Accuracy Survey of jetlab® 4 JL4-21

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1 Measurements

The jetlab® 4 print station serial number JL4-21 has been surveyed at MicroFab Technologies, on 27 August 2008, for the linearity and horizontal straightness errors of its x and y axes as well as the angle between the two axes, using a Heidenhain KGM 181 grid encoder (Dr. Johannes Heidenhain GmbH, Traunreut, Germany). This encoder measures two coordinates simultaneously. The grid has a spacing of 4 μm in both directions, and a resolution of about 0.5 μm can usually be obtained through interpolation techniques built into the control software for the encoder. The data span the x range from –80 mm to +50 mm, and y range from –70 mm to +35 mm. Limitations in mounting equipment and load carryign capacity prevented covering more of the physically available motion range.

The linearity and straightness errors and the misalignment angle of the stages have large systematic components that can be reproducibly measured, and on the basis of those measurements compensated for in the control program of the jetlab® 4 machine. For linearity and straightness, interpolation tables are derived for forward and reverse motion separately, and the angle is obtained as a single datum. The corrections are then applied in the control program such that all coordinates provided by the user are taken to mean coordinates at a temperature of 20°C. With the help of an estimated temperature of the of the x and y axes provided interactively by the user, the motion targets are then corrected for both the temperature and the surveyed errors. The quality of the correction can be judged by repeating the full survey with all of the corrections being applied. On the following pages, the raw measurements (no corrections applied to the machine motion) and check measurements (all corrections applied) are presented.

2 Results

The data were taken at temperatures near 26°C (average of the stage temperatures). The effective linear expansion coefficient is estimated to be 15 μm/m/K. The forward-reverse differences are

within a band of ~32 μm everywhere, mostly much closer. The following table summarizes the residual errors after correction, including any forward-reverse differences. The "Range" describes the range spanned by the data points plus their error bars. The "Largest error bar" is the largest individual error bar, which is determined by repeating all measurements 10 times and applying standard averaging procedures.

Error type	Range [μm]	Largest error bar [μm]
X linearity	-17.0 to 3.4	$\pm$4.6
X straightness	-19.3 to 9.3	$\pm$4.0
Y linearity	-6.8 to 10.7	$\pm$1.7
Y straightness	-2.9 to 3.1	$\pm$1.2

The total error band for positioning in x direction is then the sum of the x linearity range, and the y straightness range for a band width of 26.5 μm. The equivalent number for the y direction is 46.0 μm. Because all printing will be done with aligning the target substrate on the machine, the lack of symmetry of the ranges about 0.0 μm is of no consequence; the substrate alignment will remove all constant offsets.

Repeatability can be estimated conservatively by adding just the largest error bars of the linearity of one axis and the straightness of the other, plus half of the reversing error band ("backlash") mentioned before by using the average between the forward and reverse linearity and straightness corrections. The manufacturer of the stages quotes a repeatability of $\pm$20 μm separately from a backlash/reversing error of 100 μm. The surveying of the JL4-21 print station yields $\pm$6 μm and $\pm$16 μm for these numbers, or a conservative total bidirectional repeatability of $\pm$22 μm.

The deviation of the angle between the positive x axis and the positive y axis (first quadrant) from being a right angle is measured to be -1031 μrad, and the residual angle after correction is measured to be 17.4 μrad, for a worst-case effect of 1.8 μm within the surveyed range.

Thus, the residual errors are, without and with corrections:

Observable	raw	corrected
Positioning in x	$\pm$78.7 μm	$\pm$13.2 μm
Positioning in y	$\pm$146.7 μm	$\pm$23.0 μm
Deviation from right angle	-1031 μrad	17.4 μrad

The corrections are used by having a text file "Alignment.txt" with a correction table present in the "C:\jetlab" directory. This file is read once at the start-up of the **jetlab** control program. On the JL4-21 print station, this will be accompanied by occasional prompts for temperatures of all three stages. For all practical purposes, entering the ambient room temperature for all stages, in units of °C, is sufficient. (The value for the z axis is not used.) A backup copy of the alignment table is provided in the subdirectory "C:\jetlab\Alignment", so the corrections can be turned off by deleting the working copy "C:\jetlab\Alignment.txt" and restarting the **jetlab** program. At positions outside the surveyed range, the tail ends of the data are used to extrapolate the corrections; this may not be adequate.

