Physics Today

DARPA looks beyond GPS for positioning, navigating, and timing

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Citation: Physics Today **67**(10), 23 (2014); doi: 10.1063/PT.3.2543
View online: http://dx.doi.org/10.1063/PT.3.2543
View Table of Contents: http://scitation.aip.org/content/aip/magazine/physicstoday/67/10?ver=pdfcov
Published by the AIP Publishing

2003, when it launched the original center in South Africa. "We hope ICTP can learn from our experience," says Neil Turok, the institute's founder and current director of the Perimeter Institute for Theoretical Physics. "You have to be utterly dedicated. You have to be aware of the political sensitivities. And the international partners have to be aware that they are not in charge."

In addition to its support for the regional centers, the ICTP will continue to promote science in Africa and other parts of the developing world, says Joseph Niemela, head of the ICTP's applied physics section. In 2015 the ICTP's Office of External Activities, which Niemela also heads, will coordinate global activities for the UN-designated International Year of Light and Light-based Technologies, including a workshop in South Africa on fiber-optics technology. "If turnout and enthusiasm [for that event] are high, we will look to establish a Pan-African optics and photonics society," says Niemela.

"A lot of work and time goes into capacity building . . . but [those] efforts are paid back by seeing the progress achieved by individuals and also by research groups and institutions that have profited from our collaborations," says the ICTP's Ralph Gebauer. The Trieste-based condensed-matter physicist is cofounder of the ICTP-affiliated African Network for Solar Energy, which aims to foster research activities among African scientists in that field. Gebauer says one of his favorite outreach experiences happened in Africa; he was visiting a former ICTP diploma student who "presented his own first PhD student to me and explained that [he] was my scientific grandson."

Jermey N. A. Matthews

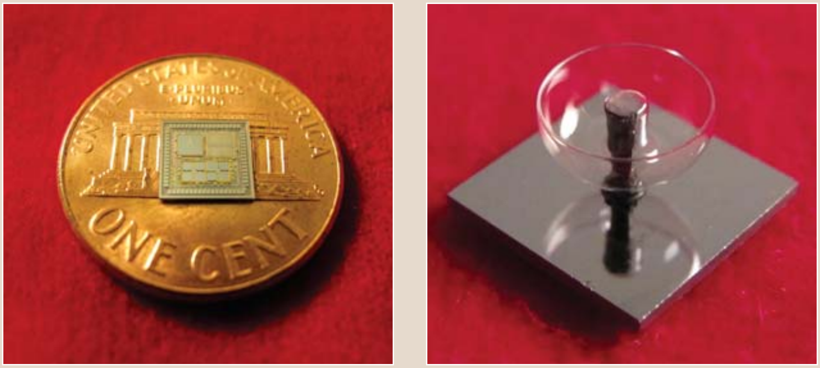
DARPA looks beyond GPS for positioning, navigating, and timing

Cold-atom interferometry, microelectromechanical systems, signals of opportunity, and atomic clocks are some of the technologies the defense agency is pursuing to provide precise navigation when GPS is unavailable.

Since its advent in the 1990s, the global positioning system has become ubiquitous in both the military and civilian worlds. But for all its precision, GPS has major limitations. Topping the list is its vulnerability to jamming of the signals from the GPS satellite constellation. Moreover, GPS does not work underwater or underground and can be degraded or unavailable during solar storms.

It's no wonder that the US Department of Defense has long been developing alternative positioning, navigation, and timing (PNT) systems that can operate independently of GPS. Five programs of the Defense Advanced Research Projects Agency (DARPA) are focused at least partly on PNT-related technologies.

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY



A prototype inertial navigation unit (left) incorporating microelectromechanical systems technology includes three accelerometers, three gyroscopes, and a highly accurate clock. Glass blowing was replicated at the microscale by researchers funded by the Defense Advanced Research Projects Agency in fabricating this wineglass-shaped inertial sensor (right). The sensor's symmetry provides a frequency split—a measure of accuracy—of 10 hertz, which approaches that required for high-quality navigation devices.

Several areas of DARPA research involve the pursuit of different technological routes to reduce the size and cost of inertial navigation systems. Long used for guiding aircraft, missiles, and submarines, inertial systems employ gyroscopes, accelerometers, clocks, and computers to calculate position. Three pieces of information are needed to precisely navigate between two known points: orientation, acceleration, and time. Once an initial position is provided, inertial systems determine where to go.

