Technical Note TN26

CFM Base Kit with trueNAV

Detailed Analysis of Closed Loop Performance

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With the CFM Base Kit with trueNAV, attocube provides an integrated solution of ANP nanopositioners combined with an external interferometric displacement sensor, enabling ultra-precise feedback over extended travel ranges and overcoming the limitations of integrated position sensing. trueNAV delivers outstanding closed-loop positioning performance under cryogenic conditions, measuring directly at the sample holder, significantly expanding the possibilities for a broad range of confocal microscopy applications.

This technical note presents a multi-faceted performance evaluation of trueNAV. It outlines the methodology applied to verify its performance, including both industry-standard tests as well as use cases closely reflecting typical microscopy applications. Key properties such as positioning repeatability, accuracy, (magnetic) drift correction, and in-position-jitter are assessed. The results confirm the benchmark performance of trueNAV, demonstrating nanometer-scale repeatability, robust closed-loop control, and active compensation of positional drifts and error motion across the full travel range.

Limitations of Integrated Position Sensing

A common approach to motion control in cryogenic environments relies on position sensors directly integrated into the individual positioning units. This approach enables compact system designs and high flexibility in the engineering of positioning systems for scanning-probe microscopes. However, this concept is limited to measuring the position of individual positioning units rather than that of the sample or the region of interest, which can accumulate undetected errors, such as lateral runout or mechanical crosstalk, often restricting overall system closed loop performance to the micrometer range. For many applications, this is sufficient, or manual compensation can be applied. However, with the advent of quantum industry, single photon sources and advances in 2D material fabrication control, the demand for efficient workflows, short measurement times and automation require a new level of positioning repeatability and the ability to compensate for drifts and alignment errors. Consequently, the need for navigating the sample within an absolute reference frame becomes evident.

The Solution

The CFM Base Kit is a versatile platform for confocal microscopy in the attocube toploading cryostats (attoDRY1000, attoDRY2100 and attoDRY2200). With trueNAV (see *Figure 1*) it has integrated interferometric sensors that use mirror targets directly mounted on the sample holder to measure the actual 2D position of the sample in the X-Y plane. The sensor itself provides accuracy and precision in the nm range. Furthermore, by measuring directly at the sample, trueNAV can detect and compensate errors that would have been undetectable for integrated sensor solutions, thereby overcoming the previously described limitations.

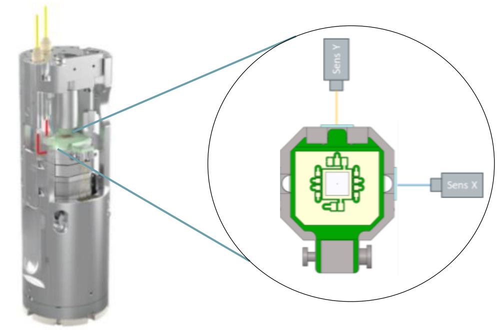

Figure 1: CFM Base Kit microscope housing with trueNAV and top view on the sample holder showing the interferometric position measurement

Test Setup and Methodology

To test and verify the performance of the 2D closed loop positioning system, an additional reference-interferometer is integrated in the system and a calibrated test sample is used in combination with an attocube LT-APO cryogenic objective and room temperature inspection optics. The following tests can be divided in two categories: one based on test procedures according to ASME B5.64 standard (using the second interferometer as a reference), the other evaluating the accuracy of retrieval of regions of interest during microscopy (as a real use case). Measurements have been conducted at room temperature and cryogenic temperatures around 2K.

Repeatability

Repeatability is one of the most important metrics concerning how well positioning tasks are executed in a microscope: It is defined as the standard deviation (σ) of a set of a device's moving target approach measurements, all made under the same conditions. Approach measurements may be done from one or both sides of a target, specifying a device’s uni- or bi-directional repeatability respectively (see attocube glossary). A typical use case is a sample with a random distribution of quantum emitters. The user's task is to first characterize a large number of single emitters among which the most promising ones are identified (points of interest, POI). The user then has to return to those POIs in order to carry out a more detailed analysis for each of them individually. This means, the exact coordinates of each single emitter must be recorded. The efficiency of this workflow is crucially determined by how precisely the microscope can navigate back and forth between the individual single emitters. This is characterized by repeatability.

