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ESTABLISHING A METROLOGICAL REFERENCE NETWORK FOR THE ALIGNMENT OF SIRIUS

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Abstract

Sirius is the Brazilian 4th generation synchrotron light source. It consists of three electron accelerators and it has room for up to 38 beamlines. To make the alignment of Sirius components possible, there is a need for a network of points comprising the installation volume, allowing the location of portable coordinate instruments on a common reference frame. This work describes the development of such networks for the whole Sirius facility. The layout of the networks is presented together with the survey strategies. Details are given on how the calculations combined laser trackers and optical level measurements data and how the Earth curvature compensation was performed. A novel laser tracker orientation technique applied for linking networks on different environments is also presented. Finally, the uncertainty estimation for the resulting network and its deformation history is shown.

INTRODUCTION

Sirius' Storage Ring (SR) is composed by over 650 magnets, which are assembled on steel girders and disposed along a circumference of 518 m. To reach the designed parameters, its components must be aligned within micrometric tolerances [1]. The chosen strategy for the alignment was the use of portable Coordinates Measuring Machines (CMMs), mainly laser trackers (LT) [2, 3], which demands a reference network of points to precisely locate the CMM in a common coordinate system [4]. This paper describes the creation of such a network, exploring details of the network layout, survey processes, calculations, and connection techniques for different environments.

METHODOLOGY

Network Layout

The network is a set of well-defined points distributed over the facility used for the location of portable CMMs in the working volume and for deformation analysis over time. For Sirius, there are two main networks: the primary one is a set of 1220 points distributed on the Accelerators Tunnel (AT) walls and slab and is used for magnets alignment; the secondary reference contains 730 points in the Experimental Hall (EH) floor, columns, and in the AT external walls, for beamline alignment. Figure 1 shows the general layout with the points distribution for both networks. These points were materialized by spherically mounted retroreflectors (SMR) nests embedded into the concrete.

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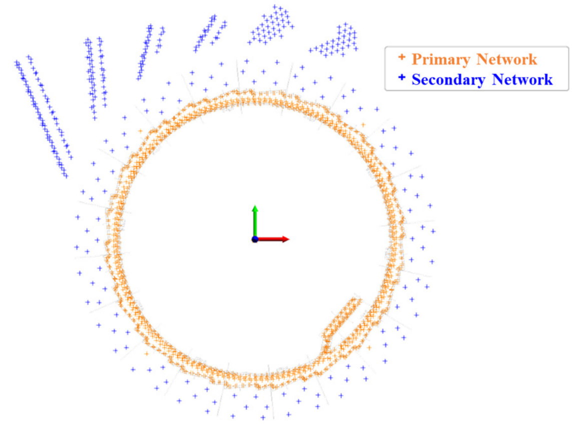

Figure 1: Sirius network layout.

Networks Survey

Each network was surveyed individually but follows similar strategies. A set of levelling campaigns were done for each region of interest using the Leica NA2 optical level: one for the AT, one for the EH and one for each long beamline extension. For the connection between the AT and EH campaigns, 4 regions (one in each quadrant) were used, where additional level stations were set up to obtain a free line of sight from one environment to the other; and for each beamline extension campaign it was included a control point from the EH. In that way, it was possible to determine the vertical floor profile for the whole building, result used onwards during the definition of the network constraints.

A classical LT survey was then carried out, with several free stations measuring the network with overlapping points. Only LT from the AT400 family (Leica) were used. For the primary network, it was required a set of 241 tracker stations with a total of 5542 measurements inside the AT. The survey strategy included a "zig-zag" layout and different heights between stations, which were mounted on tripods and wall-mounts supports [5]. As for the secondary, 195 stations performed a total of 4107 measurements distributed along the EH. Tracker stations were mounted on tripods standing on the floor and on the AT ceiling for a bigger height difference and hence a stronger network.

In addition to that, special observations of the network "radius" were done. A LT was mounted on a central pillar, close to the Sirius coordinate system origin. From this position, the tracker has five free sights of approximately 80 m directly to specific control points in the interior of the tunnel. As this tracker position is not deterministic, a centroid is calculated for the five control points, and the control radii are stated as the distance between each control point and the centroid. The average of these values is also used as a constraint parameter during the network calculations.

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Connection Techniques

The connection between different networks or environments is generally made by a tracker station which can measure points in all the environments from a single position. It was not possible to use this strategy for the connection between the primary and secondary network, because the AT is fully enclosed. The only physical connection between both environments are the holes in the AT walls, which are very restricted lines of sight with Ø150 mm for 1-meter length.

