Benchmark

Case Study

Collaborative Development of a Chip-Sized Atomic Clock

Introduction

The Defense Advanced Research Project Agency (DARPA) has been proactive, sponsoring atomic-clock miniaturization exploration since 2005, coinciding with dynamically evolving use cases where accuracy and small form factors are critical in applications from munitions to naval navigation.

The engineering team at Benchmark in Rochester, Minnesota, working alongside our customer, played a crucial role in making this technology a reality. After a multi-year engagement, this highly collaborative effort has produced a chip-scale atomic clock for mass assembly. It's several times smaller, consumes less power, and costs less than previous devices.

The Challenge: Why Size Matters in Atomic Clocks

Many of today's communications, navigation, finance, cloud, and defense applications rely on the proven accuracy of atomic clocks.

In the past, harnessing the power of oscillating atoms for the precise timekeeping required racks of CPUs and expensive, sophisticated, and bulky technologies that consume massive amounts of energy. These atomic Big Bens are housed in scores of temperature-controlled buildings around the world, including the National Institute of Standards and Technology (NIST) atomic clock in Boulder, Colorado.

More modern atomic clocks also orbit the globe in satellites, providing vital reference signals that are essential to our unrelenting reliance on the Global Positioning System (GPS) in everything from driving to national defense.

Over time, however, researchers have discovered razor-thin inaccuracies and potential risks inherent to our current outsized and orbiting atomic clocks.

Power outages, fluctuating temperatures, jammed or off-orbit satellites can upend many of the activities most civilians take for granted. For national security, the result could be even more dire.

Further, emerging technologies—especially 5G networks and GPS alternatives—require even more precise timekeeping on much smaller, more portable platforms.

DARPA Dreams Small

Preparing for greater commercial and military demand, DARPA launched the chip-scale atomic clock (CSAC) program in 2005 to fund research and development jam-resistant CSACs, 100x smaller, consume 50x less power and offer impressive timing stability for their size, weight, and power (SWaP).

This first-gen technology is now commercially available, but limitations persist due to the physics of the designs. Calibration requirements and frequency drift can generate timing errors, threatening accuracy, and reliability. So, in 2016, the agency asked engineers to dream even smaller. The Atomic Clock with Enhanced Stability (ACES) project explored next-generation development of even more miniaturized, battery-powered atomic clocks with proven stability, repeatability, and environmental sensitivity.

All modern communications, navigation, and electronic warfare systems, as well as intelligence, surveillance, and reconnaissance systems, depend on accurate timekeeping, an ACES program manager noted at the program launch. “If successful, virtually every Defense Department system will benefit.”

The Solution: Unconventional Forms Require Creative Manufacturing Processes

In 2011, between the launches of the CSAC and ACES projects, a Benchmark customer best known for its success in the semiconductor industry took on DARPA’s challenge and engaged our Rochester facility for expertise in MEMS technology and microfabrication.

“It started with neither of us knowing how we would make the clock, but both believing it was possible,” recalled senior engineer Greg Christner. “We ended up in a multi-year collaboration of back-and-forth ideas, progress, and prototypes.”

Together, they explored novel fabrication techniques and operational methodologies, using standard machinery to create uniquely nonstandard results. Commercial equipment was adapted for new uses to meet the dynamic needs of the project, including a bare die machine, ball bonding machine, and an ultrasonic gang bonder.

The initial, broad-view concept featured a solder hierarchy. But that changed over the first three concepts, each getting closer to a shared vision to improve inertial sensor precision, dynamic range, and long-term accuracy while reducing size, weight, and power consumption. Each round of prototyping brought the team closer to an improved solution where bumps and gold bonding replaced solder.

Although cesium atoms have been the mainstay in atomic clocks for decades, miniaturization lends itself to the use of rubidium, a simpler and more compact element. Unfortunately, it also burns spontaneously in the atmosphere. Benchmark’s customer had the idea of sealing the rubidium in a cell and communicated the requirements—including controlling the amount of rubidium and ensuring that no air came in contact with the substance during the manufacturing process — to the Benchmark team. Benchmark’s engineers devised a means to add a minuscule amount of rubidium into a clear glass pocket and vacuum-seal it, absent of oxygen—which “basically took brute force and ingenuity,” said Christner.

And exact calculations. The team was rethinking decades-old standards and methodologies to come up with new hyper-miniaturized solutions.

“Shrinking atomic clocks from large cesium beam tubes to chip-scale devices without eroding performance requires a rethinking of several critical components, including vacuum pumps and optical isolators, as well as new approaches to component integration,” noted Dr. John Burke, ACES program manager. For instance, in microelectronics, almost everything one works on is flat, Christner pointed out. But Benchmark’s customer had devised a part that was tipped, which was necessary for the design, but a problem for system integration. The Benchmark team devised what equated to a tiny suction cup as the solution. In addition, the Benchmark team had to develop a way to manufacture the customer’s unique MEMS “scaffolding” with traditional microelectronics equipment to enable the miniaturized solution.

“It’s the little challenges and solutions like this that makes us an easy partner to work with,” Christner said.

The Result: Precision Timekeeping at a Fraction of the Size

After years of iterations, the “team of teams” finally arrived at a design that could be manufactured at a reasonable cost. These highly reliable, uniquely designed functional atomic clocks are now ready for manufacture.

The physics package, designed to be 1 cm^3, contains the base detector for measuring time. It has a light source, VCSEL, a quarter-wave plate, rubidium cell and photodetector plus support components, heaters, and a coil for a magnetic field.

“Working at chip scale, or the scale of a bare die ranging from 100 um to several centimeters,” Christner explained, “our solution comes in at about the size of a deck of cards.”

The ebb-and-flow of ideas blurred all lines between the two teams as they worked and re-worked concepts, making this a true partnership rather than a customer-vendor relationship. The partnership between the innovative design engineers on the customer’s team and Benchmark’s had to be as air-tight as the rubidium cell. Unsurprisingly, the customer has tapped Benchmark for more projects.

“It’s all about how we focus on customer relations and collaboration,” Christner concluded. “Technical expertise is essential, of course. And new equipment is fun to use. But at the core, our job is to make sure we’re aligned with our customer’s expectations.

“In this project, we were totally in sync.”

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