EXPERIMENTAL EVALUATION OF LASER TRACKER TARGET HOLDERS STABILITY

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Abstract

The new Brazilian Light Source, Sirius, will be commissioned in 2018 and is considered by many as a fourth generation Synchrotron facility project. The Survey and Alignment activities are currently in the planning phase and one of the focus is the target holder development. These target holders will be installed in our accelerator to serve as a network of reference points to be used in the alignment process. In this paper, we are interested in assessing the capability of our concepts in maintaining the center of the Laser Tracker optical target in the same position as it is repositioned. We performed an experiment designed to compare six models and run an analysis of variance to evaluate the data. A performance measure was defined in order to take into account repeatability errors of repositioning the optical target. We were able to verify statistical differences of small magnitude between the concepts. The quantitative results will be used to help in the decision-making.

INTRODUCTION

The Laser Tracker is being consolidated as an essential tool in the particle accelerator alignment [1]. It uses optical targets called Spherically Mounted Retro reflector (SMR) to reflect the laser beam and measuring points. Therefore, the system uncertainty is affected by the laser itself, the SMR and what is called the nest for the SMR, or target holder. Some works study the laser equipment [2] but there is a lack of studies regarding target holder aspects.

Some companies manufacture these kind of devices, as can be seen in Figure 1, but sometimes, depending on the application, particle accelerator laboratories design their own target holders.

Figure 1: Commercially available target holder from Brunson™ (1.5 inches model).

The alignment of particle accelerators is a critical part of the project [3-4]. Whatever the application of the accelerator, it will achieve its functionality if its alignment tolerances are met.

Nowadays Brazil has the first and only Synchrotron Light Source in the South America, operational since 1997 [5] (UVX, in Figure 2). Sirius, the new project that is currently being carried on [6], is going to be one of the brightest light source in its category. The storage ring will have a circumference of 520 m and the survey and alignment activities are mainly in the planning phase (Figure 2).

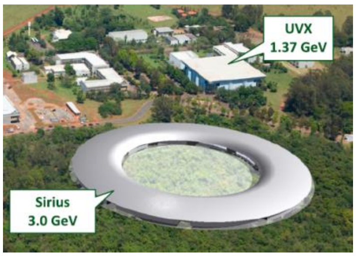

Figure 2: Aerial view from LNLS Campus and tridimensional mockup of the new facility.

The overall concept of the target holders has already been developed. Two different products have been established, one for the floor and another one for the walls and ceiling. For the floor design, we have developed an external profile that will help the epoxy resin to hold the target holder fixed to the floor. A stainless steel cover has been developed to protect the target holder. For the wall and ceiling model, the external design accounts for floor installation ease and for detection of collisions that could cause damage to the target holder (thin borders, which are intended to be visibly affected and indicate a probable mechanical impact).

The SMR is made from stainless steel and is installed upon the target holder in order to measure the position of that monuments (or reference points). The contact between the SMR and the target holder is very important because it should determine precisely the center of the SMR. Several factors could interfere with the repeatability of the position of the SMR's center, such as dust and bad support.

Contact region ideally should not change over time. This way, every time a SMR is placed in the nest the center of the sphere will be located exactly in the same spot. This kind of repeatability is what we call in this work target holder stability.

We aim to evaluate six target holder designs with respect to their stability in terms of maintaining the center of the SMR in the same position as we remove and put it back in place. The uncertainty of the Laser Tracker starts around a dozen micrometers, and depending on the

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stability difference between the target holder designs, this difference might be negligible.

MATERIALS AND METHODS

This section will describe the experiment and the designs tested. We will describe the procedure to collect data and how we defined the performance of the concepts.

Models description

Table 1 summarizes the six models that were evaluated. Within this work, we are interested solely in the SMR positioning aspect. Other factors, like cost and installation ease are not discussed.