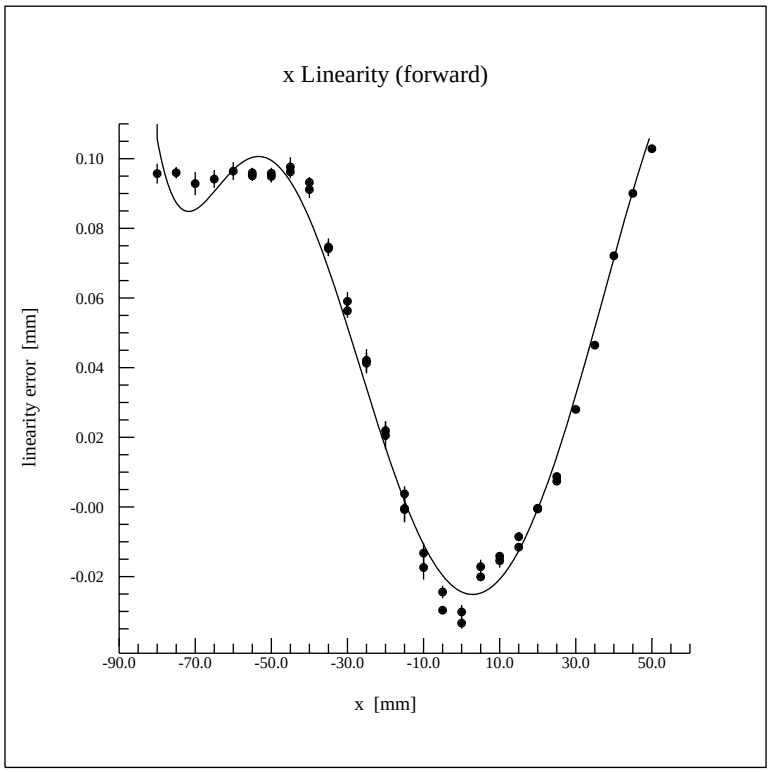
3 Positioning Errors and Printing On-The-Fly

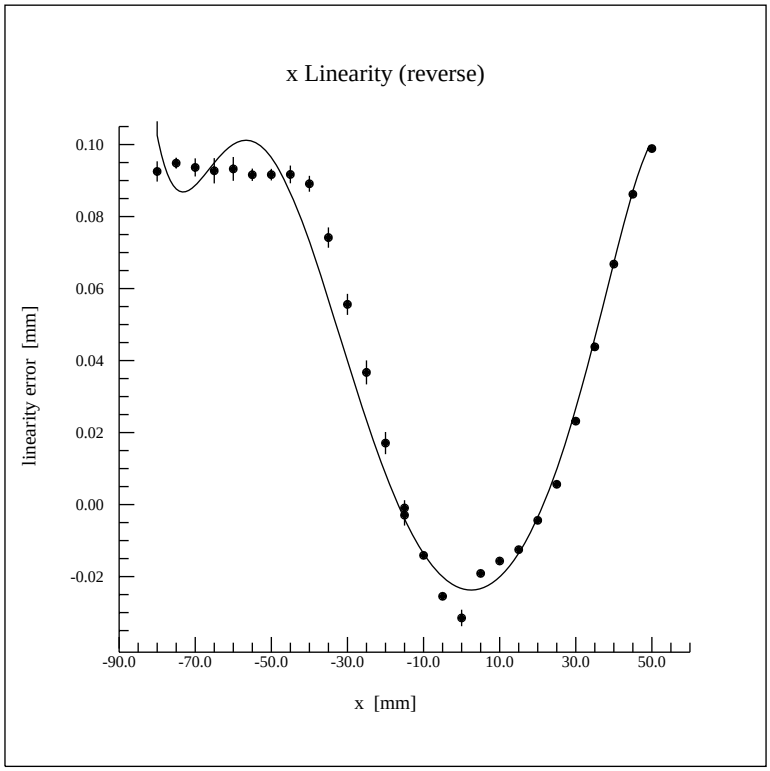
It must be emphasized that the stage survey is a static one, and the full benefit is available only for printing on position.

During motion along one axis, the transverse error (straightness) would have to be corrected in real time, which exceeds the capability of the jetlab® 4 print station and software. In this case, both the linearity and straightness errors of the other axis can be corrected for. Because printing on-the-fly requires space at either end of the printing area for acceleration and deceleration, and the errors being worst near the ends of the motion ranges, the damage incurred is limited.

