Positions of the NCal reference plates for O4
VIR-0343A-22

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1 Introduction

Three reference plates were installed at Virgo NE as detailed in VIR-1123A-21. Some measurements were made during the mechanical assembly in October 2021 on the distances of the near reference holes.

In November 2021 the EGO infrastructure team made a survey (see logbook entry n° 53883) on the position of the near and far reference holes on the reference plates around the NE tower. The geometrical survey revealed few mm offsets with the expected values.

In March 2022 a last mechanical check was made on the template around the NE tower to verify the survey offsets.

This note shows the measurements from the geometrical survey in comparison with the mechanical assembly measurements. It derives our current best guess of the position of the reference plates as well as the uncertainties taken into account.

2 Geometrical survey at Virgo NE - November 16, 2021

The geometrical survey was made using reference points around the tower and are displayed in table 1 as x and y coordinates. Three stations were used to make the measurements, some of the points were measured through several stations.

Measurement point	Station 01		Station 02		Station 03	
	x (m)	y (m)	x (m)	y (m)	x (m)	y (m)
N201	2.5115	3000.4419				
N202	4.5120	3006.4206				
N204					-4.4878	3016.413
N205			-4.4919	3006.4162	-4.4918	3006.4162
N206					-4.4924	3000.4435
N208					-5.1473	2999.1256
N209			-5.7296	3012.4501	-5.7296	3012.4500
N210	4.6477	3012.3954	4.6481	3012.3959	4.6480	3012.3963
N211	3.3389	2996.7329				
North near			-0.8956	3007.1028	-0.8954	3007.1029
North far			-1.4642	3007.9254	-1.4640	3007.9255
East near			0.9161	3007.1075		
East far			1.4807	3007.9330		
South near	0.6935	3004.8000				
South far	1.2615	3003.9770				

Table 1: NCal geometrical survey measurements from logbook entry n° 53883. Positions are in m and in the frame of reference of the interferometer.

Using the measurements of the five common points between station 02 and 03 we get ten Δ_x and Δ_y values. The rms of these ten values is $\pm$ 0.17 mm. This value is larger than the intrinsic accuracy of the measurement device used that is $\pm$ 15 μm + 6 μm/m or 75 μ m for a typical 10 m distance. We will therefore use $\pm$ 0.2 mm as the uncertainty of the North to East measurements.

For the East-South distance there is only one common point: N210. The position difference is 0.4 and 0.5 mm. Therefore we will use $\pm$ 0.5 mm as the uncertainty of the East to South measurements.

Given these values we will use a $\pm$ 0.6 mm for the North to South uncertainty.

3 Geometrical survey compared to mechanical assembly

3.1 Position of the reference plates

Table 2 shows a comparison between the distances of the near reference holes for each plate computed by the geometrical survey and the mechanical assembly and the associated uncertainties. The larger offset is on the North-South distance with about 2.2 ± 1.0 mm.

Near reference holes distances (mm)	North-South	North-East	East-South
NCal geometry survey	2797.9 ± 0.6 2797.8 ± 0.6	1811.7 ± 0.2 1811.5 ± 0.2	2318.2 ± 0.5
Mechanical assembly	2800.0 ± 0.5	1812.5 ± 0.3	2318.6 ± 0.5
Offset	2.1 ± 0.8 2.2± 0.8	0.8 ± 0.4 1.0 ± 0.4	0.4 ± 0.7

Table 2: NCal geometrical survey values compared to the mechanical assembly measured values on the near reference holes distances with uncertainties. Since the North plate was measured by two different stations we have two values for the distances involving it. The uncertainty on the offset is a quadratic sum of the two components.

3.2 Dimension of the reference plates

Table 3 shows the distance between the near and far holes within each reference plates with the theoretical and geometrical survey values. The measured values are in agreement with the expected values within 0.1 mm compatible with the expected accuracy of a single station measurement. Furthermore the reference plates were machined during summer, without any tracking of the machining temperature which could have been up to 25°C, different from the 21.5°C of the NE building. The thermal expansion of the aluminum 7075 of 23.6 μm/m/°C and the 1 m distance translates to an uncertainty of about ± 0.08 mm, larger than the expected machining uncertainty of ± 0.02 mm and not very different from the observed difference of ± 0.1 mm.

