MODELLING AND OPTIMIZATION OF SOLEIL II SURVEY AND UNCERTAINTY ASSESSMENT OF THE MEASUREMENT PROCESS USING MONTE CARLO APPROACH

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Abstract

SOLEIL synchrotron is preparing a major upgrade that will lead to the commissioning of a new and more powerful machine by 2030. Questions naturally arise about the technical solutions that will be chosen to align the components of the future machine and meet the tight alignment tolerances. To identify the best alignment strategy (implantation of the geodetic networks, fiducialization of magnets, mechanical alignment of the components, survey, smoothing etc.), the development of a model has been initiated. The aim is to simulate the measurement process, estimate the alignment uncertainties of the machine components and test various measurement configurations. This paper is focused on the approach used to develop the model and will present some preliminary results.

INTRODUCTION

The SOLEIL II project aims to provide a fourth-generation synchrotron radiation source with an horizontal emittance reduced from 3.9 nm.rad down to 85 pm.rad. To achieve this objective, the new lattice will be much denser, the magnets more numerous, stronger and more compact (use of permanent magnets and non permanent magnets). The machine design raises major technical issues in terms of alignment, and more specifically on the alignment of the storage ring.

During the upgrade of SOLEIL synchrotron, one of the aims will be to position the various components of the machine within the tolerances fixed by the physicists. The definition of alignment tolerances is fundamental. According to [1], a tolerance is "*an interval of permissible values of a property*". To define these tolerances, the physicists who design the machine carry out simulations to determine its performance. Starting from the theoretical positions of magnets and girders, alignment errors are introduced. These errors follow normal distributions truncated at twice the standard deviation (2σ). One of the criteria used to define the tolerances is that the correction budget spent for the orbit adjustment should not exceed a certain threshold in order to preserve a sufficient correction range for the machine's adjustment and operation. The simulations must therefore find the right compromise between realistic errors in terms of alignment and performance conservation. Once this compromise has been found, the tolerances are defined on the basis of twice the standard deviations used for component misalignment. The current alignment tolerances are detailed in Table 1. The latter are defined in the machine's local reference frame (S, X, Y), with S the longitudinal component which is tangent to the beam, X the radial component perpendicular to S, and finally Y the vertical component directed upwards. The origin O of this reference frame follows the electron trajectory.

Points to check	**Tolerances**
Alignment of magnets on a girder	-50 μm < T_X,T_Y < 50 μm -100 μm < T_S < 100 μm -200 μrad < R_S,R_X,R_Y < 200 μrad
Alignment of magnets on section matching girders	-20 μm < T_X,T_Y < 20 μm -100 μm < T_S < 100 μm -200 μrad < R_S,R_X,R_Y < 200 μrad
Alignment of girders with respect to each other (close or on both sides of a straight section)	-50 μm < T_X,T_Y < 50 μm -100 μm < T_S < 100 μm -20 μrad < R_X,R_Y < 20 μrad -120 μrad < R_S < 120 μrad
Control of the circumference	-2 mm < C < 2 mm

Table 1: Alignment tolerances for SOLEIL II

To align the machine, the magnetic centre of the various magnets must therefore be positioned within these specified intervals.

The measurement process shown in Figure 1 describes the various steps involved in aligning the magnets in the machine. Each step of this process contributes to the final uncertainty of the component alignment. The challenge is to control this uncertainty so that the alignment tolerances are respected.

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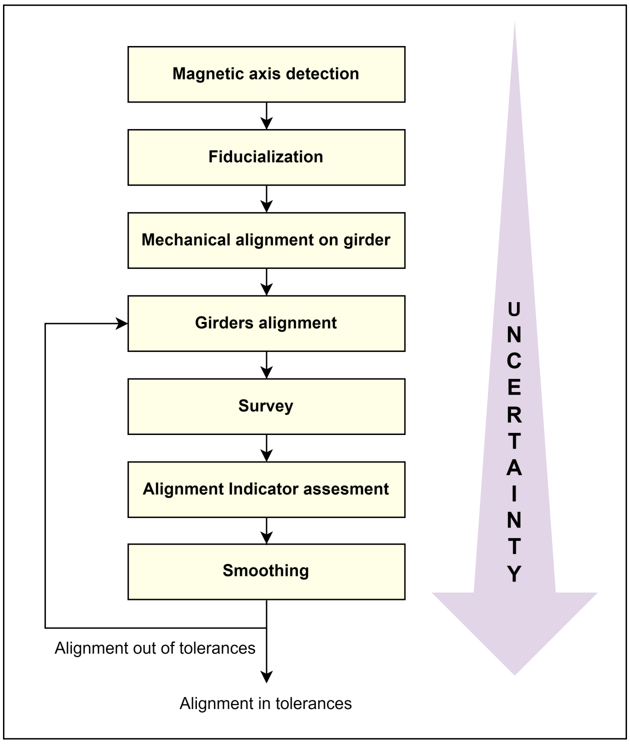