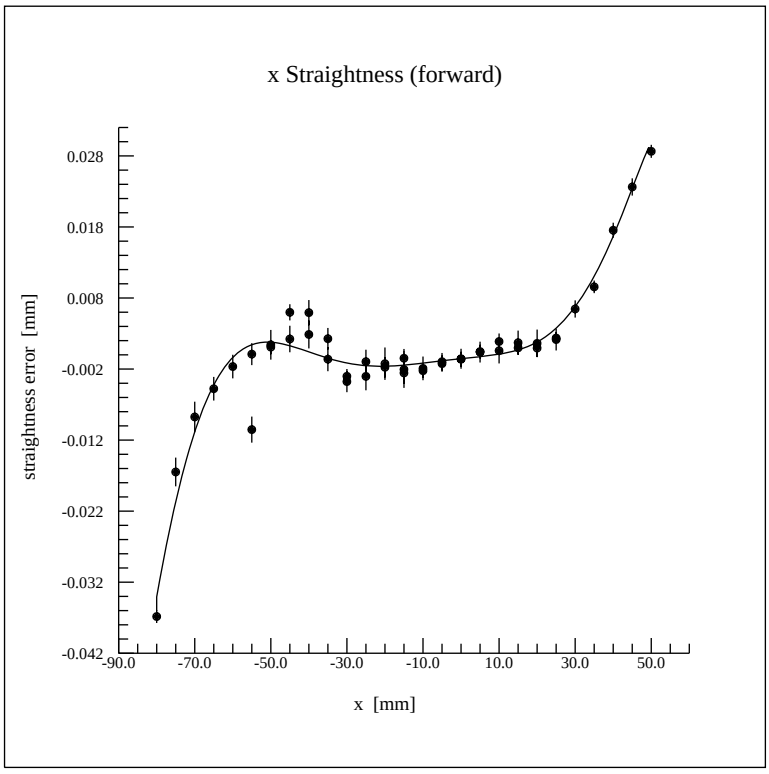
The worst case is printing along a line 45° off of either axis where only the correction of linearity of one axis and straightness of the other are in effect. Drops are located in printing on-the-fly by triggering on the coordinate axis with the larger projection of the flight path. A conservative assumption would be that the larger part of the raw errors will remain uncorrected for.

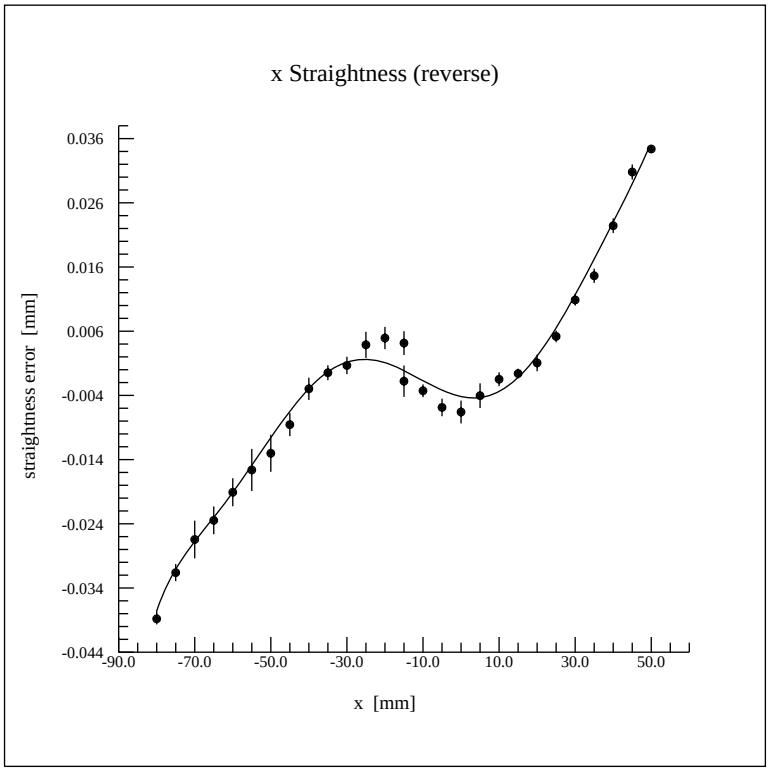
Raw forward x linearity error for jetlab® 4 JL4-21