Plate	Distance between near and far (mm)
North plate station 02	1000.0
North plate station 03	999.9
East plate station 02	1000.1
South plate station 01	1000.0
Theoretical	1000.0

Table 3: Geometrical survey values compared to the theoretical value.

4 Geometrical survey compared to theoretical values

A way to compare and understand the offsets between the geometrical survey measurements and the theoretical values is to draw diagrams showing these offsets. The theoretical values will be used since only near reference hole distances were measured during the mechanical assembly.

4.1 Offsets from a fixed reference hole

The geometrical survey gives the coordinate (x,y) of each point measured in the frame of reference of the interferometer while the drawing can give the coordinate (x,y) of those points in the frame of reference of the mirror theoretically centered in (0,0). We first have to fix one point and therefore consider it to be at the expected theoretical position so that we can compute the coordinates of the other points relative to this fixed point. In table 4 we computed the geometrical survey positions of each reference holes relative to the fixed East near reference hole using the theoretical positions to bring the positions back to the frame of reference of the mirror centered at (0,0).

Reference hole	x (mm)	y (mm)
North near	-905.35	1314
North far	-1473.95	2136.6
East near	906.25	1318.6
East far	1470.85	2144.1
South near	683.65	-988.9
South far	1251.65	-1811.9

Table 4: Geometrical survey positions x and y of the reference holes of each plates in the frame of reference of the mirror centered at (0,0). The highlighted yellow line shows the fixed East near reference hole position.

Now using table 4 and the theoretical positions we draw the displacements of each hole relative to the fixed East near hole as shown in figure 1. The geogebra software was used for all the drawing and the following computations. The colored dots represent the computed positions of each hole assuming the East near hole is fixed. The offset from the theoretical position is represented by a black line that has been exaggerated for the visualization. The black marks represent the theoretical position of each hole[1].

[1] Since the offset has been amplified on the figure, the theoretical positions of the reference holes are not placed according to their correct value.

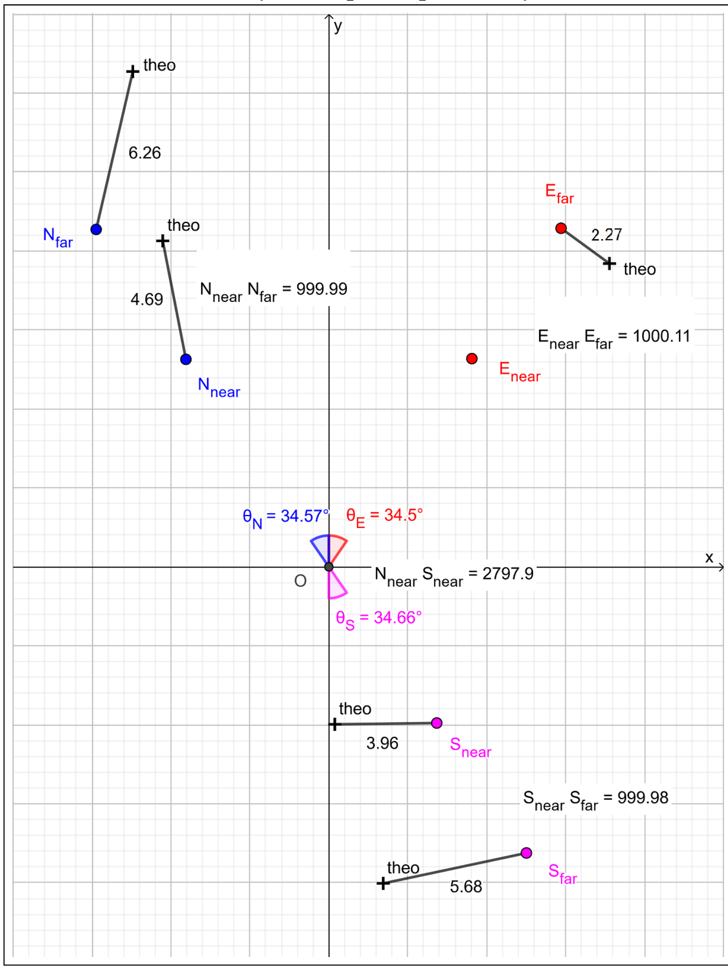


Figure 1: Representation of the offsets between the geometrical survey positions while the East near hole is fixed (colored points) and the theoretical positions. The offsets are exaggerated and shown as black lines. Distances are in mm.

