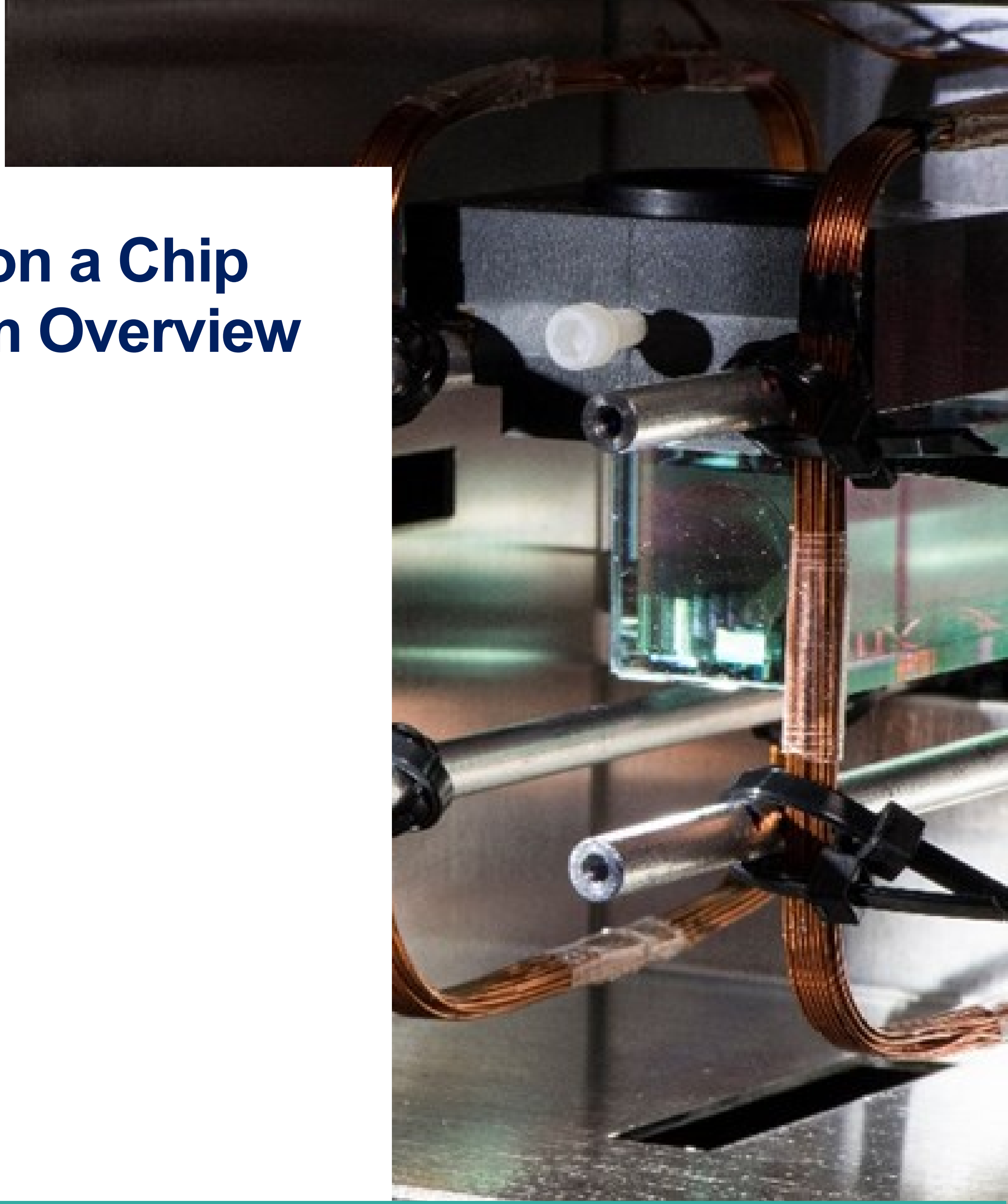
NIST on a Chip Program Overview



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NIST on a Chip Guiding Vision

NIST has embarked on a sweeping program called "NIST on a Chip" (NOAC) that will revolutionize measurement services and metrology by bringing them out of the lab and directly to the user. To that end, NIST is developing a suite of intrinsically accurate, quantum-based measurement technologies intended to be deployed nearly anywhere and anytime, performing uninterrupted *without the need for NIST's traditional measurement and calibration services*.

