THE STORAGE RING CONTROL NETWORK OF NSLS-II

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Abstract

NSLS-II requires ±100 micron alignment precision to adjacent girders which is mainly depending on the precision of survey control network. The design is determined to establish a laser tracker and digital level based control network, but it was changed to be measured by AT401 only later.

Simulation shows that an estimated accuracy of ~50 micron can be achieved. The analysis of actual measurement and the application of the control network to align girders confirm the accuracy.

A comparison between Spatial Analyzer and Star*net shows very similar estimate of instrument performance and computed coordinates which both verify the applicability of Spatial Analyzer in control network adjustment.

INTRODUCTION

The storage ring of NSLS-II has a circumference of about 792 m. The alignment tolerance is ±100 micron for adjacent girders and ±3mm globally.

The control network is comprised of primary and secondary ones. There are 5 primary monuments which can be collimated from the top of the tunnel roof and allow for direct shooting to some of the others, the primary monuments of linac and booster tunnel and the central monuments. The point error ellipse of the monuments is expected to be around 0.5 mm.

The secondary control network is the emphasis of the discussion here. To fulfil the tight ±100 micron alignment tolerance between girders, large amount of secondary monuments (more than 740) are used to get better geometry and precision. At the end of the installation stage, in order to address the ±10 micron girder profiling requirement [1], more than 250 monuments were added. As a result, the final number of the monuments in SR tunnel is around 1000.

Laser tracker and level based control network

The control network is originally designed to be measured by laser tracker and digital level, which will compensate the shortcoming of each other and get a desirable performance both horizontally and vertically. It is the only way to establish a precise survey control network in tunnel by use of laser tracker at the time of design phase. It requires a crew to run the level routine besides the laser tracker observation.

However, thanks to the technological achievement, AT401 is chosen to measure the control network as an update of design.

AT401-based control network

According the specification, AT401 has an angular precision of 0.5” and distance precision of ±5 micron. This is a significant improvement, angle-wise, compared with previous laser tracker models. What’s more, the internal level has the capability of 0.5” precision which is comparable with a precision level. It can be deemed as a combination of total station, laser tracker and digital level, which is a preferable scenario for control network survey. The merits of this substitution include unified instrument operation, simplified data processing and improved efficiency and precision etc.

The NSLS-II control network has been measured 7 times so far to record the dynamics of the tunnel and maintain a precise alignment datum. Except the first round, all others were measured by AT401.

ERROR ESTIMATE

During design stage, simulations were performed by use of Star*Net to determine the location of monuments, instruments and observations.

The relative error ellipse of adjacent monument is used to evaluate the control network performance. By assuming laser tracker has 2.0 arc-second’s accuracy for horizontal and vertical angle, and 25μm+2.5μm/m for distance, simulation shows that a relative accuracy of

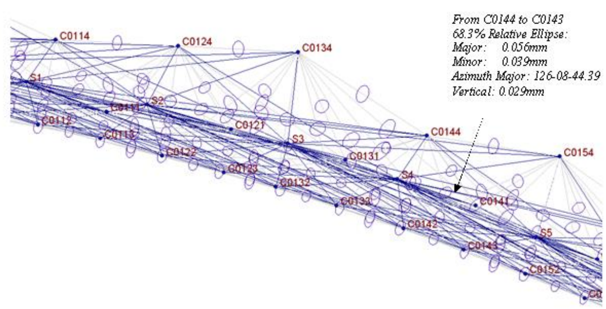

Figure 1: the relative error ellipse information.

better than 0.068mm for adjacent monuments can be achieved with the selected design [2]. Figure 1 demonstrates the control network shape and relative error ellipse information under the assumed instrument performance.

The simulation also shows that if laser tracker has 1.0 arc-second’s accuracy for horizontal and vertical angle, and 7.6μm+2.5μm/m for distance, which is probably the capability of AT401, a relative accuracy of better than 0.038mm (average for the adjacent monuments) can be achieved.