Table 1: Design Details

Design	Type of Contact	Contact Material	Description
A	Cone	Aluminium	Aluminium body
B	Three spheres	Stainless steel	Aluminium body with encrusted spheres
C	Segmented cone	Aluminium	Three frustums areas
D	Cone	Aluminium	Aluminium plated with electrolytic nickel
E	Cone	Stainless steel	Stainless steel body
F	Cone	Aluminium	Aluminium plated with chemical nickel

As we are interested in the contact between the SMR and the target holder, we are trying to understand the influence of the material and the geometry of the contact area.

For the models with a frustum cone, the contact between the sphere of the SMR and the cone will generate a circle. This circle is not as deterministic as three points, and the model B will try to accomplish this with the three spheres of two millimeters radius.

In model C, we have a smaller contact region, but still not three points. We have machined a cone target holder in order to get three segments of frustum cone.

As the friction between the material from the SMR (stainless steel) and the material from the target holder will produce a circular scratch in the contact region, the contact geometry might be even less stable.

Designs E will test the influence of using stainless steel and models D and F use nickel plating. The difference between these last designs is the type and the quality of the coating. In model F, we have much more regular and smooth coating. Figure 3 shows all designs, side by side.

Performance Measure

To quantify the ability of the models to be stable regarding repeatability, we define the stability error for each observation:

$$e_s = \sqrt[3]{\left|x_p - \overline{x_p}\right| \cdot \left|y_p - \overline{y_p}\right| \cdot \left|z_p - \overline{z_p}\right|} \qquad (1)$$

Where,

$$\vec{\mathrm{p}} = \vec{c}_{SMR} - \vec{c}_{THolder} \qquad (2)$$

And the mean values in Equation 1 are the mean coordinates after *n* observations. In order to deduct possible movements of the target holder, we use the x, y and z coordinates of the position vector of the SMR in the target holder frame (Equation 2 and Figure 4). This performance measure accounts simultaneously and equally for the influence of errors in the three Cartesian coordinates.

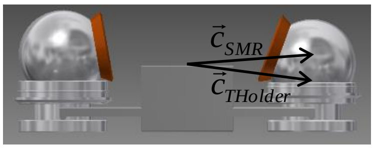

Figure 4: Scheme of the measurement.

Assumptions

In order to conduct a conclusive and reliable analysis of the experiment, some assumptions have to be made. The first one is that we expect independence of the results. This is likely to occur if we execute the experiment in a completely randomized manner.

In addition, the results of each design we are testing should have approximately equal variances. This assumption is called homoscedasticity.

It is also important that normality is achieved. This means that the results from the experiment should follow approximately a Gaussian probability distribution.

Figure 3: Designs A to F, from left to right, respectively.

Execution

We used a Coordinate Measuring Machine – CMM (Figure 5) to measure the position of the center of the SMR and the position of the target holder during the experimental process. Manual alignment to the part was made before the first time a pair of target holder was measured, but the measurement process itself, including the final alignment to the part, was performed in Computer Numerical Control – CNC mode.

We designed a support for two target holders and the alignment to the part consisted in creating the reference frame on it.

For the measurement of the SMR center, we touched 16 points on it. For the determination of the target holders position, we measured a plane in the top face and a circle around it. For each pair of target holders that we measured, we alternated the position of the SMR between each target holder model.

Figure 5: CMM from Hexagon Metrology™ used to perform the experiment.

We performed 30 observations of each model and for each observation we took measurements of the target holder as well. Alignment of the support was also made before each measurement, in order to account for any minimum movement of the system. Before each measurement, we removed the SMR ten times and for each repetition, we rotated the SMR in a random fashion (Figure 6). This procedure was used to induce possible scratching and changes in SMR center, trying to simulate the real use of the system.

Figure 6: One stage of the measurement process.

Some precautions have been taken to minimize undesirable influences:

- Use of gloves to minimize thermal gradients between operator and apparatus;
- Screw fixation of the alignment support part and glue to avoid target holders displacement;
- Thermal stabilization of the tested models for at least 24 hours;
- Use of the same SMR in the same position during all measurements, to avoid the effect of sphericity errors;
- Cleaning of the contact region to remove possible deposited dust.

