DSIAC TECHNICAL INQUIRY (TI) RESPONSE REPORT

Atomic Clocks for Use in Special Operations Forces Aircraft Platforms

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ABOUT DSIAC

The Defense Systems Information Analysis Center (DSIAC) is a U.S. Department of Defense information analysis center sponsored by the Defense Technical Information Center. DSIAC is operated by SURVICE Engineering Company under contract FA8075-14-D-0001.

DSIAC serves as the national clearinghouse for worldwide scientific and technical information for weapon systems; survivability and vulnerability; reliability, maintainability, quality, supportability, and interoperability; advanced materials; military sensing; autonomous systems; energetics; directed energy; and non-lethal weapons. We collect, analyze, synthesize, and disseminate related technical information and data for each of these focus areas.

A chief service of DSIAC is free technical inquiry (TI) research, limited to 4 research hours per inquiry. This TI response report summarizes the research findings of one such inquiry. For more information about DSIAC and our TI service, please visit www.DSIAC.org.

ABSTRACT

The Defense Systems Information Analysis Center (DSIAC) was asked to identify and locate candidate atomic clock systems to be used by special operations forces for use in global positioning system-denied and other denied environments. The inquirer specified that the technology should be in a relatively small, weight, power, and cost package. DSIAC staff searched open sources for relevant information. A request for information was also sent to the Defense Advanced Research Projects Agency Microsystems Technology Office Program Officer, the National Institute of Standards and Technology, and the United States Naval Observatory. DSIAC's response report that was delivered to the inquirer included a list of candidate technologies and associated manufacturers, and a summary of relevant organizations and references for further research.

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1.0 TI Request

1.1 INQUIRY

What commercial off-the-shelf or government off-the-shelf atomic clocks are available for aircraft platforms in global positioning system (GPS)-denied locations?

1.2 DESCRIPTION

The inquirer requested information on atomic clocks to be used for precision navigation and timing (PNT) in GPS-degraded/denied environments. The clocks needed to be in a relatively small size, weight, power, and cost (SWaP-C) package.

2.0 TI Response

The Defense Systems Information Analysis Center (DSIAC) staff searched open source databases and contacted key organizations performing research and development (R&D) in atomic clocks to provide relevant information to the inquirer. DSIAC compiled key technologies and descriptions of research programs and organizations relevant to the inquiry topic.

2.1 KEY TECHNOLOGIES

In GPS-degraded/denied environments, aircraft must rely on legacy navigation techniques such as direct reckoning or radio beacons, or more advanced navigation aids such as offboard area navigation sensors or on-board inertial navigation equipment. These legacy methods do not provide the required accuracy and precision to conduct military operations, and they are not suitable options in degraded visual environments or noncooperative/nonpermissive environments. Even the latest technologies in on-board inertial measurement equipment (e.g., inertial measurement units [IMUs] containing ring-laser gyroscopes [RLGs] or fiber-optic gyroscopes [FOGs]) must have a highly accurate and precise timing source to meet today's demanding PNT requirements for mission operations. Legacy timing sources (e.g., quartz crystal-oscillators) cannot meet these PNT requirements.

However, for decades, cesium- and rubidium-based atomic clocks have provided the desired timing accuracy and precision, but at a substantial SWaP-C. This situation changed in the 2000s, with the development of chip-scale atomic timing devices by the National Institute of Standards and Technology (NIST) and the Defense Advanced Research Projects Agency (DARPA). These devices are now commercially available in ruggedized packages suitable for industrial and military use at a relatively low cost of approximately $1,000 or less per unit [1–3].

2.1.1 Chip-Scale Atomic Clocks (CSACs)

NIST continually works to improve atomic clock stability and precision to support modeling and simulation, as evidenced by their CSACs. NIST's more recent efforts on their CSACs appear to fit the inquirer's specifications. Optical atomic clocks, like the CSAC, run at higher optical frequencies and offer increased precision because they divide time into smaller units and have a high "quality factor," which reflects how long the atoms can tick on their own without outside help. The chip-based heart of this new clock requires 275 mW and may eventually be small enough to be handheld [4].