MEASUREMENT RESULTS

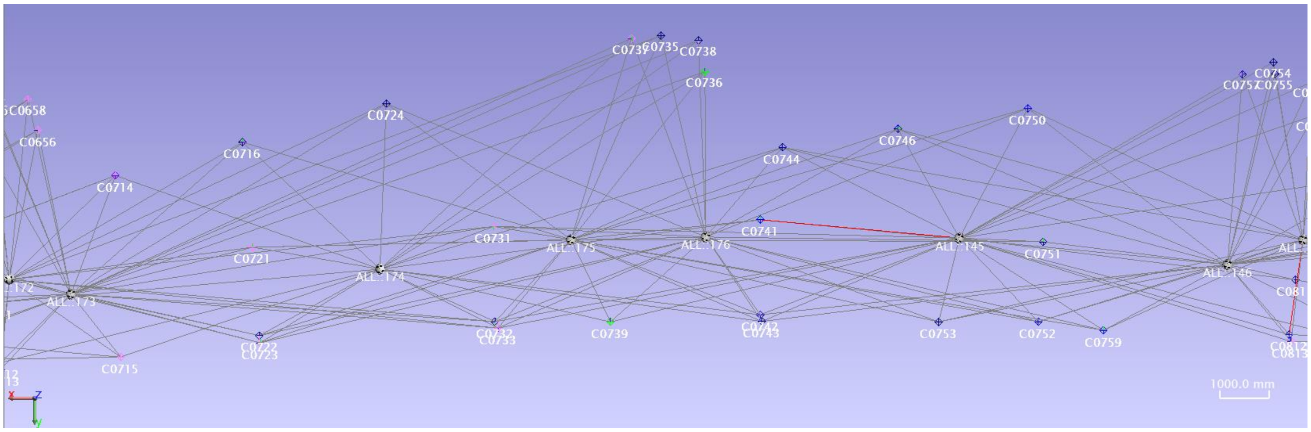

Figure 2: The monument, instrument and observations of NSLS-II control network in one cell out of 30.

The control network has been measured repeatedly in a frequency of around twice a year. The control network shows a gradually stabilizing trend by changing from the beginning of ~5 mm to the end of <1 mm. The trend indicts that large movement of the tunnel is unlikely and hence the ±3mm requirement is well achievable.

For the 6th observation, the environment control is in effect and the shape of the control network is fortified to facilitate the girder profiling task. Figure 2 shows one slice of the control network. The data processing method and comparisons will be given in the following part.

The adjustment method

Spatial Analyzer is primarily used to process the observation data. The raw files from different instruments and crews are combined together as a first step by importing raw files sequentially.

Unified Spatial Metrology Network (USMN) [3] is used to get the optimal coordinates of all the monuments and instruments.

Table 1: Statistics of USMN

Name		Value	Unit
Point Error	RMS	0.024	mm
	Average	0.015	mm
	Max	0.255	mm
Instrument accuracy	Horizontal Angle	0.894	"
	Vertical Angle	0.734	"
	Distance	0.014	mm
Count	Measurements	4747	
	Instruments	191	

In order to maintain the level information of AT401 laser tracker, their rotation in horizontal plane is forced to unmoved during the computing process. According to the computation result, some of the bad measurements have been eliminated to improve the control network performance.

With an assumed accuracy of 1.0 arc-second's accuracy for horizontal and vertical angle, and 7.6µm+2.5µm/m for distance, after USMN, the statistics is listed in Table 1.

Point error depicts the error between individual measurement of a point and its optimal value. Instrument accuracy shows the posterior performance of angular and distance measurement.

The statistics looks great if taking considerable affecting factors into account, such as environmental, dimension and human activities etc.

*Comparisons between SA and Star*net*

Although it's convenient to solve the control network by using of SA to integrate the raw data collecting, data preparation and computation together, there are questions regarding the terms, credibility and precision of it. A

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comparison between SA and Star*net is carried out to clear out the doubts.

The same raw observations are exported and transferred to a format that is recognizable by Star*net. The posterior instrument accuracy as listed in Table 1 is used as an initial guess to feed into Star*net. One monument is fixed and another point that is approximately diametrically located is given 0.5mm error three dimensionally.

After minor revisions to a priori accuracy of the instruments, the error factor is 1.001 and hence passes Chi-Square test at 5.00% level, which confirms that the posterior estimate of instrument performance of SA is reasonable in this case.

Table 2 lists the coordinate deviation between the results of Star*net and USMN which proves that the two software get similar result and the coordinates generated by USMN of SA can both be used for the alignment of storage ring.

