NETWORK SURVEY SIMULATIONS FOR PLANNING THE ALIGNMENT OF A PARTICLE ACCELERATOR

Rodrigo Junqueira Leão[1,2], _Regis Terenzi Neuenschwander_[2], _José Luiz Alves Trabanco_[3], _Maria Luisa Collucci da Costa Reis_[4]

[1] Aeronautics Institute of Technology, São José dos Campos, Brazil, rodrigo.leao@lnls.br
[2] Brazilian Synchrotron Light Laboratory, Campinas, Brazil
[3] University of Campinas, Campinas, Brazil
[4] Institute of Aeronautics and Space, São José dos Campos, Brazil

Abstract − The alignment of particle accelerators' components to the micrometric level requires a well-known network of reference points. The survey of this control network is primarily done with laser trackers, total stations and optical levels. In this paper we investigate some network parameters, such as distance between points, their disposition along the machine's area and the number of surveys in order to reduce the point cloud uncertainties to a targeted magnitude.

Keywords: alignment, geomatics, metrology, monuments network, synchrotron light sources.

1. INTRODUCTION

The mechanical alignment of a particle accelerator is essential to its performance [1]. The alignment activities are an overlap between metrology and geomatics, and currently the requirements in terms of uncertainty are pushing the development of new technologies and more sophisticated equipment. It is necessary to have a well-known network of points in the area where the particle accelerator will be installed. The accelerator is composed of electromagnets of several types. The precise positioning of these components requires good topography surveys to define machine's local coordinate system. In addition, precision levelling must be done to gather information about floor levelling and its deformation over the time. Each point of the network (or monument) consists of a nest to accommodate an Spherically Mounted Retroreflector or to place an optical level rule/target.

The network is measured a certain number of times during the surveys. With multiple observations of each point, it is possible to estimate both the most probable location of that point in space and its uncertainty. The data reduction, which in geodesy is called network adjustment, is performed through Least-squares, Bundle adjustment, Monte Carlo or other methods [2-9].

After network measurements and coordinate system creation, one can precisely locate the instrument using the reference points and align the magnets in the target position. The more we achieve low uncertainties for the network, the more accurately we can determine the instrument location in the tunnel and more precise will be the alignment process.

The magnets centres form the electrons path through the ring. By aligning the magnets one can best fit the circular trajectory with some degree of confidence. As they will not be exactly in the nominal position, even if the magnets are realigned multiple times in this rough alignment process, a second step comprises the elimination of discontinuities in the electrons' trajectory. This procedure is sometimes called smoothing [10]. Doing this iteratively it is possible to achieve desirable low uncertainties.

Different instruments are used for the alignment, due to their intrinsic characteristics. Laser trackers and Total Stations are used for the topographic survey and precision optical levels are generally employed for the levelling survey. Laser Trackers performs better in distance measurements due to its interferometer while Total Stations are capable of measuring angles with higher accuracies due to their precision encoders.

In particle accelerators, normally the reference points are disposed in a letter C formation called c-rings. These sections throughout the tunnel are a combination of floor, wall and ceiling monuments.

This work deals with a systematic approach in the design of a reference network that will be used in the near future to align Sirius, fourth generation Synchrotron Light Source being developed in Brazilian Synchrotron Light Laboratory − LNLS. The planning of the simulations will be fully detailed and preliminary results presented. Knowing beforehand the amount of uncertainty that we will find in real measurements is very useful. The number of surveys that are necessary to perform, that is, the number of observations of each point necessary to reduce point uncertainties will assist the planning of the alignment, scheduled to take place between 2017 and 2018.

2. MATERIALS AND METHODS

The accelerator is divided in 20 sectors and its total circumference is 518 meters. Each sector is a magnetic periodical structure, which means that ideally the number of reference points in each sector must be equal to allow a uniform alignment for the machine.

In this study we are using the software SpatialAnalyzer™ to adjust the network, through an implementation of a Unified Spatial Metrology Network. This algorithm performs a data reduction that weights differently the influences of each instrument station, based on its distances from the target. This package from the software is ISO compliant [4].

From the point of view of geomatics, there are a few discussions about the comparisons [11] between SpatialAnalyzer™ and dedicated geodesy adjustment software, like PANDA™ [12]. In this work we will focus on the optimization of the network and the determination of best parameters, as any small differences between the different software is assumed to affect the several arrangements in the same manner, not compromising the study.