Temperature compensation of the CMM was disabled in order to avoid any kind of mistake, as the measurements did not involve a single material. The average temperature of the part was 23.67 ºC (with standard deviation σ = 0.09 ºC) during measurement of models A and B, 23.75 ºC (σ = 0.12 ºC) for models C and D, and 23.79 ºC (σ = 0.15 ºC) for models E and F. The temperature was taken just before each observation and we used CMM part temperature sensor.

These changes in temperature are small enough to be negligible, especially with the part dimensions involved. Variability arising from a nuisance factor can affect the results. If this nuisance factor were likely to have an effect on the response, and this variability were known and controllable, a design technique called blocking could be used to systematically eliminate its effect on the statistical comparisons among treatments [7]. Unfortunately, in this case, changes in temperature were small but rapid and we only saw the changes in superficial temperature. Using this information could cause errors in data analysis when trying to correlate temperature with changes in stability error.

The uncertainty of the CMM is present in the measurements of all target holder models; therefore, we expect this influence to affect data obtained from all models.

RESULTS AND DISCUSSION

In this section, we provide detailed results and the tests we performed to verify the validity of the conclusions we can draw from the data.

Preliminary Results

Initial tests were performed to determine the ideal number of observations that we should take, as well as to determine which performance measure we should adopt.

As a collateral effect of experimentation for developing the measurement procedure, two minor findings of this work can be reported:

- Regarding the aluminium cone design (A), we run a t-test comparing a specimen already scratched with a brand new one. With a p-value of 0.03915, there is a statistical difference between the two samples with a 95% confidence interval. The mean stability error was 0.00065 mm against 0.00052 mm. That fact indicates that an already scratched contact area is more stable than a new one (we used the specimen already scratched in the main experiment of this paper);
- Using the design F as a parameter, we performed a t-test between measurements following the procedure described in this paper and measurements where we did not rotate the SMR in its nest. There is a significant difference between these two treatments for 99% confidence interval (p-value of 0.0001129). The mean stability error is bigger in the last case (0.00037 mm against 0.00099 mm) and we performed the main experiment of this paper rotating the SMR because this is the worst-case scenario.

Qualitative Results

Original data contained a few outliers for designs A and D. One could infer that they are not outliers and is just the fact that these models are not so repetitive. This can be true and we could have performed formal tests to verify if these observations are really outliers. However, Table 2 shows that removing the outliers did not change neither the conclusions from ANOVA test nor the assumptions we have made. We removed these outliers, as can be seen in Figure 7 (affecting the coordinate means present in our performance measure, changing the values of stability error for all observations) in a few steps and got the final general qualitative result plotted in Figure 8. Due to outliers in the data, we do not have an exact balanced experiment design, but this can be handled by ANOVA test algorithm.

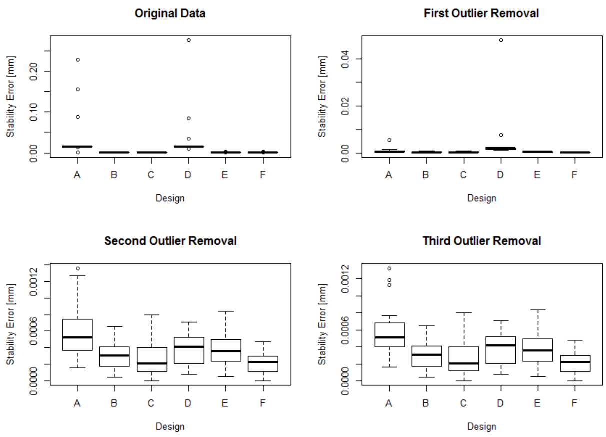

Figure 7: Boxplot of results during the removal of the outliers.