These technologies will enable users to make precision measurements referenced to the International System of Units (SI) on factory floors, in hospital diagnostic centers, in commercial and military aircraft, in research labs, and ultimately in homes, automobiles, personal electronic devices, and more. NOAC thus provides an opportunity for the "democratization" of measurement technology, where affordable devices drastically reduce the cost and increase the availability of precise measurements that could previously only be delivered at the world's best metrology institutes.

NOAC will meet those goals by creating prototypes for a new generation of ultra-compact, inexpensive, low-power measurement tools for quantities including time and frequency, distance, mass and force, temperature and pressure, electrical and magnetic fields, current and voltage, and fluid volume and flow. Many will measure two or more measurands on the same miniature platform. Imagine a chip that senses absolute temperature, pressure, and humidity to immediately detect any excursions in safe storage conditions of sensitive goods, such as vaccines or food. Others will be designed for inexpensive mass fabrication – such as a chip-scale radiation monitor that could be embedded in every driver's license or other ID card to serve as a ubiquitous monitor or early-warning system for radiation exposure.

These NIST-pioneered technologies will be manufactured and distributed by the private sector, opening new technology transfer and lab-to-market opportunities in accordance with NIST's goal of strengthening U.S. economic competitiveness by supporting advanced manufacturing.

Defining Criteria for NOAC Devices

The integrated NOAC program will develop and deploy practical quantum-based standards and sensors, traceable to the new international system of units (SI), that are:

Deployable to where customers need them, such as on the factory floor, embedded into products, in a laboratory environment, in space or at home.

Flexible, providing a broad range of "zero chain" SI-traceable measurements and standards that are configurable into a single small-form package and adaptable to customers' requirements.

Manufacturable, with production costs that scale appropriately for applications, such as low-cost/high-volume for broad deployment.

Reliable, providing either the right value of a measurement or no value at all.

Fit-to-Function, tending towards small size, low power consumption, rugged, easily integrated and operated, with an operating range and uncertainty required by the application.

Propitious Timing

NOAC innovations will be increasingly valuable to industry, medicine, defense, and science because of the current convergence of major trends in technology advancement. For example, Industry 4.0 is an optimization strategy in which the machinery of industrial production no longer simply "processes" the product, but the product communicates with the machinery of its own creation in a digital choreography of production.

This approach will come to redefine consumer-manufacturer-retailer relationships, as products in the field (i.e., in the Internet of Things) communicate back to the manufacturing ecosystem that produced them (the Industrial Internet of Things) to influence operations from cradle-to-grave, including next-generation product design, supply chain management, peer-to-peer consumer networking, product maintenance, and end-of-life. This new paradigm demands accurate sensors both in the field and in the plant to provide reliable information to drive automated, machine-to-machine communication.

At the same time, the emergence of the second quantum revolution – which depends on the control and manipulation of matter at the most fundamental levels – will spur a new generation of technologies based on phenomena such as entanglement and superposition. The preservation and manipulation of these very fragile quantum states will require reliable, in-situ sensors and measurements, a NOAC goal. In addition, progress in quantum information science will enable unprecedented advances in measurement precision and thus fuel a new generation of quantum-accurate standards and measurements.

Finally, the explosive demand for high-speed transfer of ever-larger volumes of data will benefit directly from NOAC's pioneering work in miniaturized photonic channels, novel signal transduction schemes, and accurate calibration standards for devices that must operate at frequencies orders of magnitude higher than those employed today.

NOAC – A Model for Partnering with Industry

The success of the NIST on a Chip program depends on finding industry partners to do what the government does not: turn NIST innovations into commercial products.