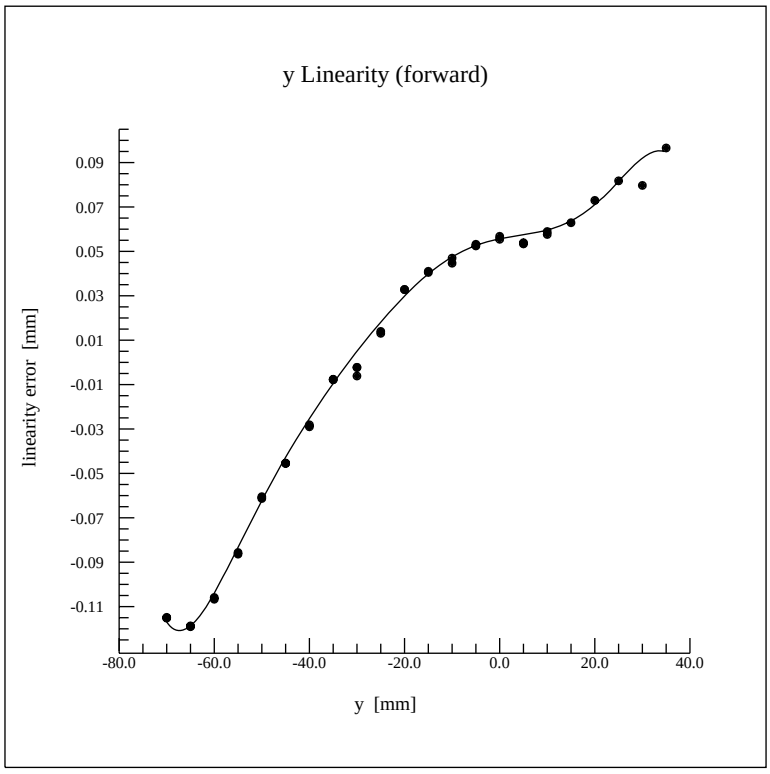


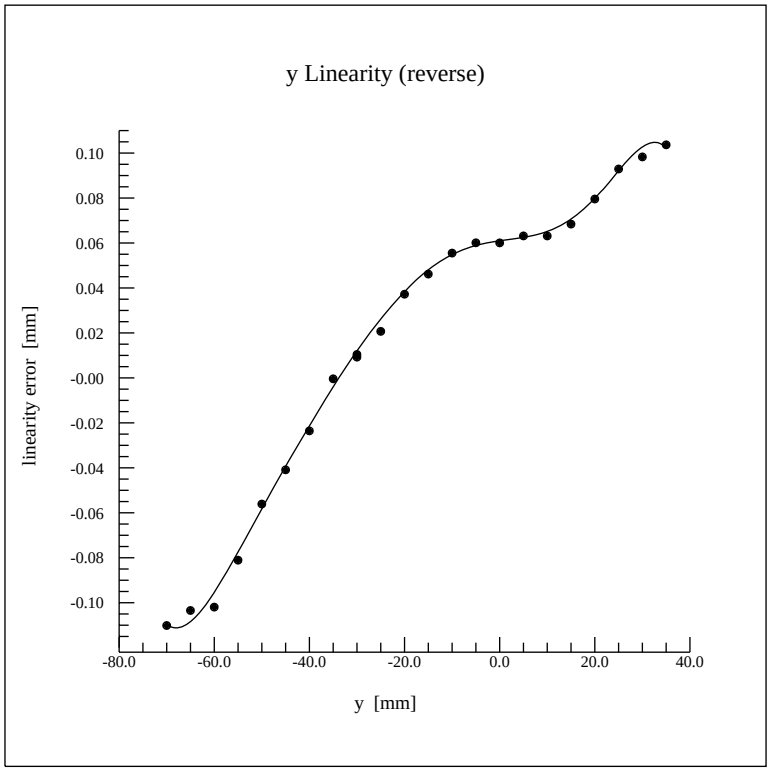
Raw x straightness measurements for jet**lab**® **4** JL4-21