Figure 1: Measurement process diagram

The first step of this process is the determination of the magnets magnetic centre position with a high degree of accuracy. Once determined, the fiducialization takes place. The position of the magnetic centre will be determined with respect to mechanical references (fiducials) placed on the magnet chassis. This operation can only be achieved on a specific bench that detects the position of the magnetic centre. This step is crucial as it contributes to the final uncertainty on the positioning of the magnets in the machine. The next step is to mechanically align the magnets with respect to each other on the different girders. The process that will be used for this operation has not yet been definitively decided, and several techniques are being studied. The girders will then have to be placed in the machine and aligned. A global survey of the storage ring enables the determination of fiducial positions and calculation of each magnetic centre position using the offsets measured during fiducialization. Following this step, a certain form of the machine will be obtained, containing both high spatial frequency errors (roughness) and low spatial frequency errors (waviness). The latter can be compensated by the corrector magnets. However, the roughness are more critical for the good operation of the machine and will have to be minimised by a physical realignment, also known as the smoothing step [2]. It is during this last operation that it will be decided if a girder is well aligned (within tolerance) or badly aligned (out of tolerance). This choice will mainly depend on the value obtained for the position of the magnetic centre and its associated uncertainty resulting from the propagation of all the uncertainty components generated during the various steps of the measurement process. Figure 2 illustrates the importance of controlling this uncertainty using two cases.

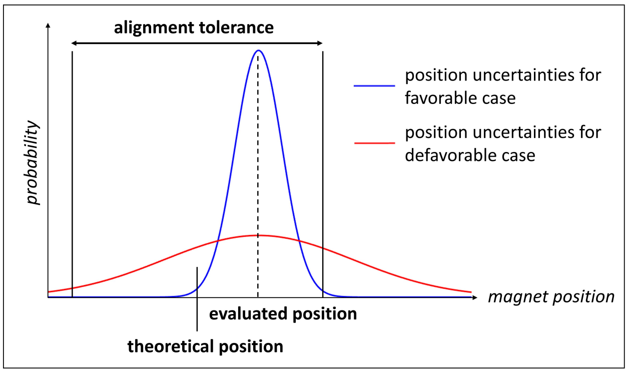

Figure 2: Example of two different uncertainties for the same evaluated position

In both cases, the assessed position of the magnetic centre is the same. However, the uncertainty (combined standard uncertainty according to the International vocabulary of metrology [3]) of this position differs from one case to another. In one case (blue curve), the uncertainty is well contained and well below the alignment tolerance. This is an ideal case because the probability that the magnet position is within tolerances is extremely high. In the other case (red curve), the uncertainty is much higher. This means that the risk of having a value outside tolerances is high. This case is therefore unfavourable and an acceptance criterion will have to be established in order to control the risk [1].

Therefore, during the smoothing, the position deviations of the machine components will be minimised, taking into account their associated uncertainty, the alignment tolerances and also the risks of being misaligned.

Although an experimental approach could be envisaged to determine the best alignment strategy by testing different scenarios, it is very difficult to implement because of the large number of scenarios to be tested, the time required for those tests and also the very limited access to the storage ring. The approach envisaged is therefore to model the measurement process and carry out calculations. These simulations will largely focus on surveying and smoothing of the machine because of the significant influence of these steps on the final uncertainty of the component positions. It is therefore important to identify and quantify the many parameters that will influence this final uncertainty. The aim is then to optimise the measurement process to obtain the uncertainty as low as possible for the position of the machine components.