Table 2: Coordinate deviation between Star*net and SA

	Name	**Value**	**Note**
Coordinate deviation	RMS X	0.036	For all the monuments
	RMS Y	0.034	
	RMS Z (elevation)	0.004	

The statistics (1σ) of Star*net solution are listed in Table 3. The relative error ellipses are computed for the points within 12 meter relative to selected points. Unfortunately, the direction of the major axis is mainly aligned with the transverse direction of beam. The relative error ellipse conforms to the error estimate result from simulation.

Table 3: Statistics of Star*net

	Name	**Value**	**Note**
Average absolute	Semi-Major Axis	0.606	For all the monuments
	Semi-Minor Axis	0.219	
	Elevation	0.030	
Average relative	Semi-Major Axis	0.041	For 39 points with an average distance of 5.9 meter
	Semi-Minor Axis	0.019	
	Elevation	0.016	

Most importantly, the relative error ellipse estimate here is a simulation of the monuments relative to instrument for future instrument setup and it indicates that better than 50 micron precision is achievable.

Global accuracy

The global accuracy of survey control network can be estimated after least square adjustment, as shown in the top part of Table 3.

It can also be estimated by comparing the coordinate difference between primary and secondary survey result. With all the epochs of control network survey, there are 4 of them that both primary and secondary have been surveyed. 3 out of 4 have preferable survey condition and the differences of the 5 common monuments are all below ±1 mm.

Another proof is that for the latest two epochs of survey, the maximum coordinate deviation is 0.87 mm, which indicates that the ground motion is slowing down and that the measurement accuracy is good.

This indicates that a ring-shaped survey control network measured by laser tracker can achieve better than ±1 mm global accuracy in a dimension of ~800 m circumference.

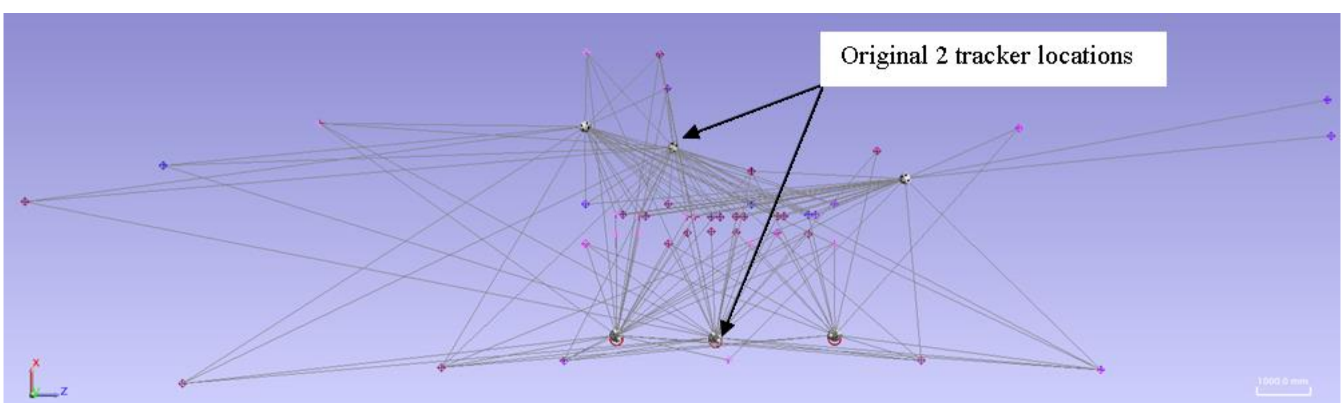

Figure 3: The tracker setups for the alignment of girder C07G4.

Local accuracy

Local accuracy is the most important part as high precision relative girder alignment is required. Both simulation and actual computation demonstrate better than ±0.050 mm accuracy.

Furthermore, the relative alignment of girders is well performed based on the control network. The re-survey result confirmed that and at the beginning of the commissioning, beam can run multiple turns without any correction strength proved that.

THE USE OF THE CONTROL NETWORK

Besides the basic function of providing installation datum for all the components, NSLS-II SR control network serves as tie to bring instruments together in order to reproduce the girder profile within about 10 micron precision.

Two laser trackers are used together to align the girder by taking care of the girder fiducials in aisle and ratchet wall side respectively, as called out in Figure 3. The monuments will help the trackers tying together as well as orienting in the reference coordinate system.

After the alignment goal is achieved, the two setups, along with 4 more setups, will record the monuments, magnet and girder fiducials and get a better and more comprehensive understanding of the alignment.