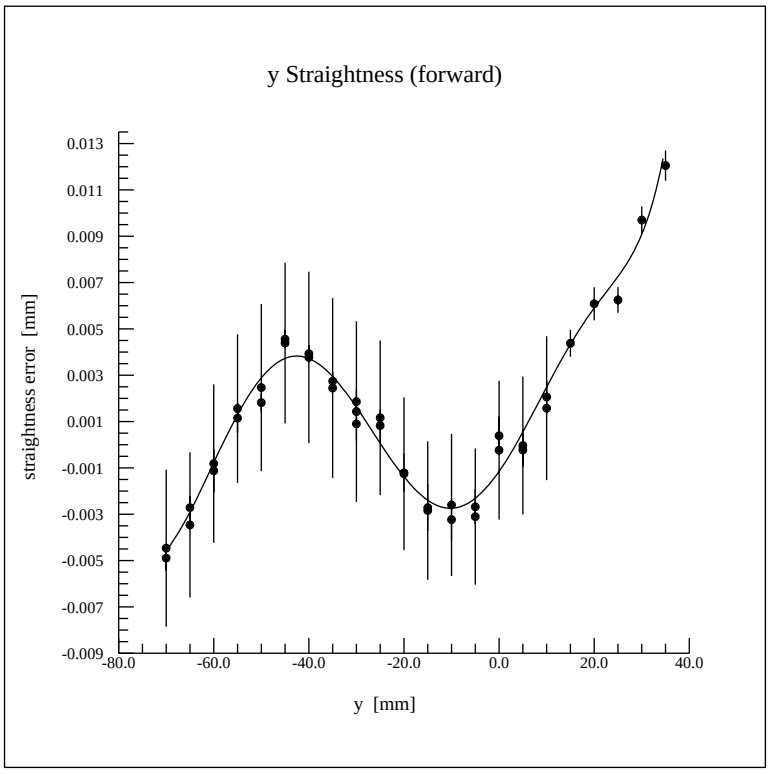


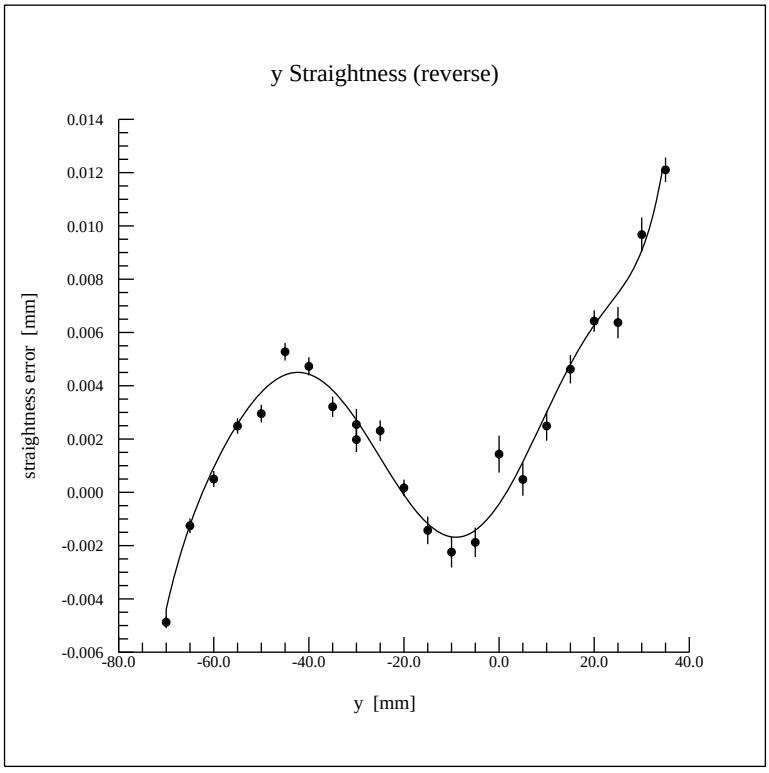


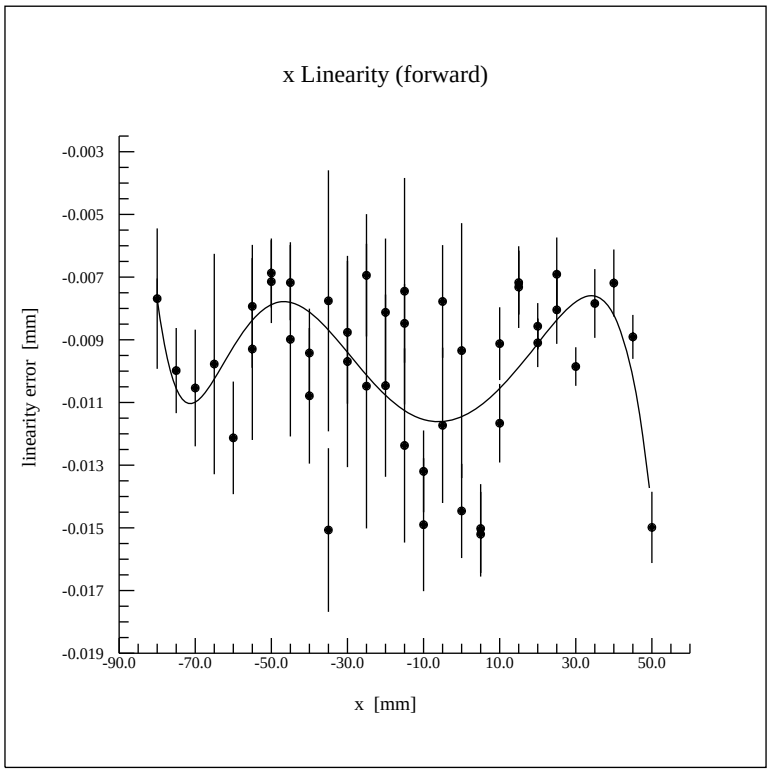
Raw y linearity measurements for jet**lab**® **4** JL4-21