The first part of this article will describe the model developed so far, the various input parameters, the output variables, and the approach used for the simulations. The second part of the paper will present some preliminary results.

MODEL

The development of the measurement process model has several aims. The main objective is to be able to assess the uncertainty of magnetic centre position at the end of the measurement process. For that, the uncertainty budget for the measurement process must be established. This budget must identify and quantify the impact of every sources of error on the measurand, i.e. the position of a magnet in the machine. These different sources of uncertainty are closely related to the measurement process, and may arise from the instruments used, the operators, the protocol used, the measurement environment, the stability of the machine, etc. The measurement uncertainty of a magnet position will be determined using the Monte Carlo approach [4]. There are several reasons for using this approach rather than a more traditional one such as the propagation of uncertainty defined in the GUM [5]. Firstly, uncertainty propagation assumes that the measurand has a Gaussian distribution, which is not necessary the case in our model. In addition, the large number of input components will make it difficult to write the propagation of uncertainty within the model mathematically. Finally, the Monte Carlo approach makes it possible to propagate input distributions to determine an output distribution, which is much more interesting from a statistical point of view. At last, the interest of such a model will be to detect the parameters that contribute the most to the measurement uncertainty. Then, a compromise between every parameters must be found to optimize the measurement process, reduce the measurement uncertainty while keeping an acceptable time for the survey.

The model developed so far focuses exclusively on the survey step of the measurement process. This is the step with the largest number of parameters to be optimized (number of stations, number of monuments, location of monuments, number of sights per station, etc.). It is also the step that takes the longest in the machine, which is why it is so important to be able to simulate it. Figure 3 shows the diagram of the model developed to simulate surveys. This model was coded in Matlab, except for the topographical compensation which uses the Unified Spatial Metrology Network (USMN) function of Spatial Analyser software [6].

To create a machine survey model, we first need to define the different variables that characterise this model. In our case, the output variable Y of the model, i.e. the measurand, corresponds to the fiducials coordinates of each magnet in the machine. The input variables X_1, X_2, ..., X_n are all the parameters required to calculate the measurand and which contribute to the uncertainty of the final result. Here are some of these input variables:

- coordinates of the monuments (points on walls) ;
- coordinates of the fiducials ;
- coordinates and orientations of the stations ;
- number of stations ;
- number of fiducials ;
- measurement time for a point ;
- etc.

All these different parameters are linked together through a function f that represents the measurement process:

$$Y = f(X_1, X_2, ..., X_n) \tag{1}$$

This function f corresponds to a mathematical model that enables the measurand to be calculated from the input variables. These input variables can even be linked together by other functions, such as the observations from the laser tracker, which depend on the theoretical coordinates of the stations and points to be measured, but also on meteorological conditions (temperature, pressure and hygrometry). So the difficulty will be to determine all the interactions between the different input and output variables.

To simulate a survey, we first need to define the points to be measured. To be as realist as possible, the lattice defined by the physicists for the future storage ring was used. This lattice contains the theoretical coordinates of the magnetic centre of each magnet. This time, the coordinates are expressed in a global reference frame (x, y, z) with the centre of the machine as the origin o. Since the points measured during a survey are the fiducials and not the magnetic centres, an offset has been added to each point of the lattice. During a survey, the fiducials are not the only points measured, there is also a monument network. The model's point generator can be used to generate a monument network that can be configured by the user. It is possible to define the number of monuments required and their position in the tunnel (inside or outside wall, ceiling or floor, height, distribution, etc.). The data from the point generator will finally be the theoretical coordinates of all the points to be measured for the simulated survey.

During a survey, points are measured from laser tracker stations distributed throughout the storage ring. The model's station generator is used to set the parameters for these stations (number, height, positions, etc.), and to define their coordinates and orientations.

Once the coordinates and orientations of the stations and the coordinates of the points to be measured have been defined, the observations connecting them need to be calculated. To do this, the observation generator developed in the model will calculate the theoretical observations (distances, horizontal and vertical angles) between the stations and the points to be measured. These observations are calculated using simple topometric formulas [7].