2.1. Automation

In order to simulate the surveys, some steps are necessary. Firstly we need to add the instrument and take it to the station position (area between the points sections). Then we can connect to its interface and fabricate measurements in simulation mode, by pointing at a target and taking a measurement.

The software works by attaching the instrument to the point's observations acquired through it. It allows the operator to add multiple instruments for each of the stations (positions) and to keep all of them in the same program. The process of adding the laser trackers and repositioning is similar to the real world act of setting up the laser and taking measurements, then move it and taking more points and so on, until one survey is done (one turn in the accelerator ring, for example).

We developed a script that allows automation in this measurement task. The software has a tool called Measurement Plans – MP that provides users with a graphical programming environment to automate measurements. This package is very powerful and allows full control of measurement equipment, analysis and reporting tasks.

For each reference point we are fabricating observations by averaging 50 samples. In order to simulate real world measurements, the software introduces random errors in the observations.

The correct metrology good practice would be to take measurements of the same point using both faces from the laser tracker and averaging them. This procedure intends to minimize systematic errors of the laser tracker. In simulation mode the software does not have the resource of back face measurement. Nevertheless the systematic errors only apply to the real instrument and the use of both front and back face measurement mode does not influence the results of this work.

2.2. Naming System

It is important to univocally identify all monuments in the network, in order to provide traceability in the measurements. Based on prior convention, the naming system for Survey and Alignment components were defined as follows:

SISA-REF-CP: sirius storage ring, survey and alignment - reference - central pillar

SISA-REF-0i-F0j: sirius storage ring, survey and alignment - reference - sector i - jth floor monument

SISA-REF-0i-W0j: sirius storage ring, survey and alignment - reference - sector i - jth wall monument

SISA-REF-0i-C0j: sirius storage ring, survey and alignment - reference - sector i - jth ceiling monument

SISA-REF-0iGj-0k: sirius storage ring, survey and alignment - reference - sector i, girder j - kth reference

TBSA-REF-F0i: transport line linac-booster, survey and alignment - reference - floor monument number i

LISA-REF-W0i: linac, survey and alignment - reference - wall monument number i

2.3. Methodology

The methodology adopted to conduct this study is shown in Figure 1. Base simulations were performed in order to fully understand the problem and answer fundamental questions. Then, with the goal of obtaining a target uncertainty for the monuments network, an analysis of the influence of the network in the positioning of the girders is done. Despite the periodical calibration of the instruments, an experimental evaluation of the laser trackers is necessary to account for out-of-lab influences, such as operator, thermal and others environmental effects. The fourth step is the optimization of the network layout, in which specific simulations will compare different geometries and arrangements. Then, before final adjustment, another set of parameters will be tested, such as the inclusion of ceiling monuments and different aspects of the survey procedures.
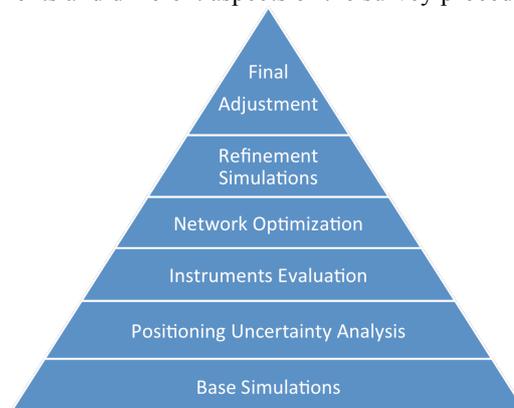

Fig. 1. Schematic of the planned simulations and experiments.

2.3.1. Base Simulations

Base simulations have the initial goal of demonstrate the capability to simulate a complete survey of the accelerator, from the fabrication of point measurements to the network adjustment. This demonstration does not intend to be quantitatively accurate nor simulate the best approach in terms of network. Rather it uses a simple version of monuments arrangement and a default value for instruments uncertainty. Besides this basic goal, in this category of simulations the following fundamental questions are to be answered:

- What is the effect of free-stationing the laser trackers around a desired point? In other words, are the different simulations biased by the

location of the instruments near their nominal positions?

- Will the overall result of a specific network change if one repeat the fabrication of measured points (simulation of a measurement with the input of random errors)?
- Does the repeated application of SpatialAnalyzer network adjustment algorithm produce different results?

In addition, four base simulations were designed, as follows:

1. Arrangement shown in Figure 2, with floor monuments only (three points per ring);
2. Inclusion of wall monuments (two per ring);
3. Inclusion of a central pillar and five connexion points;
4. Inclusion of three auxiliary pillars around the central one.