The CSAC's instability is about 1,000 times better than that of the chip-scale microwave clock, and it uses rubidium atoms ticking at an optical frequency in the terahertz (THz) band. Ticking is used to stabilize a clock laser, which is converted to a gigahertz (GHz) microwave clock signal; this is then used to stabilize to the rubidium's THz vibrations [4].

NIST-on-a-Chip is a DARPA-funded program in which NIST researchers are aiming to increase the stability of CSACs by experimenting with laser-cooled cesium atoms in a high vacuum to eliminate the need for buffer gas as was needed in previous CSAC models [5].

2.1.2 Atom Optic Sensors

AOSense's atom optic sensors can be used to develop cold (laser-cooled) atom-based gyroscopes and inertial sensors that have significantly better bias (degrees/hour) and scale-factor (parts per million) stability than RLG- or FOG-based IMUs. For instance, a cluster of atom interferometer gyroscopes and accelerometers can be used to produce a high-accuracy, navigation-grade IMU with a less than 100-m/hour drift; in comparison, an atom interferometer sensor cluster with gravity compensation can be used to produce an IMU with a less than 5-m/hour drift. NIST has also demonstrated a compact atomic gyroscope design that could lead to highly accurate, portable, low-power gyroscopes suitable for future PNT mission requirements [6, 7].

Technology using cold-atom interferometry for inertial navigation may also be suitable. IMUs using cold interferometry for high-precision navigation without dependence on external fixes for long periods of time are being developed by DARPA's Micro-PNT program and AOSense. The goals of the effort are to shrink the SWaP-C of IMU technology and develop microelectromechanical systems (MEMS) manufacturing techniques that can be combined to produce microscale IMUs at a cost that is roughly equal to today's integrated circuits [8, 9].

2.2 MANUFACTURERS

The Microsemi Corporation, Jackson Labs Technologies, AOSense, SBG Systems, and VectorNav are producing and developing CSACs, atom optic sensors, and other alternative technologies.

DSIAC has identified and summarized the technologies produced by these companies that are relevant to the inquiry.

2.2.1 Microsemi Corporation

The Microsemi produces several CSACs, including the SA.45s and the Low Noise CSAC (LN-CSAC). The small size, low power consumption, fast warm-up, superior stability, and spectral purity make these devices ideal for critical aerospace applications in harsh environments [10, 11].

The Microsemi SA.45s CSAC, as shown in Figure 1, has a very small SWaP and a volume of 17 cm^3, and it weighs 35 grams (g) and consumes less than 120 mW. The portability of this CSAC enables its use for various military systems, including improvised explosive device jammers, dismounted radios, GPS receivers, and unmanned aerial vehicles [10].

The Microsemi LN-CSAC, as shown in Figure 2, acts as a frequency and timing subsystem, with a small SWaP; the LN-CSAC has a volume of 46 cm^3 and consumes less than 295 mW [11].

Figure 1: Microsemi SA.45s CSAC [10].

Figure 2: Microsemi LN-CSAC [11].

As identified in "A Second Look at Chip Scale Atomic Clocks for Long Term Precision Timing" by A. T. Gardner and J. A. Collins, the performances of several CSACs manufactured by Microsemi were compared for use in ocean bottom seismographs. Details and findings identified in the report on the various CSAC performances may be also be useful for special operations forces (SOF) aircraft [12].

Microsemi also produces other Miniature Atomic Clocks (MACs), including the SA.31m, SA.33m, and the SA.35m (Figure 3). These rubidium MACs are cost effective and can easily adapt to a variety of timing and synchronization applications. They require little power, can operate across a wide spectrum of temperatures, and have a 2-inch × 2-inch × >1-inch compact design that is five times smaller than existing rubidium oscillators [13].