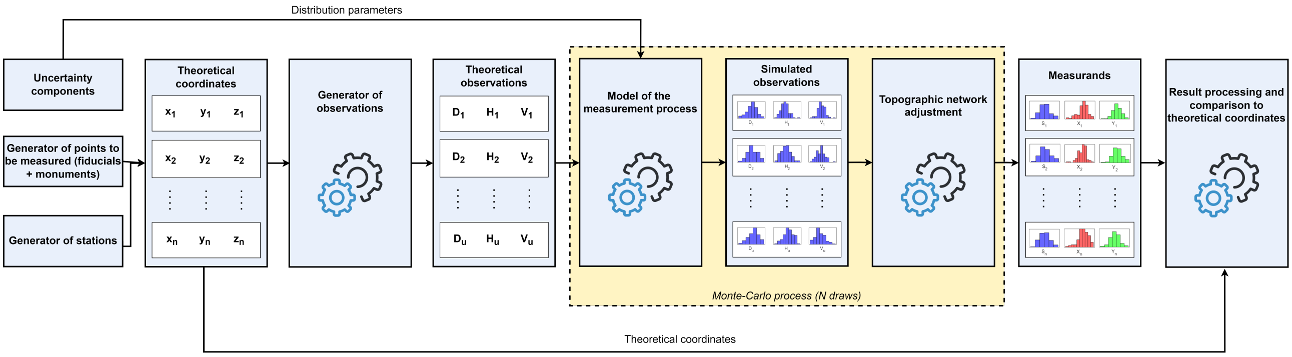

Figure 3: Diagram of the developed survey model

Noting respectively (x_S, y_S, z_S) and (x_P, y_P, z_P) the coordinates of the station S and the point to be measured P, then :

The **distance along slope** D_{SP} observed from station S to point P is expressed as:

$$D_{SP} = \sqrt{(x_P - x_S)^2 + (y_P - y_S)^2 + (z_P - z_S)^2} \quad (2)$$

The **horizontal angle** H_{SP} observed from station S to point P is expressed by:

$$H_{SP} = \tan^{-1}\left(\frac{x_P - x_S}{y_P - y_S}\right) - G_0 \quad (3)$$

with G_0 the azimuth of horizontal circle zero.

The **vertical angle** V_{SP} observed from station S to point P is expressed as:

$$V_{SP} = \tan^{-1}\left(\frac{\sqrt{(x_P - x_S)^2 + (y_P - y_S)^2}}{z_P - z_S}\right) \quad (4)$$

Depending on the filters set by the user (for example the laser tracker distance range), the observation generator will generate the distances as well as the horizontal and vertical angles between the stations and the points measured around them.

At this point of the model, the various observations generated are all theoretical, i.e. without any error. This is by definition unrealistic, because no matter how high the level of confidence is, no measurement is perfectly accurate. According to the Guide to the expression of Uncertainty in Measurement (GUM), "*a measurement generally presents imperfections that cause an error in the measurement result*" [5]. So, to make the model as realistic as possible, an uncertainty component must be added to each observation.

For the moment, the uncertainty components added to the observations are purely instrumental and are derived from the manufacturer's specifications [8]. Table 2 gives the standard measurement uncertainty for the three types of observations present in the model, as well as their probability density functions (PDF).

Observation	PDF law	Standard deviation / Mean value
Distance	Gaussian	$\sigma = 7\ \mu$m $\overline{m}$ = D
Horizontal angle	Gaussian	$\sigma = 3\ \mu$rad $\overline{m}$ = Hz
Vertical angle	Gaussian	$\sigma = 3\ \mu$rad $\overline{m}$ = V

Table 2: Uncertainties applied to model observations

Later, the model will become more complex and the combined standard measurement uncertainties of the observations will depend of other input variables. Indeed, other uncertainty components related to, for example, the Absolute Distance Meter (ADM) or the interferometer (IFM) of the laser tracker, or to the environment of the machine, will affect the uncertainties of the observations. The latter will therefore be calculated using the Monte Carlo method [4].

Once all the uncertainty components and input parameters have been evaluated, the method chosen to determine the final uncertainty on the position of the magnets in the machine is the Monte-Carlo method. The aim of this method is to simulate a random phenomenon. To do this, the Monte-Carlo method simulates a fictive sample of the random phenomenon realisation based on assumptions about the random variables. These assumptions will be the measurement uncertainties (which include standard deviation, mean value and PDF law) defined for each input variable of the model. The probability density of the measurand will then be constructed from a sample that includes all these simulated random variables. The larger the fictive sample simulated by the Monte Carlo method, the closer the statistical analyses carried out will be to the population [9].