Most manufacturers are not testing to known standards so that it can be impossible to compare values only given as "repeatability". Besides different test procedures also different evaluation methods can be found. In literature and product descriptions several different definitions of how repeatability is measured or specified can be found. Here are some of the most common:

- Unidirectional repeatability with a confidence of +/-1 σ (mostly used in spec sheets)
- Uni- and bidirectional repeatability with a confidence of +/-2 σ (ASME B5.64 standard)
- Bidirectional repeatability with a confidence of +/-3 σ (99.7%) (most relevant for practical use)

When verifying motion system performances, attocube applies automated, well-defined, and systematic testing procedures in accordance with ASME B5.64 standard, collecting thousands of data points to validate the single-axis performance of the trueNAV readout. These tests ensure a thorough evaluation of the true capabilities across the full travel range for key performance metrics such as repeatability and in-position jitter. attocube chooses to use this standard to test trueNAV against industry level benchmarks, in a transparent way.

Figure 2 shows a typical result from the single-axis repeatability evaluation of trueNAV. After evaluating many measurements, the results indicate that the unidirectional, single-axis repeatability is typically 2.5-5 nm (±1 σ) over a 4 mm travel distance. For bidirectional repeatability across the entire travel range, results demonstrate deviations of typically under 25 nm at a 95% confidence interval, assessed along a single axis at the mirror position. *Figure 3* presents the data from *Figure 2* as a histogram and indicates the 95% confidence level.

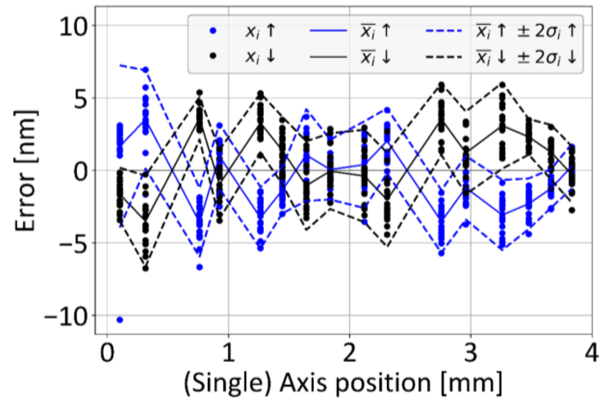

Figure 2: Bidirectional single-axis repeatability test results with 16 target positions over 4 mm range. Blue (black) data corresponds to forward (backward) motion, showing the bidirectional approach to each target location from the two sides, incl. average values and +/-2 σ envelopes.

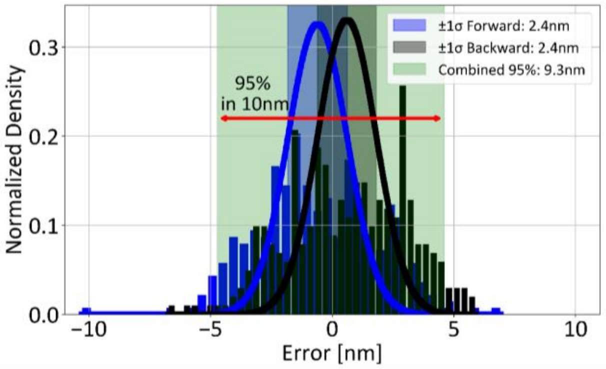

Figure 3: Single-axis repeatability test result histogram showing approaches from both directions (blue and black bars), as well as +/-1 σ confidence range per direction and a 95% confidence interval < 10 nm for bidirectional statistics.

To additionally test trueNAV in an application focussed scenario, a test sample with lithographically defined geometric patterns is mounted. The microscopy optics are used to accurately align the image at clearly distinguishable locations all over the sample, labelled 1-9 in the sample sketch in *Figure 4*. The corresponding microscope images are shown below. The sample is moved through a series of closed loop motions to retrieve these points. The direction of motion is indicated in *Figure 4* with blue arrows. Images are acquired at each location, and after multiple passes, they are analysed to determine the lateral repeatability errors in XY.