We notice in figure 1 that there is a counterclockwise rotation around the fixed East near hole. To understand the offsets of table 2 we need to apply a correction on the rotation of the East reference holes. By fixing the rotation of the East side we will therefore be able to understand if the template once assembled around the tower and fixed on the East side suffered any displacement.

4.2 Offsets from a fixed reference hole and a corrected rotation

Figure 2 shows the method used to correct the rotation of the East far hole from the axis between its theoretical position and the fixed East near hole (East axis). Once the hole position from the geometrical survey has been projected on the East axis we are left with the radial component of the displacement labelled as "offset" and the correction angle α=0.13° shown in the figure.

Figure 3 shows the method to correct the North near hole position. In a first place the angular correction is applied leaving a corrected position for the North near hole. Then both the corrected hole and its theoretical position are projected on the theoretical North-South axis and their offset can be computed.

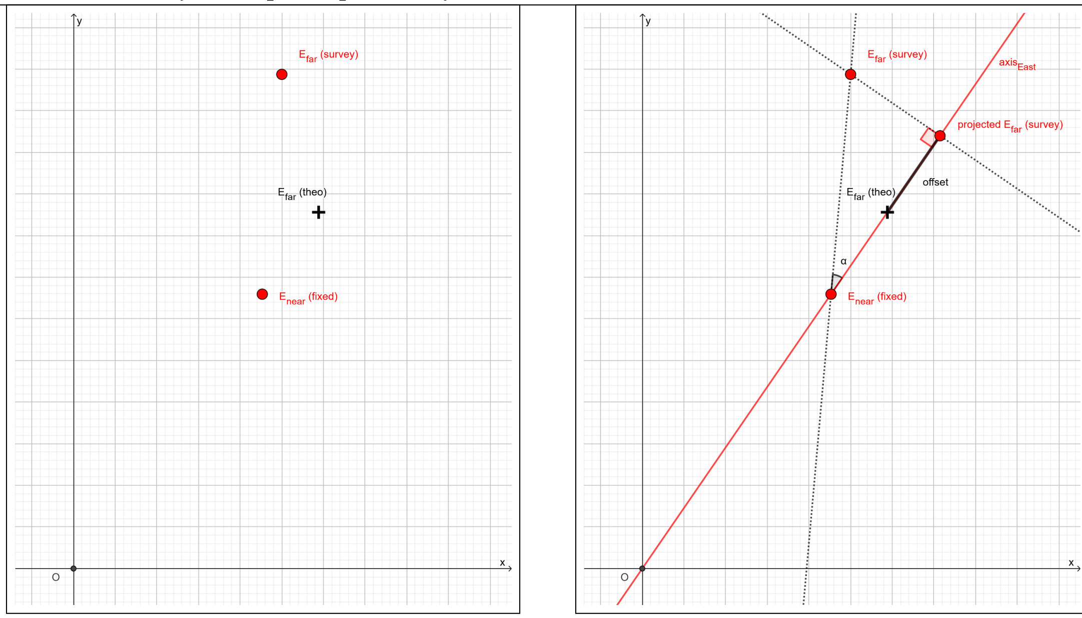


Figure 2: Method used to correct the rotation of the East far reference hole while the East near reference hole remains fixed. On the left is shown the points used, on the right is shown the correction of the rotation using the same points. The East far hole position is projected on the East plate axis (plain red line) giving the correction angle α=0.13° and the projected offset along the East axis (plain black line).