These simulations are designed to help understanding software's functioning, get confidence on the simulation process and gain insights about the effects of network's alterations in the uncertainties of the points.

Figure 2 shows a first arrangement being simulated.

Fig. 2. Screenshot of the reference points in the first sector of the machine for a first arrangement.

In this first scenario, each sector of the machine has three c-rings. The distance between the rings is about 8.5 m as can be seen from Figure 2.

2.3.2. Positioning Uncertainty Analysis

If reference points on a girder or magnet are measured, their uncertainties will essentially depend upon the uncertainty herded from the instrument and the uncertainty related to repeated measurements (redundancy).

The uncertainty of positioning the same components on a specified coordinate system, however, will depend also on the uncertainty of the network monuments used to locate the laser tracker.

The alignment requirements for Sirius, as specified in the Detailed Design Report – DDR of the machine are as follows:

- 0.030 mm from magnet to magnet, at 1 σ;
- 0.100 mm from girder to girder, at 1 σ.

The mechanical design of the girders and the magnets is being developed so that the magnets will be aligned by definition. In this case, the mechanics of the assembly and the geometrical quality of the magnets (such as quadrupoles and sextupoles) will guarantee that the magnetic axes of the magnets are aligned within tolerance.

In the case where the mechanics of the magnets does not satisfy the magnetic requirements, Fiducialization techniques will have to be used to relate the offsets between the magnetic axes with respect to external fiducials on the magnets. In both cases, however, a Coordinate Measuring Machine – CMM will be used for the alignment or verification of the alignment.

The alignment between girders (support for an assembly of magnets), however, is subject of this paper. It will rely on portable coordinate systems like laser trackers to correctly position the girders on their nominal location, on a certain coordinate system of the accelerator.

In order to establish a target for the uncertainty of the network points, it is necessary to evaluate how these uncertainties influence the final alignment.

The simulation designed to produce this information is as follows: given a network previously simulated and adjusted, measurements of two reference points should be made, simulating the real case where two girders are being aligned. What is the uncertainty of this simple alignment starting from the uncertainty of the network used to locate beforehand the laser tracker? If we measure some points on two girders and fit coordinate systems on both of them, how is the uncertainty of those coordinate systems? How do they relate to the uncertainty of the network? Knowing the ratio between those numbers one can establish a maximum uncertainty for the network so that we can still align girders to their neighbours on the ring (accelerator) below 0.100 mm. Yet, it is important to notice that this tolerance implies that error + uncertainty is to be less than 0.100 mm to fulfil specification.

2.3.3. Instruments Evaluation

As far as the instrument's uncertainty is concerned, we have four situations:

- Maximum Permissible Error – MPE attested by manufacturers in their technical specifications;
- How the particular instrument performs in the laboratory, attested by the accredited laboratory in the calibration certificate;
- A default, conservative uncertainty for each type of instrument considered by SpatialAnalyzer (software manufacturer New River Kinematics give overestimated uncertainty parameters for instruments families, despite brand or actual conditions of the equipment);
- A task-specific uncertainty for the instrument, accounting for out-of-lab influences such as operator skills, uncontrolled environmental conditions.

The latter, if estimated correctly, can provide "real" performance of the instrument and make more reliable simulations.

At this moment LNLS has two models of laser trackers: a Leica AT401 and a FARO Vantage. An experimental evaluation of both the instruments will be made, in order to estimate their uncertainties in conditions close to what we will find when performing the practical alignment of the machine.

Initial experiments are being performed in order to start the simulations with a coherent uncertainty statement for the laser tracker. In the future, however, scale-bars have to be used in order to provide traceability to the metre.

2.3.4. Network Optimization

The first step of the methodology is to list the factors we want to evaluate. Those are:

- Distance between sections of points (A);
- Points arrangement within a section (B);
- Instrument locations between sections (C);
- Measurement strategy (D);

We will consider, than, two levels for the factor A: three sections of points per sector of the machine (distance between sections is about 8.5 meters) and four sections per machine sector (distance of 6.5 meters). This parameter is constrained by machine's symmetry, because there is no reason to align one portion of the machine better than the others. Increasing the points density would place the laser tracker too close to the points, while spreading the sections would cause a small number of points to be placed around a certain girder to be aligned.

For the monuments configuration (B), we will evaluate the six possibilities: three reference points in a straight line, perpendicular to the wall; three reference points following beamlines path (tangent to the accelerator ring), three misaligned reference points in an arrow formation and three zig zag-like patterns.