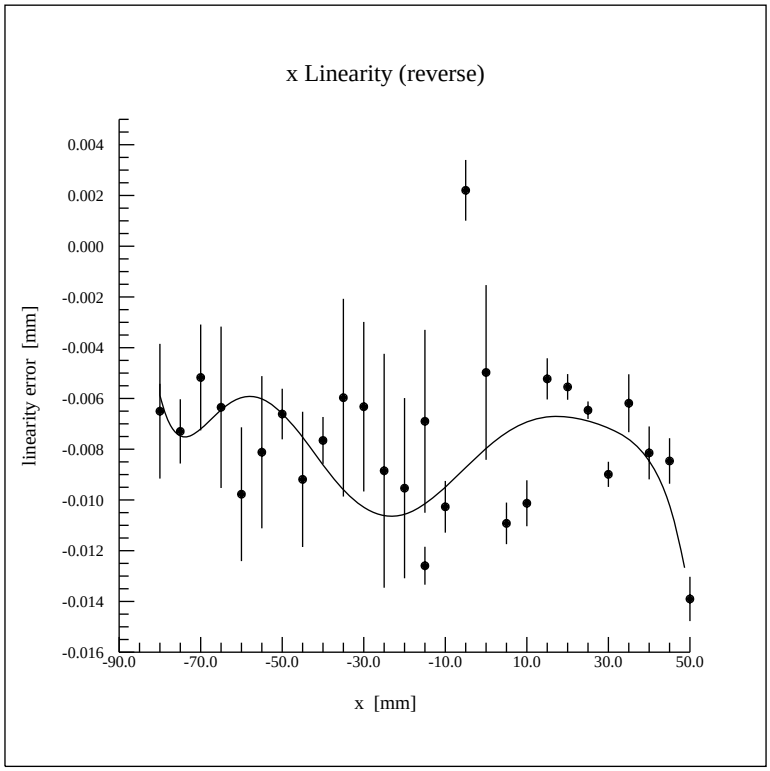


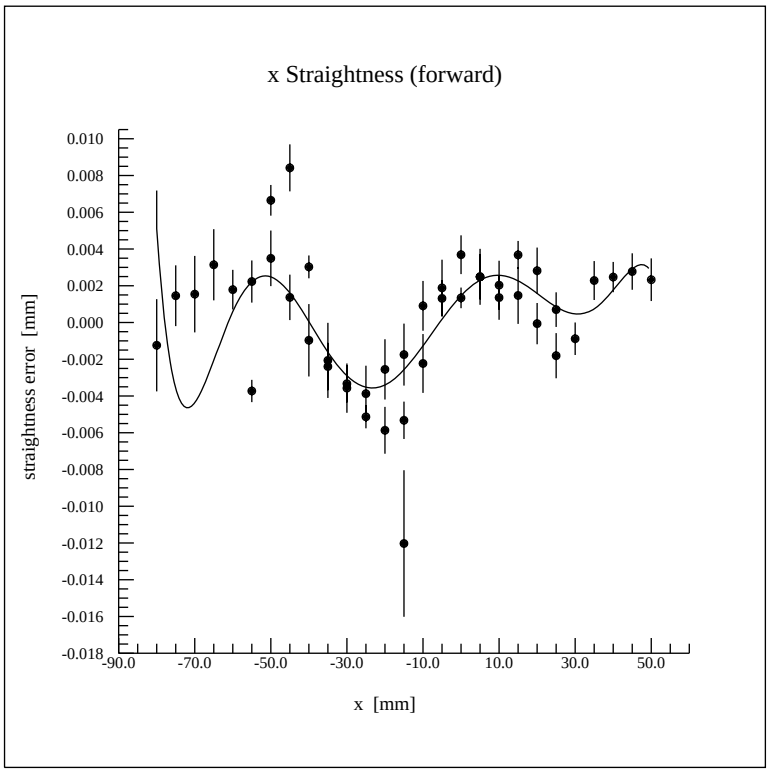


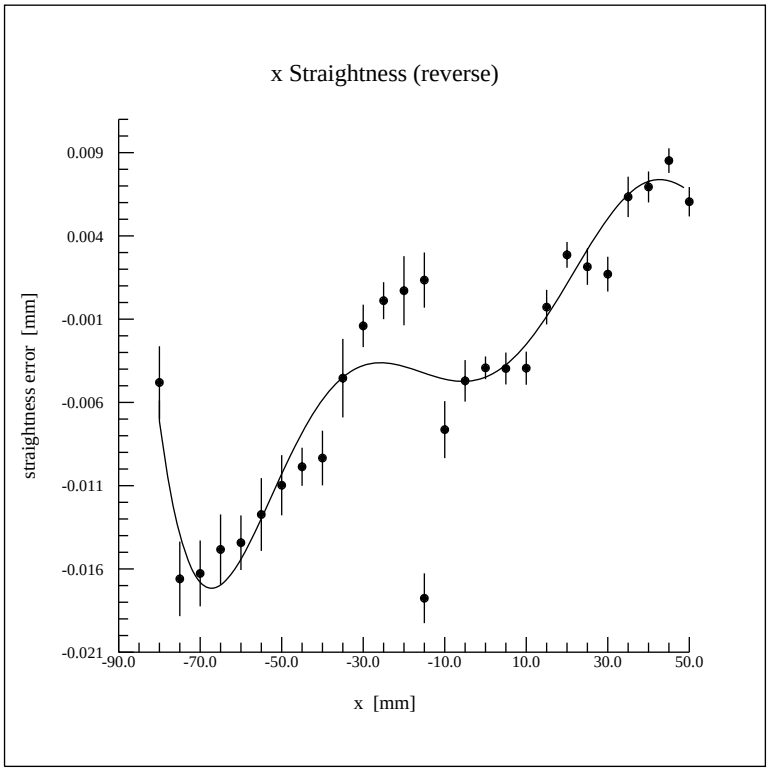

y Straightness (forward)
straightness error [mm]
0.013
0.011
0.009
0.007
0.005
0.003
0.001
-0.001
-0.003
-0.005
-0.007
-0.009
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
y [mm]