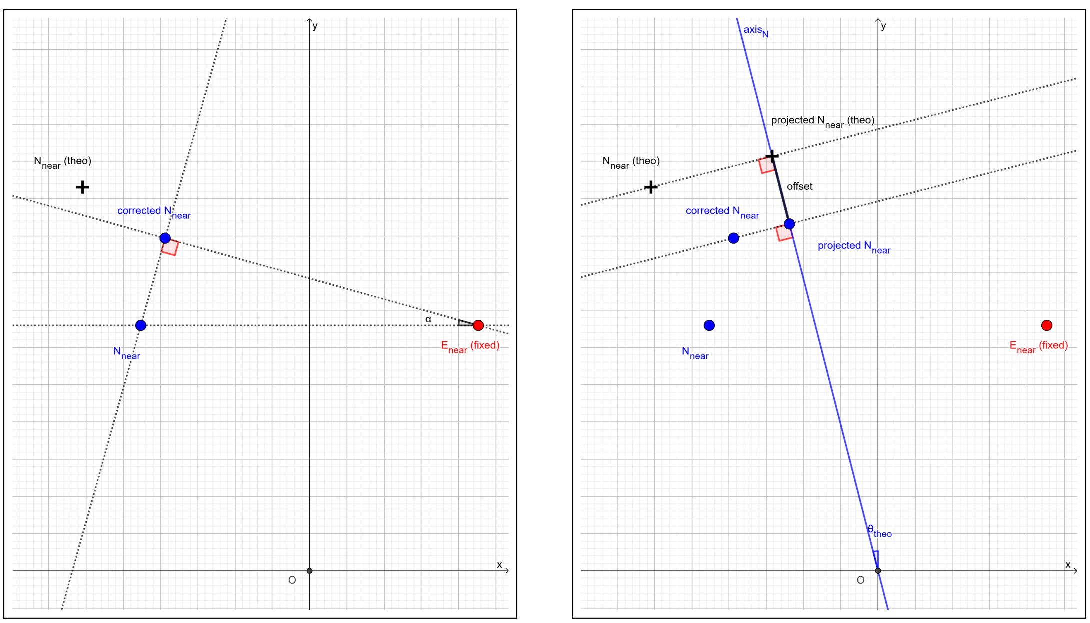


Figure 3: Method used to correct the rotation of the North near reference hole while the East near reference hole remains fixed. On the left are shown the points used and the angle correction α=0.13°, on the right is shown the projection of the corrected point on the theoretical North-South axis (plain blue line) with θ_{theo}=34.7°. The plain black line shows the offset between the theoretical position and the corrected position both projected on the North axis.

The angular correction (without projection along the axes) gives the corrected positions in table 5.

Reference hole	x (mm)	y (mm)
North near	-905.35	1318.11
North far	-1472.08	2142
East near	906.25	1318.6
East far	1472.72	2142.82
South near	678.42	-988.38
South far	1244.55	-1812.67

Table 5: Geometrical survey positions x and y of the reference holes of each plates corrected from the East rotation ($\alpha = 0.13°$) in the frame of reference of the mirror centered at (0,0). The highlighted yellow line shows the fixed East near reference hole position.

The method described in figure 3 is applied on the remaining North and South hole positions. Figure 4 shows the positions of each corrected point projected on its corresponding theoretical axis. The offsets are in mm and directed towards the mirror centered in O(0,0), negative offsets means the measured distance to the mirror is shorter than the theoretical value.