Table 2: Comprehensive Results of Tests used to Compare Changes in Response While Removing Outliers

Data	**Homoscedasticity Test (p-value)**	**Normality Test (p-value)**	**ANOVA (p-value)**
Original	2.2e-16 (Bartlett)	2.2e-16 (D'Agostino)	1.79e-06
After first filtering	2.2e-16 (Bartlett)	2.2e-16 (D'Agostino)	0.00208
After second filtering	0.0001202 (Bartlett)	0.008629 (D'Agostino)	1.31e-08
After third filtering	0.00567 (Bartlett)	0.006427 (D'Agostino)	3.69e-08

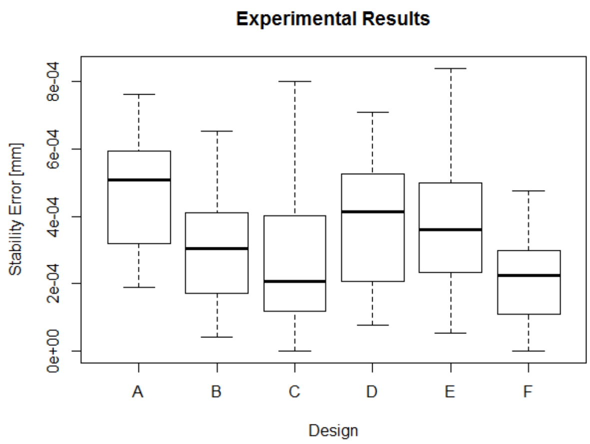

Figure 8: Results for Stability Error, in millimeters, from all target holders tested.

Boxplot of the experimental results suggest that some designs have produced more repetitive repositioning of the SMR.

Statistically speaking, these mean responses might be all equal. An analysis of variance will test two hypotheses:

- H0 (null hypothesis), in which all designs have the same mean Stability Error;
- H1 (alternative hypothesis), in which some of the designs have discrepant Stability Error.

Model Adequacy Checking

Before assessing the quantitative results from ANOVA and interpret them, it is important to check the validity of what we are getting from the experiment and the assumptions we have made.

As we executed the experiment in a completely randomized way, independence of responses is intrinsically achieved. The procedure we followed was thought to accomplish this.

To verify the homoscedasticity assumption, we performed two formal tests in the software R [8]. Table 3 provides the results from these tests.

Table 3: Tests for Checking Homogeneity of Variances

Test Name	**p-value**
Batlett	0.1987
Fligner-Killeen	0.4243

Since the p-values we find are greater than our level of significance (0.01, 99% confidence interval), we can affirm that the results from all the tested designs have equal variances.

The Normal Q-Q plot in Figure 9 indicates that our results are normally distributed. Besides, the residuals of the ANOVA test (in other words, the error between our mathematical model and the measured data) do not seem to have any tendencies (Figure 10).

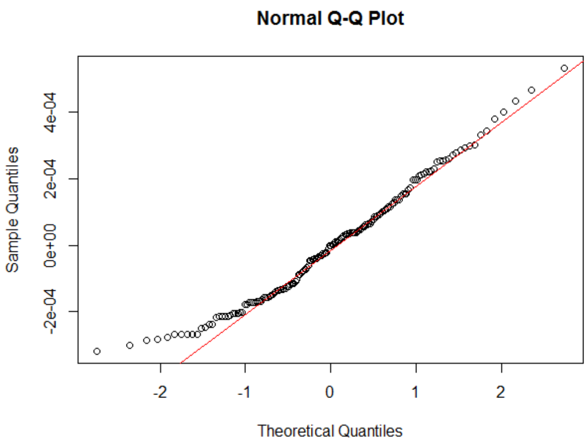

Figure 9: Distribution of data.

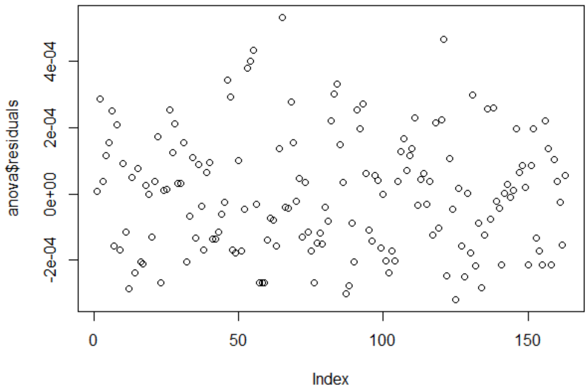

Figure 10: Residuals from ANOVA.