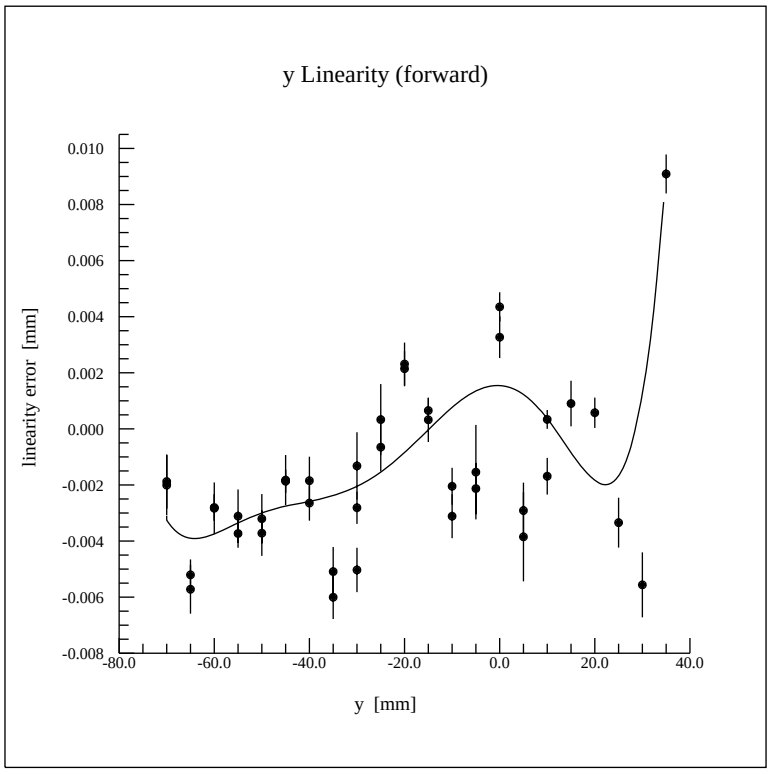

y Straightness (reverse)
straightness error [mm]
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
y [mm]

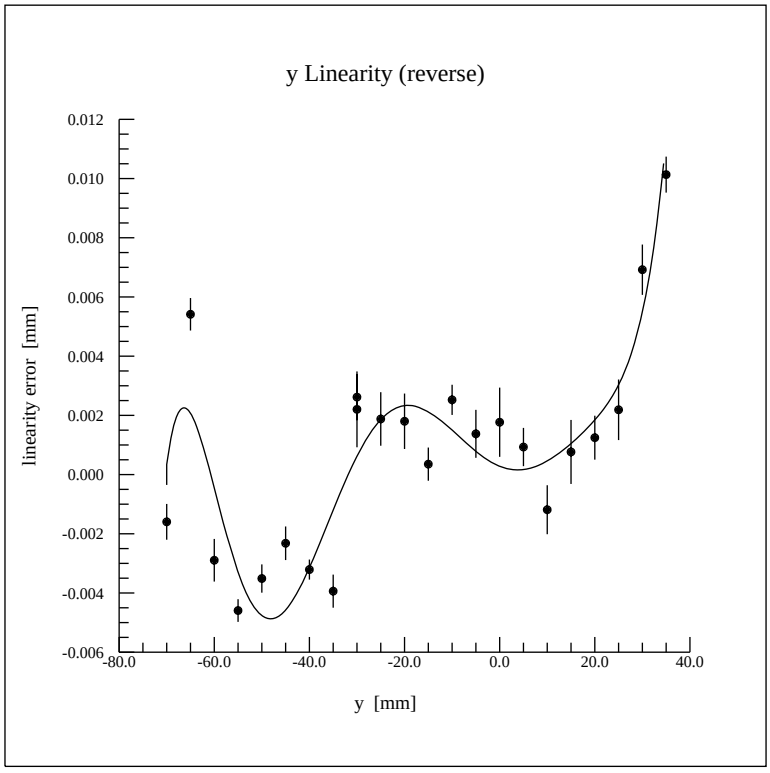

x Linearity (forward)
linearity error [mm]
-0.003
-0.005
-0.007
-0.009
-0.011
-0.013
-0.015
-0.017
-0.019
-90.0
-70.0
-50.0
-30.0
-10.0
10.0
30.0
50.0
x [mm]