NOAC benefits our partners by launching a new generation of self-calibrating and "zero-chain traceability" measurement devices that can be embedded directly into products or placed in-line on the manufacturing floor. Because these devices depend on fundamental constants of nature rather than artifacts or proxy measures, they will free industry from much of the need for periodic calibration of instruments at NIST or other calibration labs.

The devices based on NOAC technologies will help NIST deliver on its mission to enhance industrial competitiveness by spurring innovation, and will also provide new measurement tools that NIST itself can use in the delivery of measurement services.

These benefits to both industry and NIST, combined with the prospect of commercialization for widespread dissemination, make the NOAC portfolio ideal for piloting new ways for NIST to partner with industry.

The NOAC Technical Portfolio

Magnetic and Electrical Fields

One of the most promising NOAC projects is developing chip-scale atomic magnetometers. Atomic magnetometers are instruments that measure the strength, and sometimes the direction, of magnetic fields using the precession of atomic spins in trapped populations of atoms. Conventional instruments have a sensitivity of about 100 fT/rtHz, are about 0.5 L in volume, and require about 10 W of power to operate.

Chip-scale atomic magnetometers, by contrast, use microfabricated vapor cells containing alkali atoms that respond to faint changes in magnetic field and are interrogated with light beams. This allows for considerable reduction in the size and power consumption of the instrument and might dramatically reduce manufacturing costs for industry. Immediate uses for devices would be in magnetoencephalography, a technique used to diagnose epilepsy, among many other conditions.

Another NOAC project is using trapped atoms to address one of the most pressing needs in electrical metrology: a way to accurately measure electric fields with low uncertainty in a traceable, self-calibrating, portable system. Nearly all electronic systems, from cell phones to radar systems, rely on the ability to measure electric fields. Yet the best measurements available with current technology, provided by NIST calibration services, only provide 5% uncertainty, and industry has reported typical uncertainties of commercial electric field probes of 10%.

The new NOAC approach employs a population of alkali Rydberg atoms that have one or more electrons excited to a very high principal quantum number. In that state, they are extremely sensitive to electric fields, and changes in their properties can be readily measured by the fields' effects on laser beams, with the potential for highly reduced uncertainties.

Quantum Optics and Radiometry

Several NOAC projects are developing novel technologies and devices to measure optical power, provide miniaturized frequency standards, improve uniformity of electronic signals, and serve as sources and detectors of single photons.

One group has devised a system of measuring optical power by measuring the pressure of laser light on a mirror. The same researchers have also developed an electrical substitution bolometer to gauge power in fiber-optic channels, and a radiometer that can operate in space with greater accuracy than current designs.

Another group has succeeded in drastically reducing the size of frequency combs to "microcombs" that are only a few cubic centimeters in size by employing a novel technology. Traditional frequency combs result from building lasers with many complex components. Microcombs, by contrast, are generated by quantum interaction of light with a suitable monolithic microresonator, which strongly confines light inside the device's material. Eventually microcombs could be used for ultra-compact optical clocks and sensors, ultra-high data-rate communications and signal analysis, and portable optical spectrum systems.

Other NOAC scientists are meeting the growing demand for ways to calibrate and verify ultra-high-speed systems such as signal analyzers, sampling oscilloscopes, and light-wave component analyzers. Conventional systems are limited because they rely on semiconductor signals at a few GHz; the NOAC design uses switches operated by light, enabling operation up to 150 GHz.

Finally, a NOAC team is creating a system based on quantum dots that will produce a series of identical single photons for use in quantum information processing and other cutting-edge applications.

Thermodynamics

Temperature, pressure, and many other thermodynamic quantities have typically been measured electrically – for example, changes in the resistance of a platinum-wire thermometer or the capacitance of a diaphragm in a vacuum gauge. NOAC teams are developing a revolutionary, high-accuracy alternative: photonic systems that quantify thermodynamic properties with extremely fine resolution by measuring changes in optical wavelength.