Although the qualitative results above already suggest normality of residuals, formal tests can be employed to validate the assumption of normality. Several tests have been created over the years, and many works compare the tests available [9]. D'Agostino test was used and the computed p-value is 0.1262, which is sufficient to assume that our data do not have skewness (99% confidence interval).

Quantitative Results Presentation

The Analysis of Variances (ANOVA) gives us a p-value of 1.45e-05. For a level of significance of 0.01% (99% confidence interval), the null hypothesis has been refuted. Therefore, we are now interested in knowing what specific designs have a different Stability Error mean.

The Tukey Honest Significant Test performs multiple t-tests among the treatments in an optimized way to check for difference in means between treatments. Table 4 show the numbers from these comparisons.

Table 4: Tukey Honest Significant Test Results

Comparison	**p-value**
B-A	0.0168233
C-A	0.0008582
D-A	0.4164266
E-A	0.3564193
F-A	0.0000192
C-B	0.9376047
D-B	0.7385949
E-B	0.7661920
F-B	0.3477593
D-C	0.2089464
E-C	0.2216378
F-C	0.8842376

E-D	0.9999997
F-D	0.0160785
F-E	0.0166604

It is clear that only models C and F contrast from the others, with lower stability errors. Figure 11 exhibit the statistical intervals.

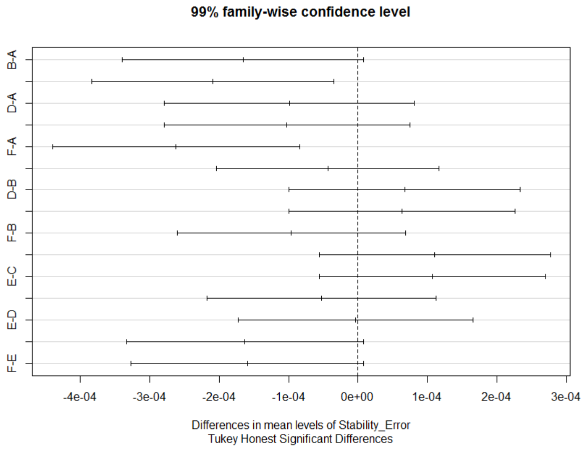

Figure 11: Graphical display of difference in stability error means.

Interpretation

It was already expected that models B, C and F would have lower stability errors than the other models, considering their design characteristics. The models with smaller contact areas would probably have more deterministic location for the SMR.

With this in mind, the segmented cone (model C) would be an approximation of model B, which was in fact our natural control design.

Considering the models with a cone as the contact area, it was already known that the aluminum and stainless steel would have approximately the same behavior, because of the circular scratches. The nickel coating was designed to reduce the scratches, with an improved superficial hardness.

Model D was tested in order to account for the effects of a bad plating process. In fact, considering model F as an improvement of this concept, the quality of the plating plays an important role. This model has not been free of scratches, and the scratches appeared in just one side of the contact line because of the irregular coating thickness.

The main surprise was the superiority of models C and F compared to model B. Our explanation is that model C had scratches on its contact lines, but smaller contact area. Model F had no scratch marks in the circular support region, but as model C, allowed the SMR to settle in its place while the operator rotated it against the target holder. Model B, despite the three contact points, do not allow the SMR to accommodate because of the hardness of the three spheres and the almost perfect support provided by the three points.

CONCLUSION

This work allowed the statistical comparison between six concepts of target holders for laser tracker optical retro reflectors, relative to their potential to repeat the position of the measured point.

We have found a statistical difference between the mean stability error of the models, and two of them showed best results.

The findings of this study suggest the possibility that a new concept, arising from the merge of designs C and F (segmented cone and aluminum with nickel chemical coating, respectively), might present better performance [10].

Although the statistical difference between the designs, the magnitude of the stability error differ no more than 0.00026 mm between all concepts. Considering the Laser Tracker uncertainty, the stability error cannot represent a major decision factor.

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