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Contributed paper

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In high-accuracy motion stages, the positioning accuracy at the point of interest is strongly influenced by guiding errors: for translation motions, straightness errors and angular errors (pitch, yaw and roll); for rotation motions, axial, radial and tilt errors. When air bearings are used for guiding, the air film averages out local irregularities of bearings surfaces, which helps reduce guiding errors considerably. Some results obtained with air bearing precision systems designed and manufactured by specialized companies and tested at ESRF are described below.

1. General characteristics of precision air bearings

See Slocum (1992) for a more extensive study.

Air gap: Typical air gap = 2–8 μm. Smaller gaps are generally preferred because they increase the stiffness and reduce the flow, but manufacturing tolerances and thermal expansion allowances limit how much the gap can be reduced. On our granite-based air bearing systems: air gap = 3 μm; flatness of bearing surfaces = 1 μm.

It is critical to mount the air pad stage on very flat support surfaces so as not to damage the geometry of the stage.

Load capacity: Air bearings can generally be designed with large bearing surfaces, to support large loads. A rough estimate of the developed force F is $F \sim 0.3 \times$ supply pressure × area. However, the actual bearing area will have to be increased by the need to establish a preload.

Preload: In order to maximize its stiffness, the air bearing must be preloaded. The preload can be applied either by opposing pads or by a vacuum preload integrated in the same pad. The vacuum preload avoids geometrical constraints and thermal expansion issues associated with two separate guides. Its disadvantage is that due to the limited negative pressure (typically −0.05 MPa (−0.5 bar) or more), a large pad is required, with a surface area for the negative pressure at least five times larger than the pressure area.

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Stiffness: A high stiffness is very important in precision systems, to reduce sensitivity to varying forces. More than 100 N μm^{-1} can easily be reached with air bearings.

An estimate of the stiffness can be obtained by stiffness~load capacity/(0.5 × gap).

2. Results obtained with air bearing rotation stages at the ESRF

For some nano-tomography experiments, the sample must be placed on a vertical axis and rotated by small angular increments over 360°. During these successive steps, the axial and radial error motions of the rotation axis must be lower than 50 nm.

Some attempts with ball bearing spindles did not reach radial errors lower than 500 nm. Air bearing rotation stages from several manufacturers have been tested. The best results were obtained with an air bearing spindle ISO 3R from Professional Instruments Company (www.airbearings.com) (figure 1). The company fitted the spindle ISO 3R with a direct drive torque motor and a rotary encoder. The motor is controlled in closed loop by an Etel (www.etel.ch) controller. Our experience showed that a very accurate fitting of the motor on the spindle and

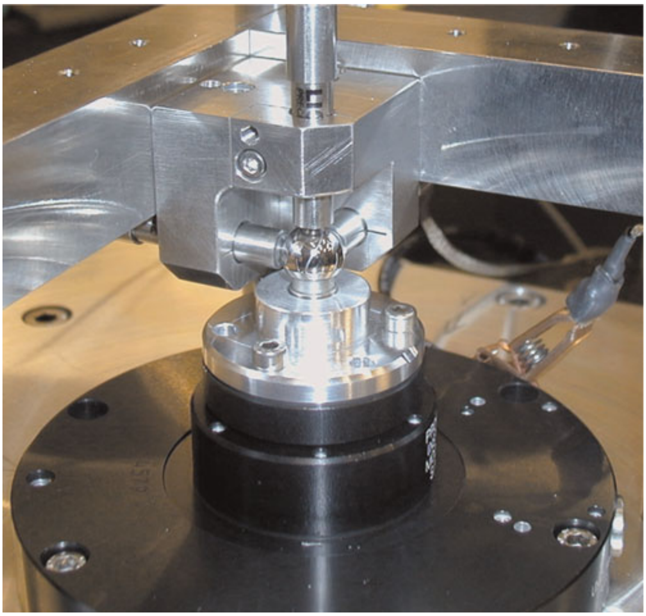
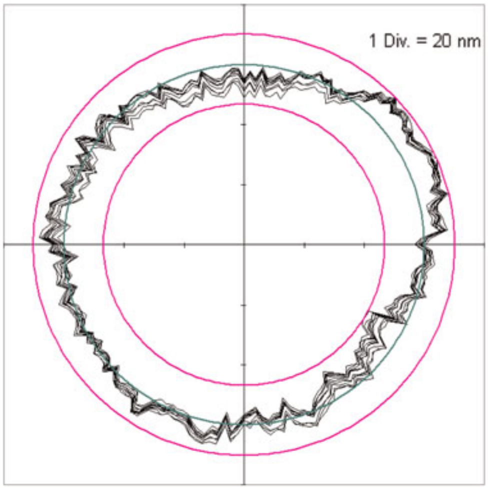


FIGURE 1. The ISO 3R spindle and the measurement setup.