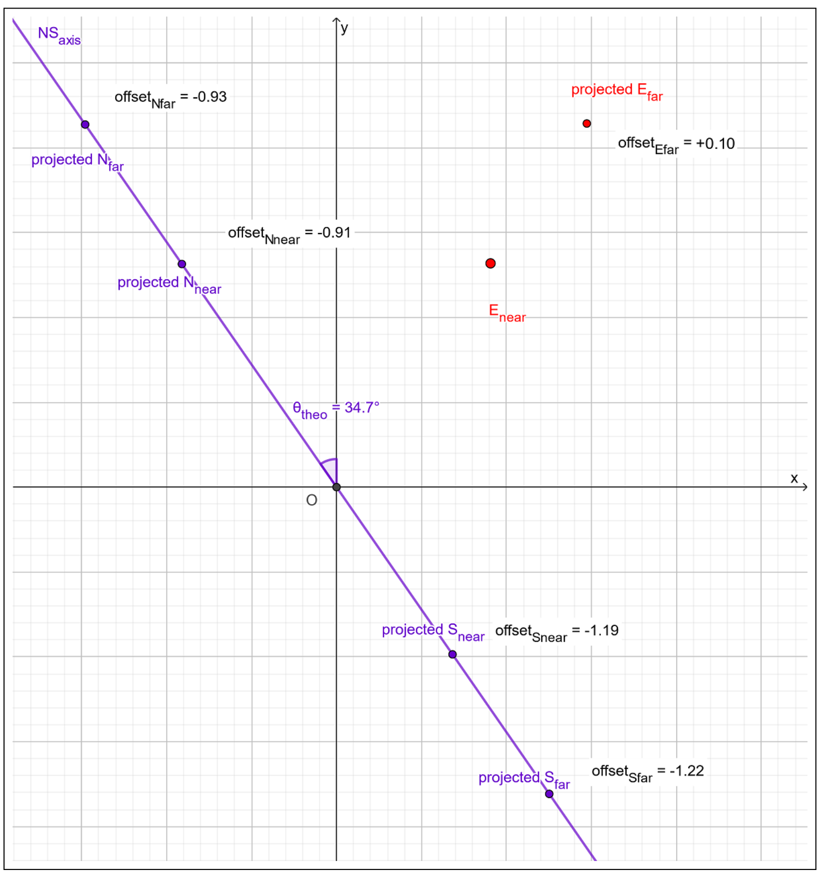


Figure 4: Positions of the reference holes projected on their respective theoretical axis assuming the East near hole is fixed and the rotation on the East side is corrected. Distances are in mm.

Figure 4 allows us to understand the offsets coming from each point assuming the East near hole is fixed and the rotation of the East side is corrected. In table 2 comparing the geometrical survey and mechanical assembly measurements we had a 2.1-2.2 mm offset between the North and South near holes, using the offsets of figure 4 we have a 2.1 mm offset on the same distance between the geometrical survey and the theoretical value. It therefore seems that the template suffered a displacement of about 1 mm towards the mirror on both North and South side during the installation of the reference plates.

4.3 Tower center relative to the East reference plate

During the position check of the support bar hanging the O3 Newtonian calibrator (available in the logbook as entry n° 45131), the EGO infrastructure team provided the position of the "mechanical center" of the NE tower at (0.0129,3005.7877) (x and y in m). These values should be in first approximation the geometrical survey position of the mirror center. These values could be converted in our reference frame (East near reference hole fixed and aligned on the East reference plate).

In our reference frame the mechanical center is (0.06,0.86) in mm.

5 Template mechanical check at Virgo NE - March 8, 2022

After observing a difference between the geometrical survey and the mechanical assembly (in table 2) we decided to place again the template on the installed reference plates around the NE tower.

In a first place we assembled the North part of the template on the ground of the NE building to check a distance we found a value 0.3 mm smaller than the theoretical value but still compatible. We will therefore recompute the expected positions by including this offset along the x axis, see table 6.

Following this mechanical check the template was fixed on the East side and let free on the other sides. On the North reference plate we noticed that the near and far screw holes on the template were respectively 1.2 mm and 1.3 mm too close to the mirror. We will therefore update the expected positions by shifting them of 1.25 mm along the radial axis.

On the South side we did not observed a significant offset using the template. We therefore do not update the expected positions.

Reference hole	x (mm)	y (mm)	Δ_x (mm)	Δ_y (mm)
North near	-905.24	1317.57	-0.11	0.54
North far	-1471.65	2141.70	-0.43	0.30
East near	906.25	1318.6	0	0
East far	1472.66	2142.73	0.06	0.09
South near	679.69	-988.95	-1.27	0.57
South far	1246.09	-1813.08	-1.54	0.41

Table 6: Expected positions of the reference holes shifted according to the template check and their respective offset from the values with East near fixed and the rotation corrected.

6 Positions to be used for NCal computation

The uncertainties on the mechanical assembly and the geometrical survey are similar (see table 2). Since we do no know what the true values are, we will shift each of them by half of the offset reported in table 6 to compute the position of the reference holes used for the NCal work. The result is reported in table 7. The quoted uncertainty is computed as the linear sum of half of the applied offset and the maximum of the mechanical or survey uncertainty reported in table 2.

Object	x (mm)	y (mm)
North near	-905.29 ± 0.36	1317.84 ± 0.57
North far	-1471.86 ± 0.52	2141.85 ± 0.45
East near	906.25	1318.6
East far	1472.69 ± 0.06	2142.78 ± 0.09
South near	679.06 ± 1.14	-988.67 ± 0.79
South far	1245.32 ± 1.27	-1812.88 ± 0.70

Table 7: Positions and uncertainties considered for each reference hole.

We can now compute the uncertainties on the North to South axis. The x and y uncertainties from table 7 describe the uncertainty areas around the reference holes as elliptical shapes, see figure 5.

