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Extreme Metrology:
Big Science Requires A Nano-Perspective

Extreme metrology applications involve more than enough unknown variables. Instrumentation whose performance has been proven should not be one of them.

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Extreme metrology represents the cutting edge in technological demand from the material researchers, astronomers, and other physicists whose work demands nearly unattainable precision. From NASA and academia to the U.S. National Institute of Standards and Technology (NIST), these scientists and researchers are asked to achieve feats others have deemed impossible; consequently, they require specialized instrumentation to achieve results.

Teams and individuals in need of such equipment usually deeply understand the principles and mechanics of their investigations already. Specifically, they are aware of their noise budget and the metrology loop relevant to their experiment.

Understanding the metrology loop means understanding not just the end goal in terms of metrology but also realizing how much (and to what extent) each component influences the activity in terms of stability, resolution, and ability to move an object at that level.

Of course, this awareness is not a given; everybody makes mistakes and it can be easy to overlook minute details from time to time. Therefore, it is important to discuss your goals and equipment setup with instrumentation partners.

In the interest of saving both time and effort – and, by extension, cost – it is vital to foster such partnerships as early in the planning process as possible, since your instrumentation partners are likely to contribute significant input toward the apparatus you are attempting to construct.

Expertise Is Gained Through Experience

Considering the stakes of scientific endeavors demanding extreme metrology, as well as the resources such projects require to succeed, partner selection is paramount, from the engineers and researchers to the equipment providers.

That determination can be helped by applying a simple metric: do they claim the necessary expertise, or have they provided tangible evidence by demonstrating that expertise?

Instrumentation providers can claim something is “possible” with a particular piece of equipment, but has that level of performance been demonstrated? Can it be shown to the customer before a purchase? Specifications are not always indicative of real-world performance.

Just because a vehicle is rated at 30 mpg and its speedometer goes to 120 mph, doesn’t mean the vehicle actually operates at 30 mpg efficiency in real-world conditions, or that it can actually attain 120 mph. Thus, make it a point to tell equipment providers, “do not just tell me you can do it; show me.”

Consider that, as a diagnostic exercise, Mad City Labs will command a small oscillation to a nanopositioning system. That oscillation might only be a few nanometers peak to peak — perhaps 100 pm. Then, the noise floor is measured, as there exists some position noise in every nanopositioning system; the input signal is clearly resolved to show that it is larger than the background noise. This diagnostic also functions as proof of a system’s promised resolution capability.

Another salient example is Mad City Labs’ diagnostic exercise to prove its atomic force microscope’s (AFM’s) capability to achieve subnanometer resolution. Testers will measure the height of atomic steps on a silicon surface using a standard AFM — essentially a measure of the thickness of the silicon atom on a surface, roughly 300 picometers high.

Thus, the instrument must provide better than 300 pm resolution; a Mad City Labs AFM can routinely achieve between 5 and 10 picometers of resolution. If you can routinely measure that, then you are able to achieve extreme metrology. Few applications currently exist, however, requiring better than 100 pm of noise.

It bears mention that these tests are conducted at standard laboratory ambient conditions; no special acoustic or environmental isolation is present. Therefore, the diagnostic is representative of what most experimentalists would consider a standard starting metrology loop (real-world conditions in which they would be working) — and extreme metrology results remain attainable.

Application Areas

External effects on an experiment also must be considered, and a capable instrumentation partner can help researchers navigate these effects – be it interference from Earth's magnetic field or the planet's rotation — particularly if the partner has experience in doing so.

A perfect demonstration of this principle is Mad City Labs' work with Stanford University in creating its 10 m atom interferometer. The researchers required the movement of a large mass with, effectively, a tip-tilt rotation, within a single nanoradian (10-9 rad) — located in a vacuum chamber (a nanoradian is the angle subtended by 1 mm at 1,000 km).

Because of the instrument's complexity, the system's design required a collaborative effort to ensure both precise motion control and an apparatus strong enough to hold the mirror and keep it stable to within a nanoradian (to eliminate the effects of Earth's rotation on experiments).

Space-based astronomy applications — sub picometer dynamic measurement — In this application, advanced adaptive optics are utilized to correct for aberration or error in the optical systems used by space-based telescopes (e.g., the lasers and measurement systems trained on points of light deep into space).

In such applications, you must be able to move an optic or aim a laser beam with exceptional control resolution (i.e., picometers). As the distance between the apparatus and the light source increases (i.e., the light gets dimmer), system demands for precision and stability also increase.

Ground-based astronomy applications — Ground-based telescopes must contend not only with the planet's movement, but with atmospheric interference. Thus, astronomers use yellow laser light to create artificial guide stars high above the Earth (~92 km), using the point of light as a basis by which to correct their optics for atmospheric errors.

Air in the atmosphere, though, is not uniform, and the beam must be adjusted to account for these changes, which requires a precise motion system.

You Have Choices

Because of the highly specialized nature of extreme metrology instrumentation, you may feel boxed in by your application's hyper-specific requirements. But your instrumentation partner should make a point to listen carefully to your needs and goals, tell you frankly what is achievable, and detail how they can help make it happen.

Maybe there truly exists only one instrument that can serve your needs. Or maybe two or three tools will do the job, in which case a knowledgeable supplier can guide your decision. Every experiment, every endeavor is an evolving field; therefore, products must evolve to meet those requirements. Ask:

1. Can a base product meet your specifications?
2. Does it need to be altered to perform as needed?
3. How will it be attached?
4. How will it be controlled?
5. In short, how will you integrate it with the rest of your setup? Everything from cabling and software to control electronics and the product's physical design must be considered and discussed.

You also want a supplier who can be honest when their product may not be able to achieve your goals – not one who insists something cannot be done, simply one who can render an informed opinion about the reality of the capability your project demands versus what is realistically attainable with their equipment.

Every customer is trying to balance price, physical size, mass they want to move, and speed they want to go — overpromising and underdelivering wastes the experimentalists' time and effort.

Finally, you want a partner who can acknowledge errors and is committed to rectifying the situation. Often, extreme metrology endeavors break new scientific ground, and the instrumentation demands can be difficult to predict. Mad City Labs has completely redesigned systems because they didn't work for the customer's intended application. This is not a common outcome, nor a desired one, but it is representative of the commitment you should demand from an instrumentation partner.

More often, Mad City Labs is able to identify other errors in the experimentalists' setup because its personnel include physicists – and not just salespeople – dedicated to understanding the customers' projects. Indeed, in some cases, the answer is as simple as an error in the system's construction, or even an air (antivibration) table someone neglected to turn on.

Conclusions

It is to be expected that not all companies are altruistic in the endeavor of furthering science. However, experimentalists partnering with an instrumentation provider on a project requiring extreme metrology cannot afford to find out after the fact that profit trumped delivery of a product with proven performance.

A good instrumentation partner does not want to be given your trust and respect; they want to earn it. Capable partners want customers who ask questions, who demand proof that their system or products perform as advertised — be it noise plots or real-world tasks — and not just specs on a sheet.

About The Authors

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About Mad City Labs

Mad City Labs designs and manufactures a complete product line of high precision piezo nanopositioners, micropositioners, atomic force microscopes, and single molecule microscopes. We provide innovative instrument solutions from the micro- to pico-scale for leading industrial partners and academic researchers. Visit www.madcitylabs.com or email mclgen@madcitylabs.com for more information.

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