Figure 3: Microsemi SA.35m MAC [13].

Microsemi recently acquired Vectron's precision timing products to manufacture ruggedized embedded atomic clocks with cesium, rubidium, and quartz oscillators that meet or exceed the complex, high-reliability requirements for frequency references in the space, defense, and avionics markets. Microsemi also offers custom design services for specific feature requirements [14].

2.2.2 Jackson Labs Technologies, Inc.

Jackson Labs offers the CSAC GPS disciplined oscillator (GPSDO), which has been integrated with Microsemi's SA.45s CSAC. The GPSDO module allows a cesium vapor cell atomic reference oscillator to be produced in a small package, with more than an order of magnitude in power reduction, outperforming many industry-standard atomic oscillators [15]. Shortly after the release of the GPSDO, Jackson Labs developed the Selective Availability Anti-Spoofing Module (SAASM) HD GPSDO (Figure 4), which was optimized to provide a highly accurate position, velocity, time, and frequency reference under extreme environments; they are used in aircraft, tracked- and wheeled-vehicles, and man-packs [16].

Figure 4: SAASM HD CSAC GPSDO [16].

2.2.3 AOSense

AOSense developed a small, atom-based, high-bandwidth gyroscope as part of the DARPA Precision Inertial Navigation System effort for the High Dynamic Range Atom Sensors (HiDRA) program. One of the HiDRA program's goals was to extend sensor operation to demanding real-world platforms [17].

2.2.4 SBG Systems

SBG Systems offers an ultra-small IMU, the Ellipse 2 Micro (Figure 5), which is advertised as having the highest accuracy in the smallest and most economic package. It embeds three gyroscopes, three accelerometers, and a temperature sensor [18].

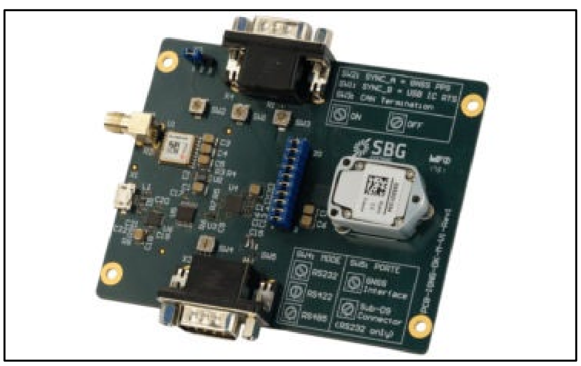

Figure 5: Ellipse 2 Micro IMU [18].

2.2.5 VectorNav Technologies

VectorNav offers the VN-100 IMU/Attitude Heading Reference System (AHRS) in either a surface-mount (Figure 6) or rugged package (Figure 7). It is a high-performing IMU and AHRS incorporating the latest MEMS sensor technology. The VN-100 combines three-axis accelerometers, three-axis gyroscopes, three-axis magnetometers, a barometric pressure sensor, and a 32-bit processor [19].

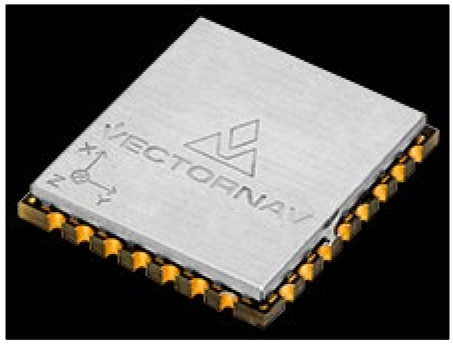

Figure 6: VN-100 Surface Mount Device (SMD) [19].

Figure 7: VN-100 Rugged [19].

2.3 ORGANIZATIONS COMPLETING R&D

There are multiple organizations performing R&D in atomic clocks and other, similar options:

- NIST Time and Frequency Division.
- DARPA.
- U.S. Naval Observatory (USNO).
- Massachusetts Institute of Technology (MIT) Department of Electrical Engineering and Computer Science (EECS).
- U.S. Army.
- Aurora Flight Sciences.