To overcome this issue, a novel technique for reciprocal orientation between laser trackers was proposed, resembling theodolites collimation. It consists in having one tracker (#1) located in the primary network and another tracker (#2) in the secondary network. They must be fine levelled with respect to the gravity and have a free line of sight between them. Using a special SMR nest, one tracker should be able to measure the movement of the other tracker head, fitting a sphere which centre point represents the measured tracker position. By the end of procedure, each tracker will have registered its own position and the other tracker position. Performing a least square transformation of tracker #2 measurements while keeping tracker #1 fixed and not allowing any level transformation, will result in a correlation between the location points in the primary and secondary network. This procedure was done in the same four regions used to connect the levelling campaigns of the AT and EH. In practice, it means that the primary network has now common points with the secondary, which will be used for the mathematical link between both networks.

Calculations and Parameter Optimization

To allow the alignment of distant components with respect to its source in a true geometrical plane, the compensation of the Earth curvature must be done. The first step of the network calculation was, then, modelling this effect and defining the relation between the distance from source and vertical offset. Due to the distances involved, a spherical model was adopted, rather than using geodesical ellipsoids. This compensation was applied in the results of the combined levelling campaign and the general profile can be seen in Fig. 2.

The next step was setting up the constraint parameters. It was defined that, in large scales, the height difference between points from the levelling campaign and the average radius would define the global shape of the network and, in smaller scales, the trackers stations should be forced to comply. For both parameters, the measurements were repeated several times for statistical analysis, summarized in Table 1.

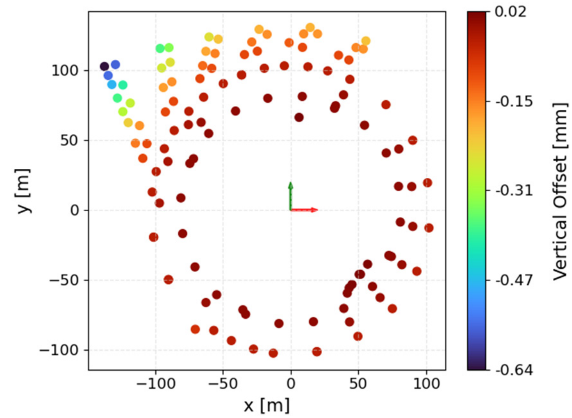

Figure 2: Earth curvature compensation profile applied to the level control points of Sirius Network.

Table 1: Constraint Parameters Statistics

Parameter	Uncertainty	Standard Error
Level	0.108 mm	0.017 mm
Radius	0.034 mm	0.009 mm

The third step was applying the defined constraints into the Unified Spatial Metrology Network (USMN) algorithm embedded in the SpatialAnalyzer® software. The USMN is used to combine several tracker stations and calculate a composite points group where each point has a cartesian coordinate and a related uncertainty. The algorithm uses different weights for each measurement depending, for example, on the distance between the tracker station and the measured point [6]. The constraints were input into the USMN also by using weights. For the levelling campaign, a dummy tracker station was created with the height measurements and with a specific weight for the vertical coordinate. For the radius stations, weights were applied in their absolute distance meter (ADM) measurements.

The definition of the weight's values passed through a sensitivity analysis in which the network was calculated for different weights. For each resulting network, the average radius and the maximum height difference between level control points were analysed. These results were compared to the original estimation of the given parameter, and these data (deviation from the original measurement as a function of applied weight) fits exponential curves that were used for the definition of an optimum weight for each parameter. The final weight was defined such as the deviation of each parameter should not exceed the original estimations by more than one Standard Error summed with the exponential curve asymptote. After adjustment, the resulting primary network was transformed in a Least-Squares sense to the last available epoch, from 2018 [7].

Finally, the last step is the mathematical link between the primary and secondary networks. It is done with a special method of the algorithm called "USMN with point groups", in which the calculations are made considering a static reference. In this case, the primary network is set as the reference and the secondary is adjusted with respect to the primary, while preserving its initial level.

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RESULTING NETWORK

Uncertainty Estimation

The combined network is already in use for the alignment of the accelerators and beamlines, and Figs. 3 and 4 shows its estimated uncertainty (average of 34 µm for the radial direction and 83 µm for the vertical) reported in a coverage probability of approximately 68%.