Temperature changes alter the dimensions and thermoelectric properties of silicon structures such as ring resonators with radii smaller than a micrometer; that, in turn, changes the wavelengths of light that will propagate through the structure. Pressure changes affect the refractive index of light in a cavity; detecting that change is a very sensitive measure of pressure. Because the output in both cases is light, it can be quantified in fine detail.

Fluid Measurement and Control

There is increasing demand from industry and science to measure flow on scales as small as nanoliters per minute and to track the properties of individual cells moving in liquids. As a result, microfluidics has become a fundamental tool enabling a wide range of measurements and applications for medical diagnostics, molecular biology, genetics, and pharmaceuticals, biophysics, chemistry, nanotechnology, and engineering. For those and other applications, there is a growing need for standards for traceable measurements, enabling reproducibility of results from device to device as well as device interoperability.

NOAC scientists are meeting that need with new technologies, device control methods, and embedded sensors, among other innovations. They have devised micro-channels in the range of 100 micrometers to 1 mm embedded in silicon, glass, or polymers. The channels can be used to precisely control flow of a single liquid component (e.g. a drug) or be organized into complex networks that facilitate high-speed assays of large arrays of substances (e.g. a gene expression or drug discovery tool).

They have also developed advanced, high-precision systems that use multiple light frequencies to characterize microparticles or cells moving along extremely narrow channels in real time, enabling high-speed processing of samples.

Biochemical Sensing

Many NOAC projects are developing technologies that will contribute directly to applications in biochemical sensing. By integrating microfluidic structures with systems that employ light to interrogate samples as they interact with reagents, coupled with the capacity for on-chip electrophoresis and polymerase chain reaction, NOAC scientists are hastening the advent of a "lab on a chip." Other NIST projects are devising and improving drone-carried laser systems that can determine the concentration of multiple gases in a localized air column, and methods of using light to detect chemical and/or morphological changes in samples. Biomedical sensing is a priority area for future growth.

Radiation

Many sectors of the U.S. economy increasingly depend on accurate measurement of radiation dose – from medical device sterilization to food irradiation to clinical radiation-beam therapy and beyond – for precision medicine and more efficient manufacturing. Many conventional radiation detectors (e.g., ionization chambers, Geiger counters) use electrical signals and can be hard to miniaturize. NOAC researchers are developing novel, silicon-based photonic detectors whose output is light, which can be measured to great precision. They offer small size, low power consumption, and robust performance. Such devices are also of great interest for use in harsh environments, such as space or nuclear reactors.

At the same time, U.S. manufacturers are transitioning away from using radioactive material to adopting machine-based electron and ion beams, which are more effective, efficient, and secure, and can be highly customized for specific applications. No sensors are currently able to meet all the associated industrial and medical needs for these new techniques. But the NOAC designs, based on commercial silicon chip fabrication and telecommunications technology, can, for example, be made small enough to accurately measure radiation beams focused on very tiny areas.

Another NOAC group has demonstrated a chip-scale radiation dosimeter that can be embedded in an ID card. In the event of a nuclear event, the technology would enable rapid, real-time screening and triage of exposed individuals.

Mass, Force, and Acceleration

Mass and force measurements have traditionally involved sets of standard weights, but that system does not scale well to small masses and forces. For example, the pharmaceutical industry, nanoscale manufacturing, biomedical applications, and other endeavors increasingly require measurements in the microgram range, which cannot be accomplished mechanically. NOAC researchers are meeting this challenge by using the force exerted by a stream of photons as a measure of very small forces and masses by cavity opto-mechanics.

Conventional methods of quantifying acceleration entail either detection of piezoelectric current produced by stress or measurement of changes in electrical resistance as accelerometer components are displaced or deformed. The goal of the optomechanical sensors program is to replace such traditional *electro*-mechanical devices with a new generation of chip-based *opto*-mechanical sensors that are more sensitive, more accurate, and much smaller and lighter. NOAC's optical accelerometer design allows direct measurement of sensor displacement in terms of the wavelength of light, substantially decreasing uncertainty.