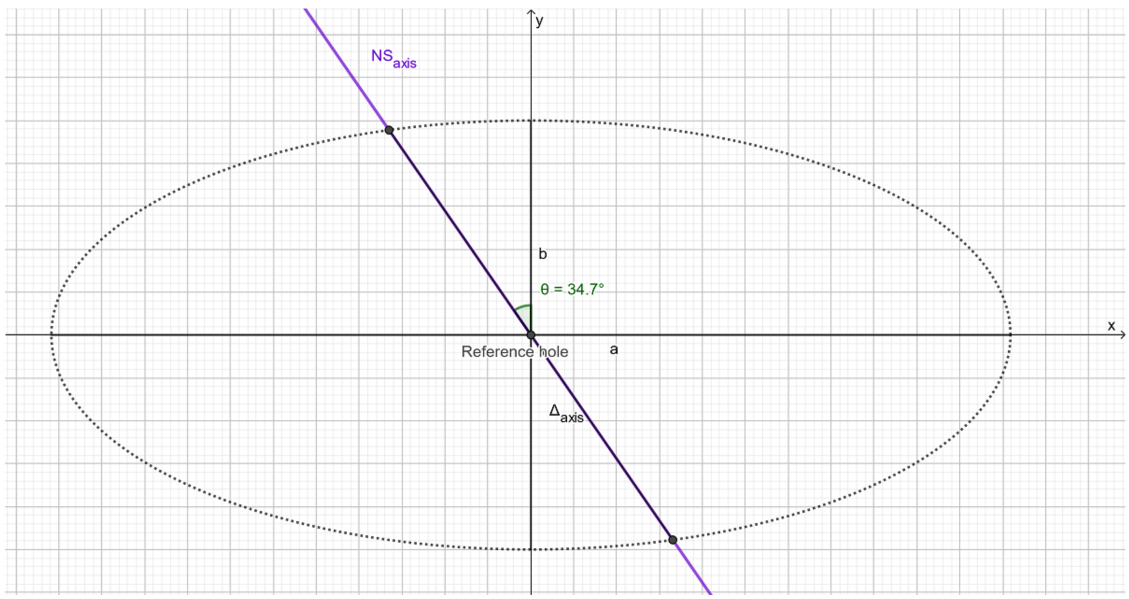


Figure 5: Elliptical shape described by the x and y uncertainties on a reference hole, a is the semi-major axis and b is the semi-minor axis. The North to South axis implies that the reference hole considered is along this same axis and the uncertainty on this same axis is labelled Δ_{axis}.

The following formulas give the x and y position of a projected point on an ellipse along the North to South axis:

$$\begin{cases} x = \dfrac{ab\ \cos\theta'}{\sqrt{b^2\cos^2\theta' + a^2\sin^2\theta'}} \\ y = \dfrac{ab\ \sin\theta'}{\sqrt{b^2\cos^2\theta' + a^2\sin^2\theta'}} \end{cases} \tag{1}$$

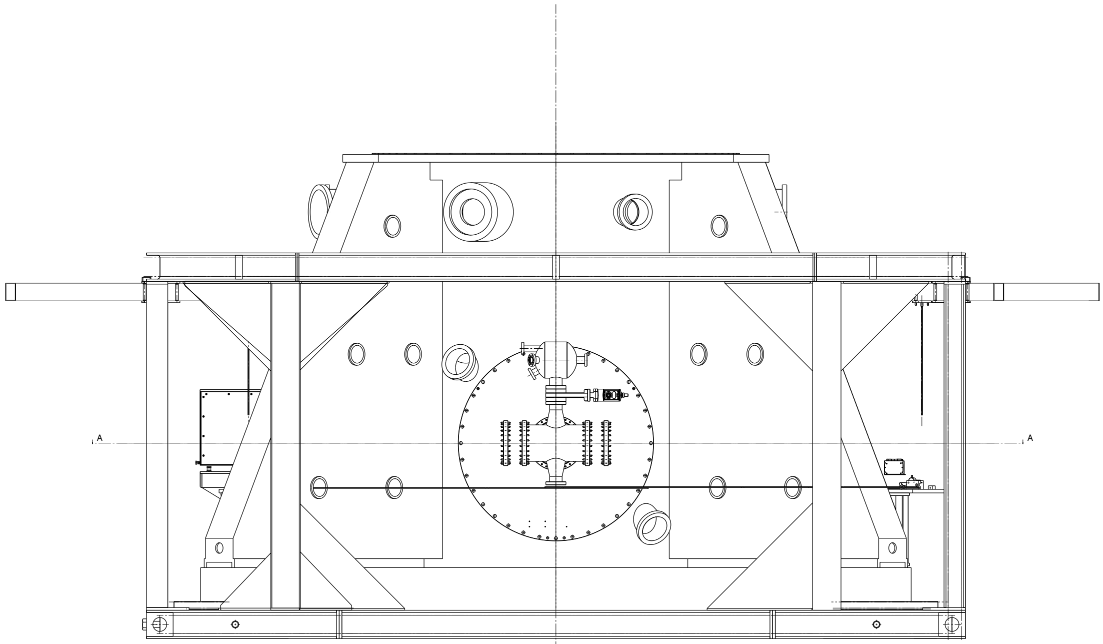
with:
a the semi-major axis
b the semi-minor axis
θ' the angle of the axis to the x axis, here $\theta' = \pi/2 - \theta \approx 0.965$ rad.