For most of the points configurations there are three possible placements for the laser tracker (C): in between two point sections, around the middle distance between the internal wall and the girders and two more possibilities, near the girders and near the internal wall (where the booster accelerator will be installed).

The measurement strategy (factor D) yields two levels: from a certain laser tracker station one shoots every possible point in the line of sight or the measurements can be restricted in a smaller volume. In the first case we get more redundancies (more measurements for all points). On the other hand, doing so the uncertainties for the more distance points will increase and those observations may have to be rejected if they worsen the network.

One approach to test the factors of interest would be to evaluate every combination of factors. Using Design of Experiments [13] theory it is possible to plan a factorial design for the simulations, analysing the four factors with less effort. An analysis of variances – ANOVA will compare a specific criterion among the different simulations. The performance measure in this case is the average uncertainty of the network points, which we intend to minimize. Other parameter of interest could be considered as the variance of the points' uncertainties, because uniformity in the network can benefit the alignment process.

For these simulations we will adopt a standard instrument with a default uncertainty. Also, we will run three surveys of each configuration to have enough samples for the statistic tests.

2.3.5. Refinement Simulations

With the optimized network and procedure available, some simulations will be made in order to improve our understanding about the alignment process and suggest better ways to perform the alignment:

- Adequate the monuments positions so that cable trails and instrumentation do not coincide with them;
- Test the inclusion of ceiling monuments (intrinsically less stable than wall and floor references);
- Test the inclusion of more connection monuments linking the central pillar to the internal area of the accelerator (the possibility is on the external wall);
- Test the inclusion of more random error in the measurement of wall and ceiling monuments than that of floor to improve the model;
- Test the substitution of the laser tracker by optical levels for height measurements;
- Test the inclusion of total stations for the angle measurements in the surveys;
- Test the inclusion of the secondary central pillars in opposition with zeroing the angular errors from the laser tracker from the central pillar;
- Test not to free-station the laser trackers located in the central pillars and check uncertainty behaviour of those points;

2.3.6. Final Adjustment

Finally, an adjustment of the network will be performed, in order to have information of the uncertainty of the optimized arrangement of monuments with the consolidated measurement strategy.

Then, a second survey will be simulated and the generated data will be also considered in the adjustment process. This procedure is repeated until the uncertainty of the points is reduced to a desirable level.

3. RESULTS AND DISCUSSION

The results produced in this paper concern an initial version of the accelerator monuments network, with 180 points and 60 laser tracker positions. Each survey of this network using scripts to automate the process of pointing at a target and taking measurements takes approximately 30 minutes. This effort, without automation, takes about half a day due to the complexity of the simulation.

In Figure 3 we can see three laser tracker stations. Each station is placed in-between two points sections. Only the second laser tracker in the image is connected (green halo). Each machine's sector has three sections of three points each.
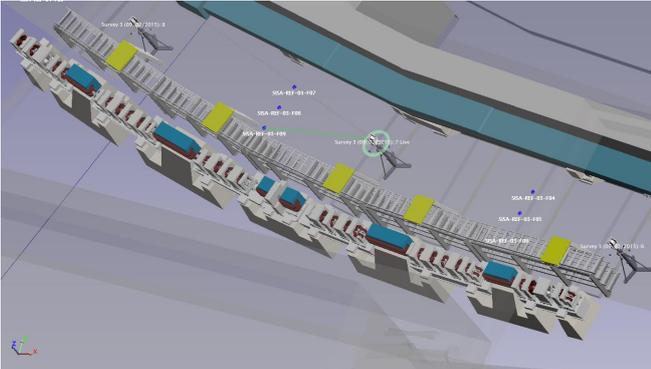
Fig. 3. One sector of Sirius, showing three laser trackers, reference points, girders, magnets and other components.

After the survey it is possible to visualize the shots from the instruments as in Figure 4 below.
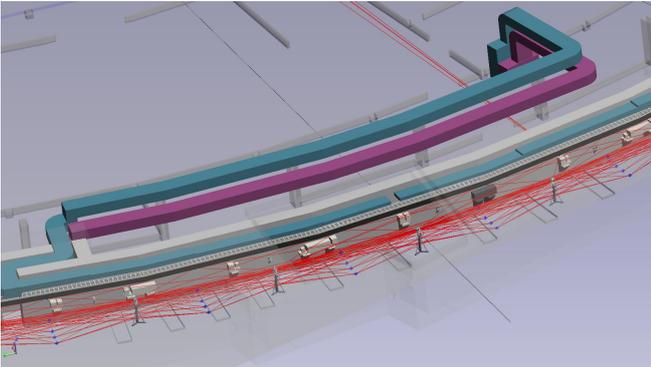

Fig. 4. Instruments shots.