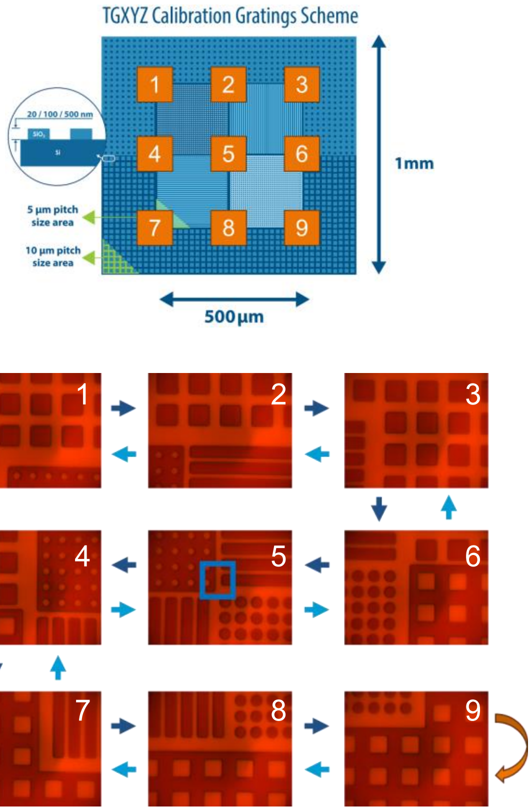

Figure 4: Sketch of the test sample and 2D test pattern path that was used to evaluate the optically observed 2D bidirectional repeatability in a realistic application scenario.

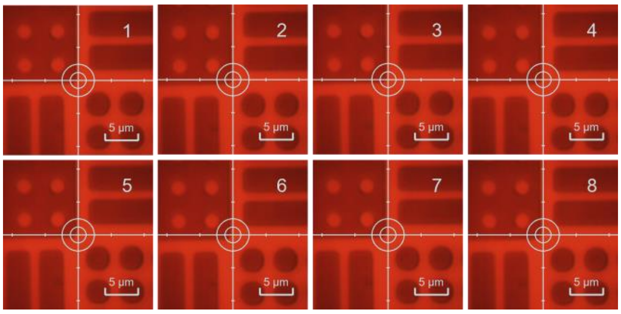

Figure 5: Graphical representation of repeatability, showing eight bidirectional approaches of the same sample feature with virtually no detectable shift within the optical resolution of the setup.

The images of one of these locations are shown in *Figure 5* are nearly indistinguishable. They immediately reveal that the bi-directional repeatability is clearly <1um, close to the resolution of the optical microscope. We point out that the total travelling path of the sample during this test is about 15mm and it involves many changes in direction along both x and y direction. Using specialized image recognition software, a quantitative analysis of the full data set reveals that the repeatability of trueNAV does typically stay within +/- 100 nm (see *Figure 6*). This is exceptionally good and well within precision requirements for typical confocal measurements.

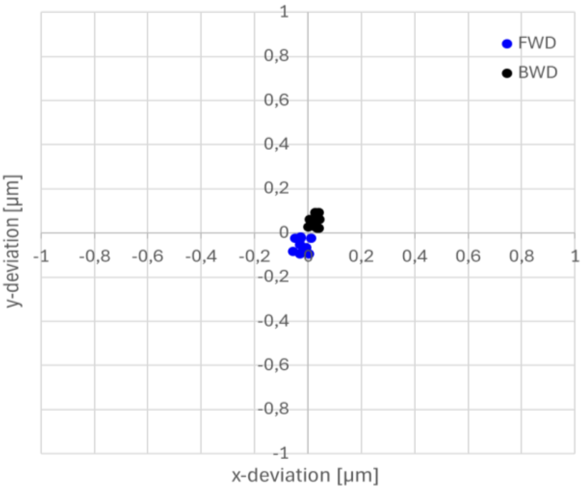

Figure 6: Optical microscopy measurements of bidirectional 2D repeatability reveal a peak-to-peak distribution of approximately ±100 nm.

Absolute Accuracy

Absolute accuracy refers to how closely the actual position of the positioning system matches the commanded position within a defined coordinate system. It is typically expressed as a deviation in micrometers or nanometers from the intended position. Accurately fabricated samples with well-known structures can be used as reference artifacts for determining absolute accuracy in a 2D setup. These samples are often equipped with identifiable markers with relative positions precisely defined by the fabrication process. The system navigates sequentially to these markers in closed-loop mode, using known distances.

Tests for absolute accuracy were conducted in a manner comparable to the 2D repeatability tests using a calibrated reference sample and the microscopy optics. The maximum travel range used was limited by the sample size to a distance of about 1000 µm.

Initially, the optics are aligned with a clearly identifiable corner of the sample (point 1 in *Figure 7*). The distance to the further target points (2, 3 and 4) are well known from the accurate map of the calibrated sample. The positioning system is then commanded to move to the coordinates of the target points, and the deviation is observed with the microscope optics. In the first attempt a significant deviation is visible as shown in *Figure 8*. The main contributor is the angular error of the sample in relation to the positioning system coordinate axes since the sample is usually simply glued on the sample holder and aligned visually. Additional errors are induced, e.g. by errors in the orthogonality of the positioning axis and the measurement axis. For improved accuracy and usability, a calibration procedure can compensate most of these errors and improve the performance as shown in *Figure 9*, reducing errors to a few µm or less.