To determine the Δ_{axis} uncertainty we compute a quadratic sum of both formulas from equation 1. The resulted uncertainties along the North to South axis are shown in table 8.

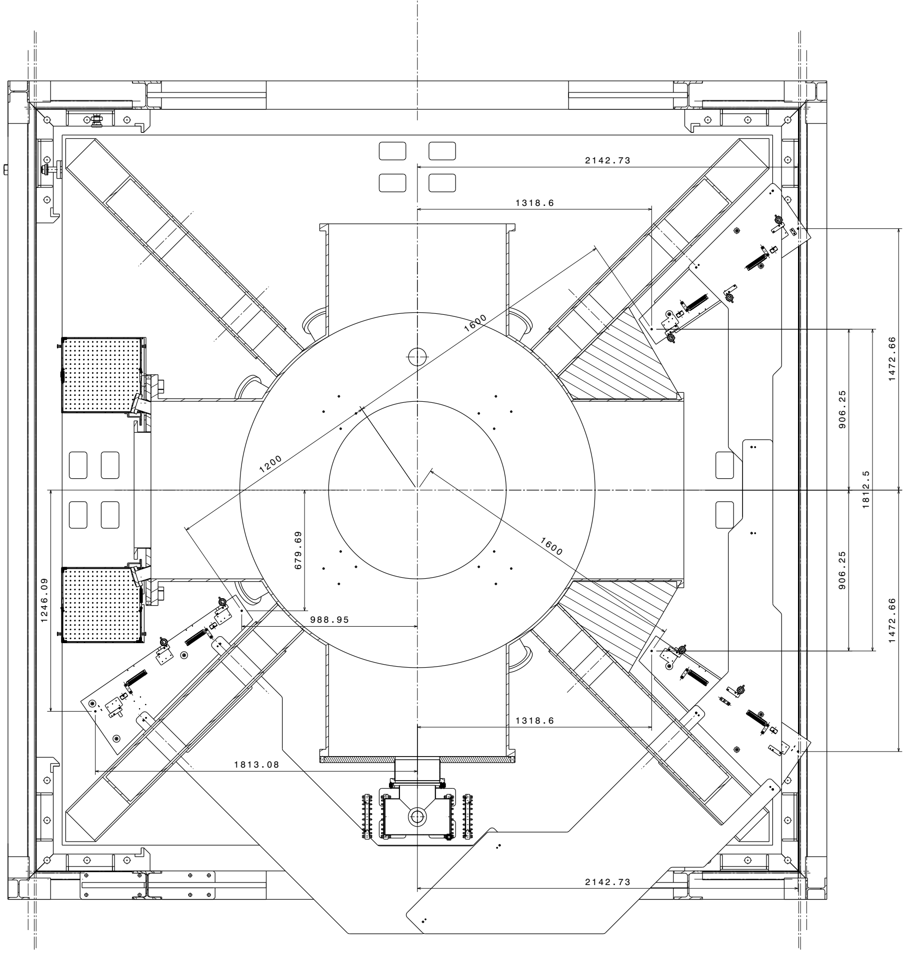
Object	Δ_{axis} (mm)
North near	$\pm$ 0.45
North far	$\pm$ 0.47
South near	$\pm$ 0.86
South far	$\pm$ 0.80

Table 8: Uncertainties on the reference holes along the North to South axis.

VIRGO emplacement plaques (bleus) et gabarits



Vue de face
Echelle : 1:10



Coupe A-A
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