Modern high-end inertial navigation systems are large, power-hungry, and expensive, says Robert Lutwak, a program manager in DARPA's microsystems technology office. The Defense Department wants packages that can fit into weapons such as guided munitions and devices that can be carried by infantrymen. And the instruments often need to withstand extreme mechanical and thermal environments.

Lin Haas, a program manager in DARPA's strategic technology office, says one objective is to shrink to fingertip size the so-called inertial measurement units (IMUs), the instruments containing the gyroscopes and accelerometers. By comparison, IMUs found on today's commercial and military aircraft are the size of a soccer ball, employ ring-laser or optical-fiber technologies, and can cost up to $250 000.

In addition to improving the portability of IMUs, DARPA managers also want to improve their accuracy. "The general concept is, we want to be able to coast, or dead reckon, longer on our inertial sensors without having to rely on GPS to correct any accumulated errors," says Haas. "The longer we can go without GPS, the better."

Errors that build up over time cause drift in an inertial navigation system. Current navigation-grade IMUs have a drift rate of about 1.8 kilometers (1 nautical mile) per hour. Haas declines to specify the drift rate that the DARPA programs aim to achieve, but Mark Kasevich, a physics professor at Stanford University, says it should be feasible to maintain accuracy to within a meter, equivalent to GPS resolution, for much longer than today's inertial navigation systems.

Cold atoms

Kasevich and his spinoff company AOSense have been applying cold-atom interferometry to inertial navigation. While it's early in development, he says they have demonstrated cold-atom sensors that would support system drifts of 5 m per hour—close to GPS accuracy. The technology exploits quantum physical properties to measure the relative acceleration and rotation of a cloud of laser-cooled atoms in a sensor. (See the article by Markus Arndt in PHYSICS TODAY, May 2014, page 30.)

Neither Kasevich nor Haas would offer a development timeline for the cold-atom technology. "I've been thinking it's 5 years away for the last 10 years," Kasevich says. "It seems like things are coming together and we've had excellent support from DARPA to mature the technology."

Cold-atom instruments will require three lasers generating five beams for cooling and moving the atoms through interferometers to determine movement and rotation. Although shrinking lasers to microsystem size would be a significant engineering challenge, Kasevich draws an analogy to the progression that occurred from the transistor's invention to the integrated circuit.

Existing low-power semiconductor lasers, some as small as 100 μm and requiring only a few milliwatts of power, could be adapted to cold-atom use, says John Kitching, leader of the atomic devices and instrumentation group at NIST. And the telecommunications industry has made rapid advances in photonics, he says, pointing to micro-optics and single-mode optical waveguides. "The playbook [for lasers] is from the telecommunications industry," agrees Kasevich. "If we could take what exists in telecom now at 1550 nanometers and bring it down to 850 nanometers, we'd have all the components we need."

Microelectromechanics

A second, longer-running DARPA effort is advancing IMUs built with microelectromechanical systems (MEMS). Newly developed microfabrication processes have been used to fashion toroids, hemispheres, and wineglass-shaped inertial sensors from materials that include bulk metallic glass, diamond, and ultralow-expansion glass. In operation, the three-dimensional inertial sensors send out vibrations across their surface. The precession of the standing wave is measured, and any changes represent a shift in orientation.

If successful, the MEMS effort may allow precision microscale IMUs to be manufactured at a cost roughly equal to today's integrated circuits, according to DARPA documents. By comparison, today a single, bulky gyroscope designed for use in a precision missile can take a month to be handmade and cost $1 million. Researchers at the University of Michigan have fashioned a prototype MEMS-based unit for both timing and inertial measurement. The device contains three gyroscopes, three accelerometers, and a highly accurate master clock on a single chip just 10 mm^3 (see photo above).

Drift rates for MEMS sensors don't yet match those of today's large fiber-optic and ring-laser gyros. And MEMS properties face physical limits, says Kasevich. He says he doubts that MEMS will reach high accuracy levels "because there are really hard limits that the materials are going to be pushing against."

Kitching agrees. "I think that the larger systems, because they are larger and they have additional flexibility and high power, are going to outperform MEMS in terms of stability, accuracy, and precision. What MEMS offers is small size, low power, and low cost," he says. The technology excels for lower-performance applications, such as accelerometers for automobile air bags.