In the current model, an initial random error will be drawn for each observation in accordance with the PDF law of its assumed uncertainty, and then added to the theoretical observation. An initial scenario of observations is thus shaped. Then the operation is repeated according to the number N of Monte Carlo draws chosen by the user: N measurement scenarios will be calculated, i.e. N sets of simulated observations.

Each of the N sets of simulated observations must then be compensated by a topographical adjustment. This will enable the most likely values to be calculated for the unknown parameters, i.e. the S, X and Y coordinates of the machine's fiducials. At the end of this step, the measurand will therefore describe an output probability density based on the N compensated coordinate values calculated for each scenario. Various statistical analyses and comparisons can then be carried out, particularly in relation to the theoretical coordinates of the fiducials.

At the moment, the topographic compensation of the N sets of observations is carried out by the USMN tool in the Spatial Analyser software [6]. This raises several problems, starting with the software's lack of transparency with regard to the functional models and algorithms used, which questions the trueness of the results. Furthermore, as Spatial Analyser is not a software specialised in the adjustment of point networks, it does not offer many useful indicators for the interpretation of the results (normalised residual errors, partial redundancy, internal reliability, etc.). Finally, since the measurement process model is developed in Matlab, a script is required to adjust the N sets of observations. This involves a considerable amount of computation since the script has to use N ASCII files of simulated observations and then generate N ASCII files of compensated coordinates as output. For all these reasons, a compensation software specific to SOLEIL is currently being developed under Matlab. It is based on the work described in [10] and used for Netobs software development.

RESULTS

Using the model presented in the previous section, it will be possible to simulate specific survey configurations, and find the one that gives the lowest final uncertainty on the fiducials. The idea is to vary the model's input variables in order to find the ones which contribute the most to final uncertainty. Although the model remains fairly simplistic, the initial results obtained already give some idea of the survey's behaviour. The influence of two parameters on the final uncertainty of a survey will be analysed in this section.

In order to analyse the influence of certain parameters on the behaviour of the machine, it is first necessary to define a reference configuration. This was chosen arbitrarily, but an attempt was made to define realistic parameters. The parameters used are defined in Table 3 and a graphical representation of this configuration can be seen in Figure 4.

Configuration
Number of fiducials : 1277
Fiducials height : 1.565 m
Number of monuments (interior wall) : 50
Number of monuments (exterior wall) : 50
Monuments height (interior wall) : 1.540 m
Monuments height (exterior wall) : 1.640 m
Number of stations : 100

Table 3: Parameters used for the reference configuration

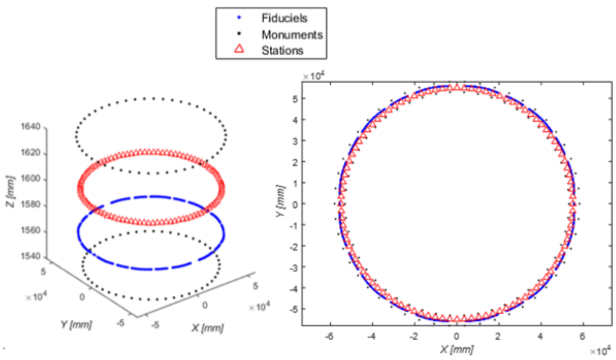

Figure 4: Reference configuration used for simulation

To limit the calculation time, the number of Monte-Carlo draws was set at N = 100. This low number of draws is due to the long calculation time, around three hours. To increase the reliability of the results, the number of draws will probably need to be increased, which will requires optimization of the code and the use of a computing cluster.

The same approach was used for each of the two configurations tested below. Using the 100 sets of compensated coordinates obtained, a Helmert transformation was performed for each set of coordinates in order to register all the points with the theoretical coordinates. The aim is to analyse the dispersion of the compensated points around the theoretical points by calculating the standard deviation of the 100 measurement scenarios. The combined standard uncertainty obtained for each configuration and the estimated duration of the survey will be the main parameters to compare the relevance of one configuration over another.

The two parameters whose influence will be analysed below are the number of stations and the number of monuments. Even before analysing the results of the simulations, it is obvious that these two parameters are very important and will influence the combined standard uncertainty. The number of stations will mainly influence the redundancy of each target point, while the number of monuments will influence the number of sights per station.