2.3.1 NIST

There are multiple atomic clock research efforts ongoing at NIST. Experimental atomic clocks at NIST have achieved three new performance records allowing detection of faint signals from gravity and perhaps even dark matter [20]. This new atomic clock is so precise it won't gain or lose more than 1 second in 14 billion years, with an extremely stable ticking rate [21]. Many of the improvements in this latest research is due to a new heat shield to protect the clock from the effects of heat and electric fields.

2.3.2 DARPA

DARPA is pursuing the following projects that are relevant to atomic clocks [22–25]:

- The Spatial, Temporal and Orientation Information in Contested Environments (STOIC).
  - The STOIC program aims to develop GPS and PNT alternatives. Specifically, is it developing PNT systems that prove GPS-independent PNT with GPS-level timing in a contested environment.
- Atomic Clocks with Enhanced Stability (ACES).
  - The ACES program applies modern physics techniques to develop a battery-powered atomic clock with 1000X-improved performance over prior CSACs.
- CSAC.
- Micro-PNT.
  - The Micro-PNT program aims to develop high-performance, miniature, inertial sensors to enable self-contained inertial navigation in harsh environments relevant to military needs.
- Adaptable Navigation Systems.
- Program in Ultrafast Laser Science and Engineering (PULSE).
  - The PULSE program applies the latest laser technology to significantly improve the precision and size of atomic clocks.
- Quantum-Assisted Sensing and Readout (QuASAR).
  - The QuASAR program aims to develop optimal atomic clocks with a timing error of less than 1 second in 5 billion years.
- Chip-Scale Combinatorial Atomic Navigator (C-SCAN).
  - The C-SCAN program aims to develop advanced gyroscopes and accelerometers based on modern atomic physics.
- Direct On-Chip Digital Optical Synthesis (DODOS).
  - The DODOS program aims to control optical frequency and wavelength with the accuracy of electronics.
- Advanced Inertial Micro Systems (AIMS).
  - The AIMS program explores future inertial sensors based on novel architectures of photonics, MEMS, and photonic MEMS.
- High Dynamic Range Atomic Magnetic Gradiometer (HDRAMG).
  - The HDRAMG program aims to develop 1000X-improved magnetic sensing outside of shielded environments.

2.3.3 USNO

The USNO GPS/Global Navigation Satellite System Timing Operations and Time Transfer Division has been exploring alternatives to GPS navigation and timing regarding atomic clocks [26].

2.3.4 MIT EECS

Researchers at MIT have developed the first molecular clock on a chip, which may significantly improve the accuracy and performance of navigation on smartphones and other consumer devices. MIT worked with Terahertz Integrated Electronics Group, part of MIT's Microsystems Technology Laboratories, to develop the chip-scale molecular clock to be used for more efficient time-keeping in operations that need a precise location but involve little to no GPS signal [27].

2.3.5 U.S. Army

The following divisions and programs associated with the U.S. Army are performing research related to atomic clocks [28]:

- Communications-Electronics Research, Development and Engineering Center PNT Division.
- U.S. Army Manufacturing Technology (ManTech) program.
    - The ManTech program works under the Deputy Assistant Secretary of the Army for Research and Technology.

2.3.6 Aurora Flight Sciences

Aurora Flight Sciences launched the Synchronized Position Hold Engage Re-Orient Experimental Satellites (SPHERES) program in collaboration with MIT Space Systems Laboratory. This program allows researchers on the ground to test control algorithms in the microgravity environment of space, while testing the battery-powered, cold gas propulsion systems and onboard communications and navigation equipment which constitute the SPHERES system. The SPHERES program was designed to demonstrate the CSAC performance in a relevant space microgravity environment to make the CSAC a viable candidate for application in micro- and nanosatellites [29].

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