Radial error (nm)	
Minimum	23
Maximum	33
Axial error (nm)	36

TABLE 1. ISO 3R spindle – summarized results.



GRAPH 1. Radial errors plot of ISO 3R spindle 1 division = 20 nm.

proper settings of the electronic controller parameters are both crucial to avoid parasitic magnetic forces and to achieve low error motions.

The main characteristics of this rotation stage are diameter 126 mm, height 180 mm, load capacity 380 N (axial)/140 N (radial) and stiffness 260 N μm^{-1} (axial)/ 80 N μm^{-1} (radial) (supplier's data).

The axial and radial errors were measured by capacitive sensors, at 23 mm above the top face of the spindle, on one bidirectional cycle of five full turns, every 2°, at stationary positions (total duration 150 min). The measurement method is described by Nicola *et al.* (2010). The results are shown in table 1 and graph 1. The graph demonstrates the excellent repeatability of the errors.

3. Results obtained with air bearing translation stages at the ESRF

Some results are given below, obtained on an *XY*-stage supplied by Newport (www.newport.com), part of the ID13 nano-goniometer (see figures 2 and 3).

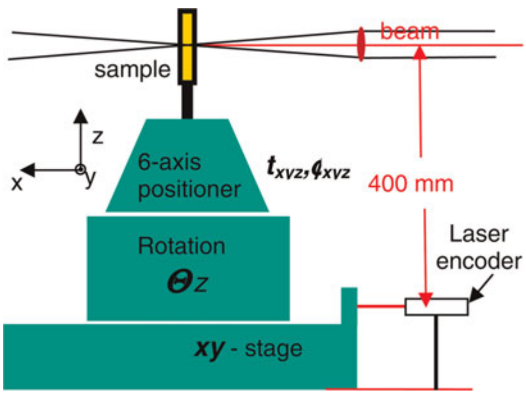


FIGURE 2. The stack of motion stages constituting the ID13 nano-goniometer.

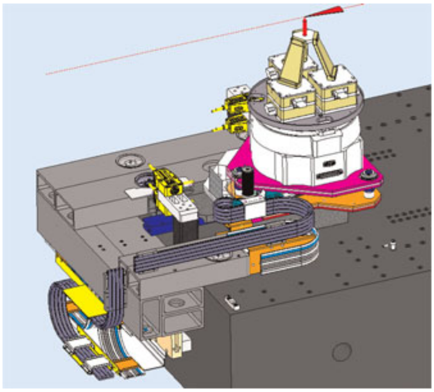
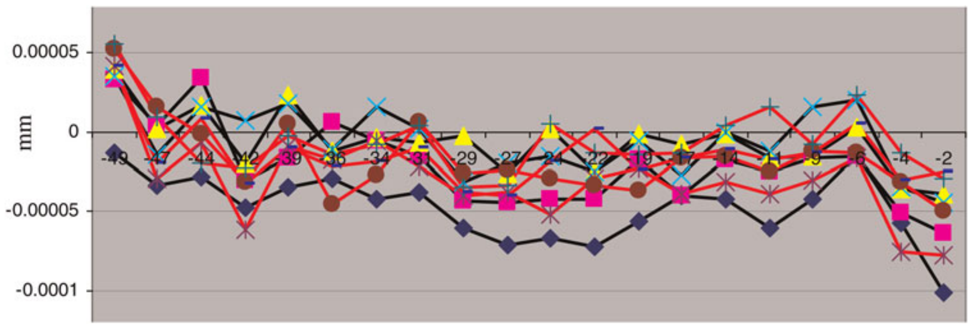


FIGURE 3. 3D view of the ID13 nano-goniometer.



GRAPH 2. Newport *XY*-stage – error of the *Y*-stage over 50 mm travel, measured at the sample over five bidirectional runs.

The *X* and *Y* motions, travel ranges 100 and 50 mm, are driven by linear motors and guided by air bearings with vacuum preload. The air pads are shaped into the SiC girders of the mobile carriages and slide on the very flat surfaces of the granite base. The linear motors are controlled in closed loop with two Renishaw (www.renishaw.com) laser interferometric encoders. Due to the 400 mm distance between the laser encoder beams and the sample, the angular errors from the air bearing guides during the *X* and *Y* translations must be extremely low in order to obtain the expected accuracy at the sample position. The obtained results plotted in graph 2 (bidirectional repeatability of 90 nm over 50 mm travel, measured at the sample) indicate that the repeatability of the angular guiding errors is better than 0.3 μrad, which is extremely low.

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