Number of stations influence

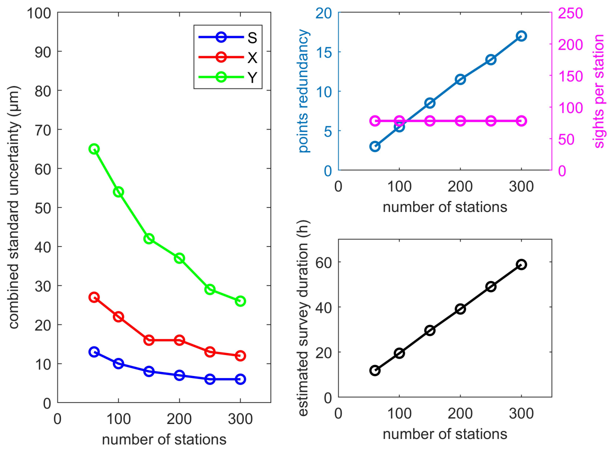

Figure 5: Results obtained by varying the number of stations

Figure 5 shows the results obtained by varying the number of stations. As expected, the combined standard uncertainty of the survey decreases as the number of stations increases. This combined standard uncertainty decrease is correlated with the increase of measured points redundancy. As the number of stations increases, more points will be measured by different stations. This results in greater accuracy in the position of the points, a better estimated network and thus a reduction in the combined standard uncertainty. Finally, the estimated survey duration increases linearly with the increase of the stations number. By doubling the number of stations, the duration is also doubled, which is problematic.

Number of monuments influence

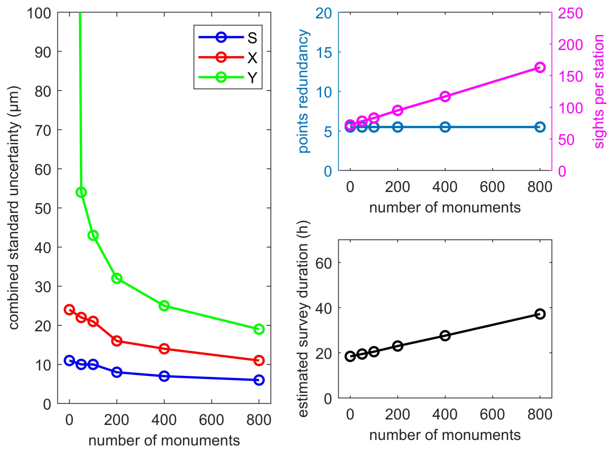

Figure 6: Results obtained by varying the number of monuments

Figure 6 shows the results obtained by varying the number of monuments on the wall. As with the number of stations, the combined standard uncertainty of the survey decreases as the number of monuments increases. This time, the decrease of the combined standard uncertainty is correlated to the increase of the number of sights per station. As the number of monuments increases, each station will measure more points and will therefore have a more accurate position. This better estimate of station position will mean a lower combined standard uncertainty on the position of the machine components. Finally, the estimated survey duration also increases linearly with the increase of the monuments number. However, this time, by doubling the number of monuments, the duration is multiplied by 1.3.

Discussion

The results obtained are interesting, particularly with regards to survey duration. Although increasing both parameters reduces the combined standard uncertainty of the survey, it does not imply the same increase in survey time. Increasing the number of stations involves a greater increase in survey duration, mainly due to the fact that installing a station takes much longer than measuring a point. It is therefore much more efficient in terms of survey duration to increase the number of monuments on the wall than to increase the number of stations. Through the optimization process, it will therefore be necessary to find the right compromise between the number of monuments and the number of stations. This reasoning should be applied to every parameters that will be tested.

CONCLUSION

This paper presented the measurement process model currently under development to define the best alignment strategy for the synchrotron SOLEIL upgrade. The aim of this work is to ensure that each component of the machine can be aligned within the tolerances set by the physicists. To achieve this, a very precise measurement process has been established, comprising different steps. Among these, the paper focuses on the machine survey step, which is crucial because it is this step that will determine the position of each component in the machine. Many parameters can have an impact on a machine survey, which is why an optimization of the measurement strategy is necessary.

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