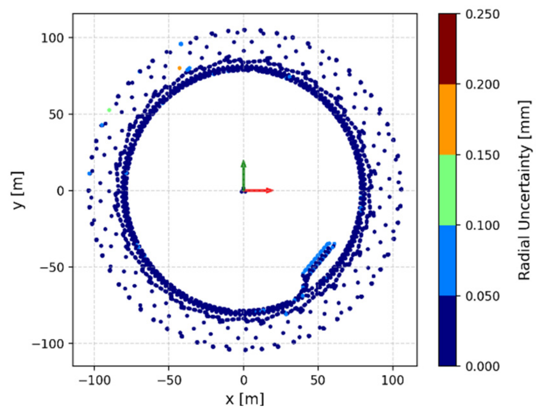

Figure 3: Sirius Network radial uncertainty (1σ).

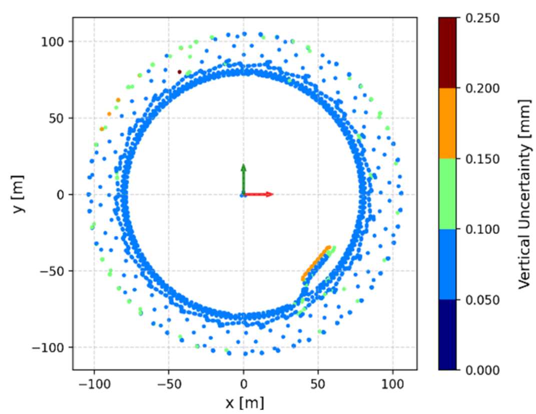

Figure 4: Sirius Network vertical uncertainty (1σ).

Deformation History

The network was first surveyed in 2018 for the accelerator's pre-alignment. Back then, the building did not have thermal stability and groundwork and concrete curing were recent, so a deformation was already expected. In 2020 the network passed through an update and the Storage Ring profile was also surveyed. Figure 5 illustrates the network deformation between the two mentioned epochs.

Besides the networks update that should occur regularly, the Sirius facility contains monitoring systems and verification routines to investigate deformations over time in shorter periods, which confirmed the magnitude of the deformations assessed by the network update [8].

Since the SR was surveyed together with the network update, it was verified that the accelerator followed the same deformation profile as the network. Then, in early 2021, a first round of fine alignment was performed using the updated network [9].

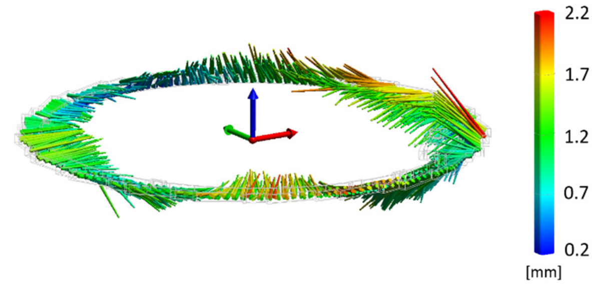

Figure 5: Network deformation between 2018 and 2020.

CONCLUSIONS AND NEXT STEPS

The strategy chosen for the alignment of Sirius demanded the use of a metrological reference network for the precise location of laser trackers. This work described the methodology used for establishing such a network and presented results regarding its uncertainty estimation and deformation history since its first survey. The accelerators alignment has proven to be of a major importance, and the first round of fine alignment performed early this year helped to improve the machines parameters and aided in the Sirius commissioning [10].

Further studies need to be made on how the USMN algorithm deals with propagation uncertainty between networks, because when the same steps of calculations were used to propagate the uncertainty from the secondary to tertiary networks, the results expressed smaller uncertainty values, which did not seem to be correct. In that sense, studies on uncertainty propagation between networks using Monte Carlo simulation should be conducted. Also, in the long term, it will be extended for the development of a Python-based software for networks adjustment.

An immediate improvement that should be done is using a more accurate optical level, namely the Leica N3 (the unit was under maintenance during the 2020 surveys), and an increased number of control points for the levelling campaigns. This would reduce the measuring distance and thus the uncertainty included in the network. Investigations on the relation between the distribution of points used to locate a LT and the number of control points used as level constraints should be conducted. Studies on the use of a rotary laser system instead of an optical level are also being carried out.

Finally, there is an idea of using the laser trackers in a multilateration approach, in which the network would be adjusted based in the ADM measurements only, which could drastically reduce the survey overall uncertainty.

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