One of the first trials resulted in a network reinforced with three auxiliary central pillars, as can be noticed in Figure 5:
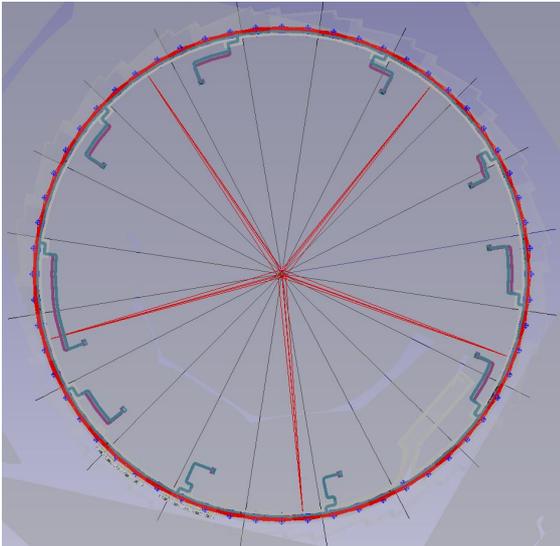

Fig. 5. Shots from every laser tracker in the survey.

After performing the surveys, we have a number of observations of each point. To analyse the data we first have to adjust the network and calculate the uncertainties for each point.

In Figure 6 we can see a sensitivity cloud for one of the reference points. This kind of tridimensional representation is easier to understand and analyse then the traditional commonly used error ellipse.
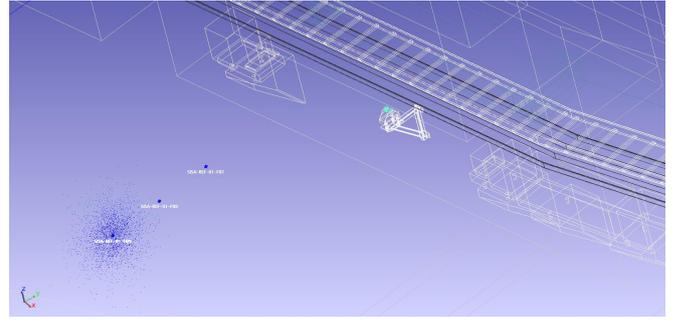

Fig. 6. Magnified graphical depiction of a point uncertainty field (1000 sensitivity samples).

3.1. Base Simulations

In the sequence is presented a compilation of results for the base simulations.

Table 1. Uncertainty results of the base simulations.

Average monuments uncertainty (1 σ) [mm]			
#	U_x	U_y	U_z	U_{mag}
0	0.060	0.060	0.445	0.453
1	0.056	0.056	0.213	0.228
2	0.050	0.050	0.169	0.184
3	0.043	0.043	0.127	0.142

For each of the simulations, the results shown are an average of three different surveys of the accelerator ring. In the start simulation (0), we have used only floor monuments. In simulation number 1 we have included wall monuments (two per point section). For simulation number 2 the central pillar (origin of the accelerator coordinate system) was included, as long as five connection points. These points are accessible through removable windows in the concrete radiation shield (walls of the accelerator tunnel).

In the last base simulation three auxiliary pillars were simulated near the central pillar. These pillars also have force-centring plates for the installation of laser trackers and all of them can be seen from the connection points. The inclusion of these pillars seems to strengthen the network, especially in the height (z axis). This can be explained by the triangulation that is formed with these additional monuments.

With these base simulations we have also determined that:

- Positioning the laser tracker near the nominal position (in this case the middle region between main accelerator and booster) does not bias the results of the simulations;
- The fabrication of points, despite its random nature, produce repeatable point observations in terms of magnitude and probability distribution;
- The adjustment algorithm used by SpatialAnalyzer (Unified Spatial Metrology Network – USMN) uses sensitivity analysis and Monte Carlo method, but different analysis produce comparable results and does not affect the result of the comparisons.

3.2. Instruments Evaluation

It is currently being constructed a real scale partial mock-up of Sirius (Figure 7). This project is intended to mitigate installation problems and help the design process of Sirius.

This environment is being used to evaluate the task-specific uncertainties for the instruments that will be used for Sirius alignment. First results are of the order of 10 μm for the distance component for a measuring volume of three point sections. The uncertainty of the angles will remain below 1 arcsec for this system.