Clocks

In another effort, dubbed quantum-assisted sensing and readout (QuASAR), DARPA is attempting to make portable, ultra-accurate atomic clocks. Existing GPS clocks are based on microwave (in the few-gigahertz range) transitions in alkali atoms, a technology that was state of the art 50 years ago, says Kitching. In recent years, says Jim Gimlett, a program manager in DARPA's defense sciences office, clocks based on high-quality optical transitions in alkaline earth atoms have been developed with resolution and stabilities about four orders of magnitude better. (See PHYSICS TODAY, March 2014, page 12.) But they also are larger and more complex than the GPS clocks and require expensive infrastructure for laser stabilization and conversion of optical signals to usable radio frequencies.

The best-performing of those clocks, including the one NIST uses for the time standard, employ cold-atom technology, says Kitching. But they are even more complex than warm-atom versions.

Kitching sees two other impediments to miniaturizing cold-atom technology, whether for interferometers, gyros, or clocks: the required very high vacuums (10^{-17} torr or better) and the small number of atoms that will be available for cooling at a microscale. "Nobody quite knows how to create such a high vacuum in a very small package. Most vacuum pumps you can buy are 100 cubic centimeters or something like that," he notes. "And the number of atoms that you can trap and laser cool is very strongly dependent on the size of your system. If you go from 2 millimeters to 1 millimeter, you've lost a factor of 100 in the number of atoms."

Kasevich is confident that the issues can be resolved. "I think those of us in the field think it's just a matter of having the will and the financial resources to take that engineering step. But there's no surprises left in the physics."

Navigation on the fly

Additional DARPA programs address other aspects of non-GPS PNT. The all-source positioning and navigation system (ASPN) program is exploring using "signals of opportunity"—essentially any non-navigational RF source such as commercial satellites, radio, and television stations—to triangulate position. Those signals are much stronger and more numerous than signals from GPS satellites and could provide alternative points of reference in an environment that lacks GPS access. "What we are talking about is, Can we develop a navigation system that can extract spatial and temporal information from any sensor, such as communication and imaging systems?" says Haas. "The answer is yes, of course you can."

But the ASPN program goes further: It aims for the capability to rapidly reconfigure a signal-of-opportunity navigation system to automatically adapt to new signals without having to go through a multimonth or even multiyear effort to tune the navigation filter. "We want to be able to—on the fly—switch out sensors that a navigation system has never seen before and be able to navigate off that sensor," says Haas. He adds that the program is fairly mature and is expected to demonstrate some initial capabilities in the next 6 to 12 months.

Lightning bolts are one potential signal of opportunity. Lightning strikes produce millisecond-long pulses of very-low-frequency waves (3–30 kHz) that travel for thousands of kilometers. Known as sferics, the signals can be geolocated using an array of receivers, Haas explains. There are several global receiver networks, such as the 800-sensor Earth Networks Total Lightning Network. Some insurance companies have been using the information gleaned from lightning strikes to help verify claims from storm damage, he notes. And the very-low-frequency signals may be detectable underground and underwater. Indeed, the US Navy has used those frequencies for submarine communications for decades.

The DARPA program in ultrafast laser science and engineering (PULSE) seeks to move beyond the microwave-based techniques that are used in GPS for distributing time and frequency information from a master clock. To employ the timing signals from the higher-accuracy optical clocks, PULSE researchers are developing techniques for producing femtosecond laser pulses from an optical frequency comb to implement free-space time and frequency transfer between distant timing sources, says Prem Kumar, a program manager in DARPA's defense sciences office.

A DARPA program known as STOIC (spatial, temporal, and orientation information in contested environments) is soliciting proposals, so agency officials say they can't discuss it. A 3 June funding opportunity announcement lists four technical areas of interest: robust reference signals, ultrastable tactical clocks, PNT using multifunctional systems, and adjunct technologies. The STOIC announcement says that although all current PNT technologies have weaknesses, the program seeks to overcome them.

Nondefense applications

Kitching says it's not possible to predict how the new PNT technologies will be used as the cost comes down enough that consumers can afford them. "What tends to happen with any sort of basic technology like clocks, gyros, and accelerometers is that as the performance gets better and size, power, cost, and reliability improve, new applications emerge that were not possible before the emergence of the technology. Eventually people will figure out a way to use these."

Kasevich envisions inexpensive cold-atom IMUs being used to guide autonomous vehicles. More whimsically, he suggests they could be stitched into baseballs to give TV sportscasters the ability to show how well a pitcher's curveball or slider performs.

David Kramer

New telescope in Turkey

The realization of a homegrown, bottom-up telescope is a source of national pride. The next challenge will be to grow a community to exploit it.