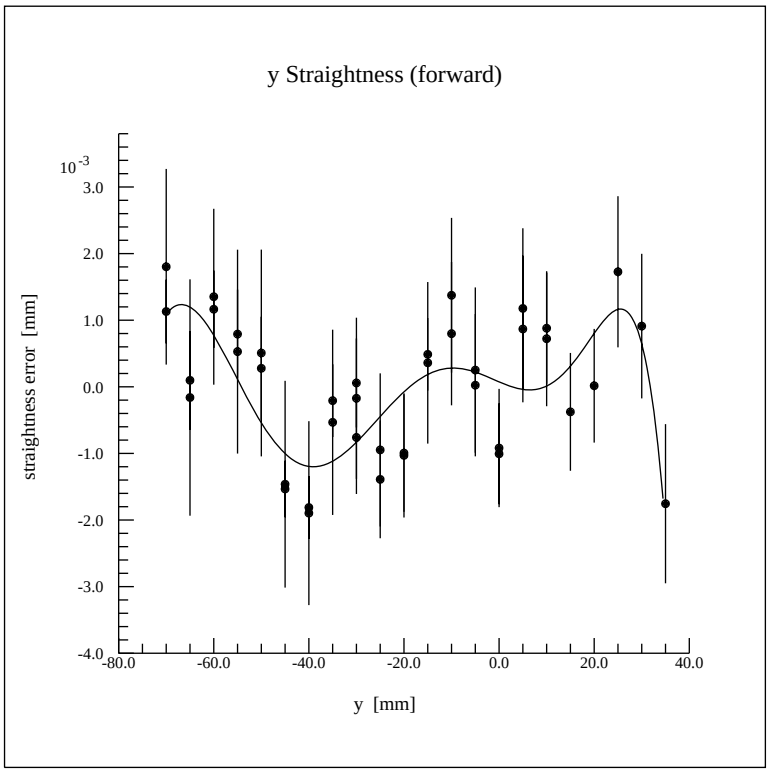

x Linearity (reverse)
linearity error [mm]
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
-0.014
-0.016
-90.0
-70.0
-50.0
-30.0
-10.0
10.0
30.0
50.0
x [mm]

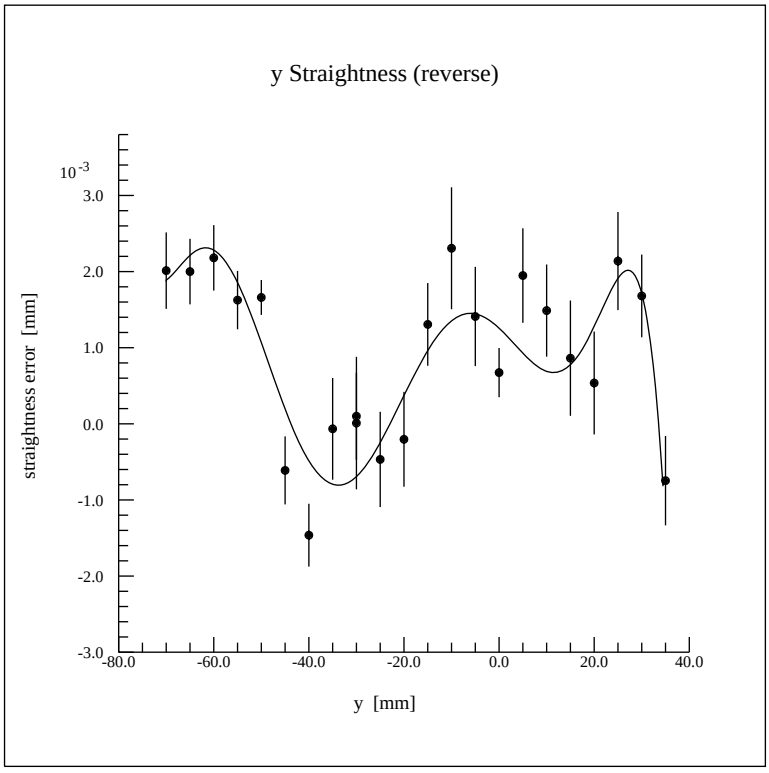

x Straightness (forward)
straightness error [mm]
0.010
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
-0.014
-0.016
-0.018
-90.0
-70.0
-50.0
-30.0
-10.0
10.0
30.0
50.0
x [mm]


x Straightness (reverse)
straightness error [mm]
0.009
0.004
-0.001
-0.006
-0.011
-0.016
-0.021
-90.0
-70.0
-50.0
-30.0
-10.0
10.0
30.0
50.0
x [mm]


y Linearity (forward)
linearity error [mm]
0.010
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
y [mm]


y Linearity (reverse)
linearity error [mm]
0.012
0.010
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
y [mm]


y Straightness (forward)
straightness error [mm]
10^-3
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
y [mm]


y Straightness (reverse)
straightness error [mm]
10^-3
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
y [mm]