Dimensional Metrology

Many NOAC projects utilize the interaction of lasers and trapped alkali atoms to measure various quantities. One group is adapting this technology for use as a quantum-accurate length standard. Optical measurement of transitions in atoms can serve as SI-traceable reference for length if the wavelength is known. The industry standard for length metrology at present is the polarization-stabilized He-Ne laser referenced to an atomic transition in the Ne atom. This instrument has a fractional accuracy of about 10-8, costs roughly $10,000 per unit, and is a ~ $100M/year industry that underlies a broad range of market sectors from aerospace to telecommunications.

NOAC researchers are developing a low-cost, chip-scale version of this laser that – if commercialized by industry – could substantially impact an already large market and open opportunities that are currently unrealistic due to the size and cost of the He-Ne laser. Widespread adoption of such instruments, of course, would depend on how manufacturers can achieve larger-scale, lower-cost fabrication. At present, quantum-based chip-scale atomic devices such as clocks and magnetometers are still largely assembled by mechanical pick-and-place tools (or sometimes by hand). The team is at work on solving that problem by finding ways to integrate microfabricated alkali vapor cells with single-mode photonics.

Time and Frequency

For timekeeping, colder atoms mean higher accuracy. The cesium beam clocks, hydrogen masers, and vapor-cell rubidium clocks that are the workhorses for establishing the world's time are exclusively based on "warm" atoms. But the most accurate and precise instruments are all based on laser-cooled trapped atoms in large-scale laboratory apparatus. Now a NOAC project is developing ways to miniaturize cold-atom technology for critical practical applications in the field, such as: timekeeping and sensing for timing infrastructure and as a backup to GPS; quantum information technologies; inertial navigation; and mineral exploration and geodesy.

Reducing these devices to chip-scale dimensions is prompting many NOAC innovations, including development of a miniature magneto-optical trap and a cold-atom platform for interferometry, among numerous others.

Vacuum

As feature sizes in integrated circuits continue to shrink, chip fabrication for advanced research, quantum information processing, and other emerging technologies demands virtually contamination-free chambers. Many processes now require vacuums approaching 10-10 Pa. But at present, there are no trustworthy gauges that operate below 10-7 Pa.

To fill this need, NOAC scientists have designed a new kind of primary-standard vacuum gauge that measures the number of interactions between a trapped population of ultracold atoms and residual gas molecules in the vacuum chamber. Each interaction reduces the number of atoms in the trap. The number of remaining atoms is detected photonically. If eventually commercialized, the Cold Atom Vacuum System (CAVS) will provide much higher accuracy and dependable performance than conventional gauges.

The researchers intend to build a laboratory-scale CAVS and then miniaturize a prototype to dimensions small enough to serve as a drop-in unit for fabrication vacuum chambers.

Current, Voltage, and Resistance

Prior to the recent redefinition of the international system of units (the metric system), the ampere could not be realized with complete accuracy, even in a highly sophisticated laboratory setting. The new definition is based on the elementary charge, and NOAC researchers are closing in on a quantum-accurate measurement of current using a technique called single-electron transistor (SET) in a massively parallel configuration. The project is comparison-testing three different SET configurations with the goal of reaching output around 1 µA – the minimum threshold current needed to use such a device so that a manufacturer could make a working current standard.

Meanwhile, another NOAC project is building on NIST's landmark development of the 10V Programmable Josephson Voltage Standard (PJVS, now disseminated through the NIST Standard Reference Instrument [SRI] program) and the 2V Josephson Arbitrary Waveform Synthesizer (JAWS, in continuing development, but with prior versions of the system still in demand and available through the SRI program).

Now the researchers are exploring the potential of two other experimental superconducting configurations: a JAWS system that can operate at radio frequencies, and another version that can manipulate and process information at the level of the single flux quantum. Using the same kind of technology, they have successfully measured thermodynamic temperature using a low-voltage version of the JAWS system that exploits Johnson noise thermometry. This approach has near-term potential for establishing a quantum-electrical-based primary temperature standard.