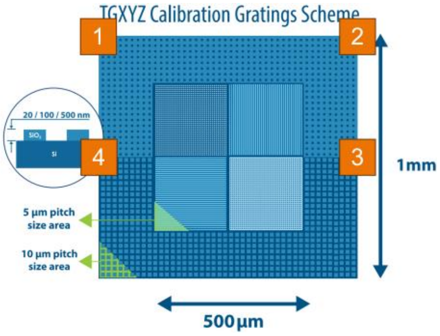

Figure 7: An overview of the sample used as reference artifact for the absolute accuracy tests. The target points are indicated from number one to four.

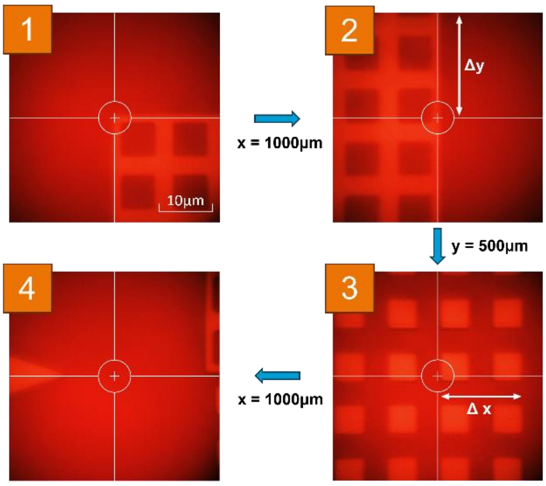

Figure 8: Deviations of several tens of µm between the sample and optics before angular error calibration.

Angular Error Calibration

Angular error calibration, used to correct for imperfect sample mounting, only needs to be performed once per sample. After calibration, navigation relative to a marker is possible across the full travel range, with resulting deviations typically below one micrometer, enabling direct access to standard structures (see *Figure 9*).

To perform angular error calibration, alignment features on the sample defining the x and y axes are required. The calibration process consists of two steps. The first step corrects the rotational misalignment between the sample and the positioning coordinate system and must be repeated for each new sample. The second step compensates for angular deviations from orthogonality within the positioning system itself and can be performed once per system using a calibration sample.

Calibration method - Step 1: To align the sample with the positioning system, the angle between a sample axis (typically the x-axis) and the corresponding axis of the positioning system is measured. This calibration angle can be determined by either moving along the positioning system's x-axis and capturing images of the alignment features to assess deviation, or by centering the positioning system sequentially on the alignment features along the x-axis and recording the resulting x and y positions. The choice of procedure depends on the specific object and the camera capabilities of the system.

Once the first calibration angle φ is measured it is used to transform the coordinates by applying following equations:

$$x' = x\,cos\varphi - y\,sin\varphi$$

$$y' = x\,sin\varphi + y\,cos\varphi$$

Calibration method - Step 2: Once the first axis is aligned (using the transformed coordinates) the angular deviation ϑ of the second axis can be measured, usually the y-axis, with one of the same two procedures described above. The coordinate transformation for step 2 is expressed by the following equations:

$$x'' = x' - y'\,sin\,\vartheta$$

$$y'' = y'\,cos\,\vartheta y'' = y'\,cos\,\vartheta$$

Applying calibration steps 1 and 2 and repeating the absolute accuracy test routine yields the images shown in *Figure 9*. The data shows that the axes of the markers patterned on the sample and the axes of the sensors are now nicely aligned and trueNAV navigates reliably to the marked corners of the calibration sample within a few µm. The reachable performance is highly dependent on the accuracy of the sample and the possibilities to align and calibrate.

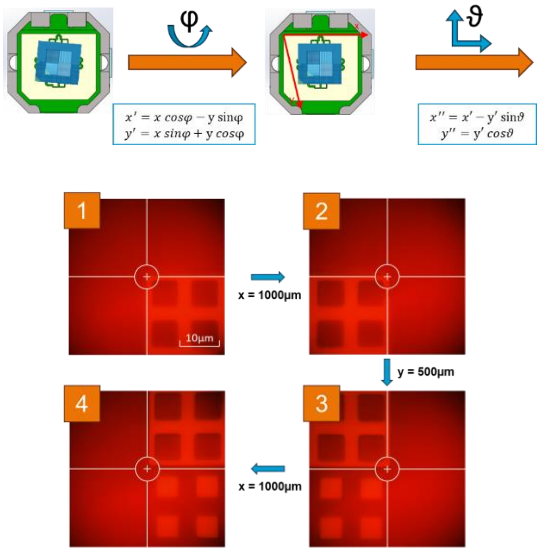

Figure 9: Angular error compensation showing correction of offsets due to misalignment between sample edges/coordinate system and motion direction in XY (ϕ), as well as non-orthogonality of XY motion (ϑ), resulting in substantial accuracy improvements.