Fig. 7. Mock-up of 1/27th of Sirius. Three monuments can be seen in the bottom of the photo. We can also see cable trails, pedestals, girders and magnets. Dipoles are in blue, quadrupoles in orange and sextupoles in green.

4. CONCLUSIONS

We conclude that measurement simulation allows the visualization of the alignment process and the characterization of the procedure in virtual reality, and it is possible to optimize important parameters for the control network of reference points.

This study, initiated two years before the actual alignment process of the Synchrotron Light Source Sirius, when fully conducted will provide relevant results with potential to enhance the quality of the planning phase of the installation, surveying and commissioning of the machine and its components.

This article comprises the development of a sequence of simulations intended to guide the decision making for the alignment process; initial simulations have answered fundamental questions about the network establishment, and a comprehensive set of simulations has been proposed to optimize the network and provide expected uncertainty for the alignment of the particle accelerator. The objective function is the average uncertainty of the reference points, which should be minimized.

The study proposed, whose execution is initiated in this paper, makes use of experimental and numerical steps. A performance evaluation of two models of laser tracker is intended to be performed in field, to serve as input for the simulations. Also, we will compare the results of the simulations with the measurements of a true-scale mock-up of one section of the accelerator. Numerically, we will determine, in addition to base simulations, studies that will be run to find the network that better minimize the uncertainties of the individual points within the network. To achieve this, Design and Analysis of Experiments – DAE theory is used. A full factorial design is chosen and a set of

task specific simulations are planned to study simultaneously important parameters of the network. Finally, we establish the procedure to produce a complete adjustment of the network. This process will, in the future, provide not only an expectation of the behaviour of the network and quantitative information about the alignment, but will also allow the determination of the number of surveys, that is, the number of redundancies that one need to have, to minimize random errors and achieve a targeted uncertainty. As a complete survey of the accelerator is time consuming, knowing how many surveys is necessary is crucial for a successful planning of the installation and alignment routines.

REFERENCES

[1] D. Martin, "Review of Accelerator Alignment", *FIG Congress*, FIG Congress 2010 Facing the Challenges – Building the Capacity Sydney, Australia, 11-16 April 2010.

[2] D. Wilson. Survey And Alignment For The Diamond Light Source. IWAA2004, CERN, Geneva, 4-7 October 2004.

[3] F. Q. Wei, K. Dreyer, U. Fehlmann, J.L. Pochon and A. Wrulich. Survey And Alignment For The Swiss Light Source. IWAA1999, ESRF, Grenoble, 1999.

[4] J. M. Calkins. Quantifying Coordinate Uncertainty Fields In Coupled Spatial Measurement Systems. PhD Thesis, Virginia Polytechnic Institute, 2002.

[5] J. E. Muelaner, Z Wang, O Martin, J Jamshidi and P G Maropoulos. Estimation of uncertainty in three-dimensional coordinate measurement by comparison with calibrated points. Meas. Sci. Technol. 21 (2010) 025106 (9pp)

[6] W. Liu and Z. Wang. Coordinate uncertainty analyses of coupled multiple measurement systems. Meas. Sci. Technol. 21 (2010) 025106 (9pp).

[7] M. Schloesser, J. Prenting. Status Report on Survey and Alignment Efforts at DESY. IWAA2004, CERN, Geneva, 4-7 October 2004.

[8] C. Le Cocq, Brian Fuss, Robert Ruland. Status Report on the Alignment Activities at SLAC. Proceedings of the 7th International Workshop on Accelerator Alignment, SPring-8, 2002.

[9] B. Schaffrin, Andreas Wieser. On weighted total least-squares adjustment for linear regression. J Geod (2008) 82:415–421.

[10] S. Lee, A. Maeng, K. Seo. Measurement of Storage Ring Deformation and Smoothing Method for Pohang Light Source. IWAA1997, ANL/FNAL, Illinois, 13-17 October 1997.

[11] C. Herrmann, M. Lösler, H. Bähr. Comparison of SpatialAnalyzer and different adjustment programs. The 1st International Workshop on the Quality of Geodetic Observation and Monitoring Systems (QuGOMS'11) International Association of Geodesy Symposia Volume 140, 2015, pp 79-84.

[12] J. Dale, A. Reichold. Simulation of the Alignment of Linear Accelerators. Proceedings of PAC09, Vancouver, BC, Canada.

[13] D. C. Montgomery. Design and Analysis of Experiments, John Wiley & Sons Inc., 8th edition, New York, NY, USA, 2013.