There will be slight differences between the two instrument configurations due to the imperfection of control network and the measurement error of instrument, as listed in the left part of Table 3. For the 6 girders out of 90, the maximum deviation in one dimension is 13 micron. The very small deviations indicate that the control network can provide a very reliable and precise alignment datum.

The right part of Table 4 shows the RMS deviations of monuments during the best-fit process after 6 tracker measurement. The measurement result of 2 trackers shows similar statistics which is not listed here. The fact that all the numbers are below 50 micron is another verification of the precision of the control network. It should be pointed out that the girder alignment is taken place after about 3 months of the latest control network survey. Very limited amount of monuments were excluded during the best fitting process due to apparent large deviations. The measurement error and slow crawling of monuments could be the culprit of it.

There are two areas of the tunnel where truck and utility tunnel are underneath it and cracks had formed and fixed. Control network shows different behaviour there and there are fitting problems in both areas. This is actually more of an engineering problem, instead of control network issue.

In a word, the control network demonstrates very high precision and withstands the effect of time in most of the area for a long time.

Table 4: Errors of control network

Girder name	Deviation between 2 and 6 tracker setup			6 tracker setup RMS deviation of monuments			Count
	DX	DY	DZ	DX	DY	DZ	
C06G2	0	-0.007	0.002	0.046	0.023	0.036	21
C06G4	0.001	0.003	0.003	0.044	0.024	0.039	26
C06G6	-0.01	-0.001	0.003	0.029	0.016	0.022	13
C07G4	0	-0.002	0.007	0.023	0.028	0.028	19
C07G2	-0.007	-0.013	-0.02	0.027	0.025	0.019	17
C07G6	-0.008	-0.007	0.002	0.029	0.017	0.021	14

FURTHER DISCUSSIONS

Control network is a basic topic of accelerator alignment. A properly designed one should have the following properties:

- Enough global accuracy. This will ensure good absolute positioning accuracy of each sub-system of the complex and also the absolute positioning accuracy of all components in one sub-system. For NSLS-II storage ring control network, with all the measurement errors and ground motions included, the recent rounds of surveys show below 1 mm coordinate difference which proves that the global accuracy is good.
- Adequate local accuracy. This is more important for storage ring since local alignment tolerance is much tight. Local accuracy ensures that the local alignment can be satisfied. For a modern machine, due to schedule pressure, alignment group may not have enough time to do re-survey or smoothing for all the girders after fine alignment. This means the local accuracy of survey control network defines, to a great extent, the local alignment accuracy

achieved before commissioning. NSLS-II faced this situation. However, the beam can run through the ring many turns without any corrector strength proved good relative girder alignment also achieved, which was attributed to the local accuracy of survey control network.

- Can be easily re-surveyed. The construction activities will change the control network significantly at the early stage of the installation. This requires the control network can be re-surveyed easily to re-establish the alignment datum. NSLS-II storage ring survey control network can be easily established by using AT401/2 laser tracker only in a couple of weeks. 7 epochs have been done till now. Without the current technique by phasing out digital level, this seems to be a mission impossible. Although in hindsight, one could question whether it is necessary to establish the control network so many times, we do notice the coordinate difference changes from initially 5 mm to less than 1 mm recently between adjacent epochs.

In a word, for all the aspects discussed above, NSLS-II storage control network performs very well. The only shortcoming is that the amount of monuments seems more than adequate, which is a response to the girder profiling requirement. However, the great performance of it and hence no difficulty commissioning may well justify it.

SUMMARY

The substitution of instrument from traditional laser tracker and digital level to AT401 is a success in NSLS-II project. It shows improved measurement efficiency and precision. The local accuracy is better than ±0.050 mm and global accuracy is better than ±1 mm.

Spatial Analyzer is convenient and reliable to be used for the computation of control network. It has comparable result with respect to traditional software.

The combination of AT401 and Spatial Analyzer has promising prospect in accelerator control network survey.

ACKNOWLEDGEMENT

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REFERENCES

[1 C. Yu, F. Karl, S. Seiler et al. NSLS-II Girder Profiling Activities. International Workshop on Accelerator Alignment 2012 Proceedings.
[2] C. Yu. The NSLS II Control Network Design. October 2013, Technical note, Brookhaven National Laboratory.
[3] SA User manual. New River Kinematics. August 2013.