Magnetic Drift Compensation

High magnetic fields on the order of several Tesla generate large forces on even slightly ferro, para- or diamagnetic materials. Even in setups designed rotationally symmetric, and despite using mostly non-magnetic materials for all components, typically finite forces remain, acting differently on the various parts in a microscope setup due to large field gradients. During magnetic field sweeps, for example from –9 T to 9 T, these forces change in magnitude and direction, causing the sample to drift under the microscope optics by several micrometers. This requires frequent manual realignment, disrupting workflows, and consuming valuable measurement time. trueNAV actively compensates for these shifts to just a few pixels in the imaging system. This improves efficiency and ease of use by ensuring stable imaging across all field conditions. As an example, a set of images with and without compensation was recorded. While ramping the magnetic field from –9T to 9T the positioning system is actively kept in place by the trueNAV controller. Constantly monitoring the sample through the inspection optics provides proof: the sample shifts by only a few pixels. *Figure 10* shows multiple pictures at different magnetic fields with active trueNAV compensation. Comparison measurements without trueNAV show much bigger shifts that require manual corrections, depending on the field, setup and sample used.

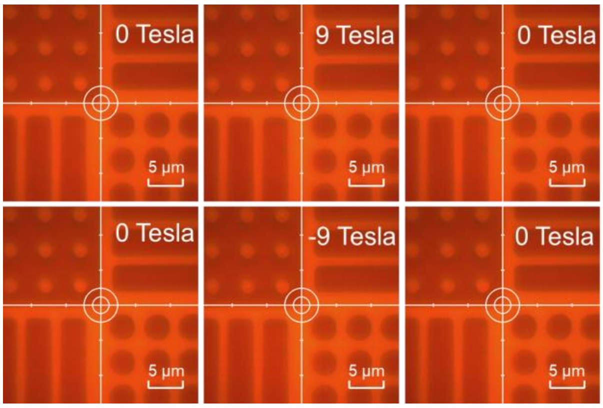

Figure 10: Optical verification of drift in XY-position upon magnetic field sweeps between -9..9 T. The results show a minimized drift of only a few pixels when compensation is on

In-Position Jitter

In-position jitter refers to rapid, small-scale fluctuations of the sample that can degrade image quality and limit scanning probe microscopy precision. Evaluating closed-loop performance with respect to jitter is therefore essential for stable, high-resolution measurements.

Due to their slip-stick working principle, nanopositioners are most stable when electrically grounded. Measuring a stack in this state with an external interferometer and microscope optics reveals the system's minimum vibration level, limited by environmental background noise and the resolution of the measurement. In ultra-low vibration cryostats like the attoDRY2100, optics usually will not see any vibrations of the sample. To judge if a closed loop positioning system is performing well regarding in-position jitter, it is advisable to compare vibration levels in grounded state (background noise) with those in closed loop positioning state (in- position jitter). In our tests, the CFM base kit with trueNAV shows the same vibration levels in both states. This demonstrates that active closed-loop control does not introduce additional vibrations and can maintain the sample at the lowest achievable vibration levels.

Conclusion

Leveraging an external interferometer, the CFM Base Kit with trueNAV demonstrates exceptional positioning performance, achieving unprecedented repeatability and accuracy in the XY sample plane. These capabilities are particularly advantageous when working with travel ranges of several millimeters to characterize or investigate larger samples, as the interferometer maintains its precision across the full travel range of the positioners.

With a bidirectional single-axis repeatability of typically 10 nm (95% confidence interval) and a two-dimensional bidirectional repeatability of around ±100 nm, the system delivers positioning accuracy well below the typical optical resolution of a confocal microscope directly at the sample. A unique strength of the system is its ability to compensate for error motion induced by magnetic forces on the sample.

This level of performance enables users to reliably reach targets across the entire sample with exceptional precision, reducing time-to-result by accelerating routine positioning tasks, minimizing manual readjustments and maximizing measurement efficiency and automation.