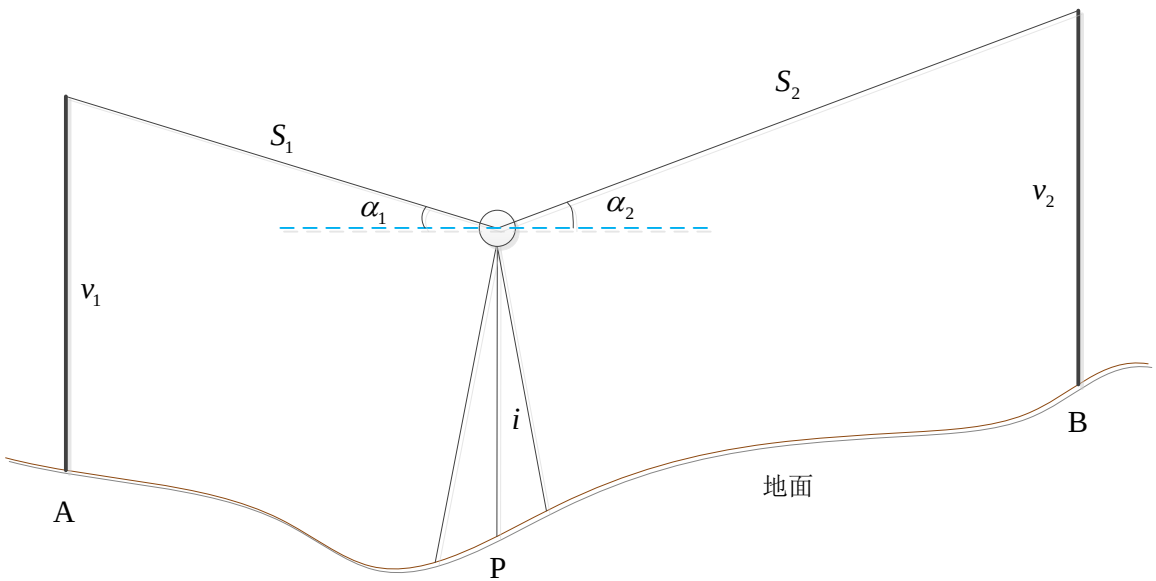
principle of middle method by total station

equation of elevation between two points：

$$h'_{j,j+1} = Z_{i,j+1} - Z_{ij} = S_{i,j+1}\sin V_{j,j+1} - S_{i,j}\sin V_{i,j}$$

condition equation：

$$\phi = V^T PV + 2K^T (B_X \delta X + w)$$



Thanks for your attention!