A 4-meter optical–IR telescope promises to catapult Turkey into astronomical modernity. The state-of-the-art Eastern Anatolia Observatory (DAG) is also intended to build up the country's strengths in engineering, data mining, analysis, and modeling. First light is slated for 2019.

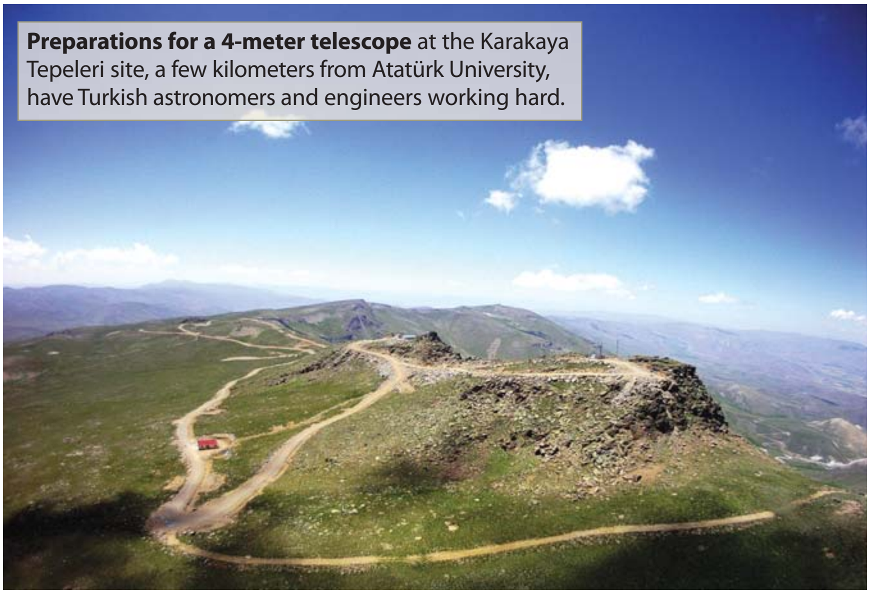
The idea for DAG originated with young Turkish astronomers who were frustrated with the light pollution and other limitations of the 1.5-m and smaller telescopes at the national observatory near the coastal city of Antalya in southern Turkey. Around the same time, in the late 2000s, Cahit Yesilyaprak, now principal investigator for DAG, was making observations of weather conditions outside Erzurum, a few hundred kilometers from Turkey's borders with Armenia and Iran. The conditions looked good for a telescope, and he and colleagues proposed to build "the biggest telescope in Turkey, from scratch," as project spokesman Sinan Kaan Yerli puts it. "We will switch from 1.5 meters to 4 meters, and from visible to IR." DAG will observe optical wavelengths (0.4–0.8 μm) and up to 2.5 μm in the near-IR. Says Yerli, "Engineering-wise, observation-wise, DAG will be a revolution for Turkey."

A no-nonsense workhorse

The government gave the green light for DAG in 2012. The tab is expected to exceed €20 million ($26 million); adaptive optics and instruments will be extra. DAG is being built atop a 3170-m-high plateau. Nearby Atatürk University is managing the observatory and will host a room from which the telescope can be remotely controlled. Eventually, a second operations location may be established elsewhere in Turkey, says Yerli, who is on the physics faculty at the Middle East Technical University in Ankara. About 80% of the civil infrastructure—roads, electricity, fiber optics, and the like—for DAG is in place.

A couple of decades ago, a 4-m telescope was large, but now it's "moderate," Yerli notes, and to get the best use of DAG, "it has to be done really quickly. There are a lot of satellites being launched. We can efficiently and effectively do follow-up observations." He adds that anything larger would have been unaffordable. Infrared astronomy is "a hot topic in science and is where we have a gap in wavelength" for observing, he says. "So the choice was 4 meters and near-IR."

Among the topics likely to be explored with DAG are exoplanets, transient objects, stellar evolution, galaxy formation and evolution, and galaxy clusters. Astronomers from anywhere will be able to apply for time on the telescope. And, says Yerli, the location should make it useful for working with other telescopes to follow interesting objects over time as Earth turns. "Telescopes in South Africa, Chile, and Aus-



Preparations for a 4-meter telescope at the Karakaya Tepeleri site, a few kilometers from Atatürk University, have Turkish astronomers and engineers working hard.

DAG/ATASAM