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# Robust Technology to Augment or Replace the US Reliance on the Global Positioning System

by

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## Disclaimer

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## Biography

Lieutenant Colonel Suriano is currently a student at the Air War College, Maxwell AFB, AL. Prior to the College he served as the Commander of the 510th and 511th ICBM Systems Squadron of the 526 ICBM Systems Group, Hill AFB, UT. He is a science, engineering, and acquisition professional who has served at research laboratories, system program offices, and Joint organizations. He has worked on a variety of nuclear issues from power, propulsion, weapons, proliferation, and treaty monitoring as well as directed energy systems and highly classified weapons programs. Lieutenant Colonel Suriano has a Bachelor and Masters Degree in Nuclear Engineering and a Doctorate in Nuclear Physics/Nuclear Weapons Effects. He is also a graduate of the Joint Forces Staff College and the Defense Systems Management College's Advanced Program Manager Course.

## Introduction

Precision has become an all important force multiplier in the employment of US forces, and this employment has become routine. Precision has allowed US forces, specifically Air and Space forces, to provide global capabilities across the spectrum between lethal and non-lethal engagements. The inherent flexibility and versatility of air and space power allows the exploitation of mass and maneuver through synchronization of action. Mass is one of the foundations of US Joint warfighting capabilities allowing US forces the ability choose the time and place to concentrate effects against an adversary. Additionally, maneuver places the adversary at a disadvantage to the Joint force capabilities. The advent of the Global Positioning System (GPS) provided a monumental leap in precision for US and allied forces providing data for very accurate position, navigation, and timing (PNT). The use of this data has allowed precision employment and synchronization across the forces from personnel, land vehicles, ships, aircraft, missiles, and weaponry. The reliance on GPS data has proved a force enabler; however, this reliance has concurrently generated a vulnerability creating substantial risk[1]. Adversaries look to offset the US advantage and disrupt operations by spoofing GPS signals. Operational forces have grown dependent on GPS data, so this data loss would prove to be a huge impediment in the nominal execution forces train to with tactics, techniques, and procedures. With the heavy reliance on GPS and the growing threat to GPS data by potential adversaries, the US must look to augment, strengthen, or replace GPS data for force employment.

The US must continually adapt to rising threats, across a broad spectrum that aims to deny the use of GPS. There are many paths to pursue, and one such path can lead to an inherently

[1] Scott Pace et al., *The Global Positioning System: Assessing National Policies*, RAND Report MR-614-OSTP, RAND Corporation, 25 Jan 1996, pp XVI – XVIII.

non-corruptible system to augment and eventually replace GPS. This requires a concerted investment by the US to develop and field a replacement technology. Recently the research and development community demonstrated a new technology that is impervious to jamming or spoofing. This new technology, properly funded and guided, will enable US and allied nations to regain the asymmetric advantage of precision.

The US has built upon the ability of the GPS constellation to provide reliable and accurate PNT data for platforms, weapons, and forces. Users do not really bother themselves with the requirement that their receiver acquire a minimum of four satellites in the constellation to resolve the timing distances of the radio signals. Nor do they realize each GPS satellite has an atomic clock providing a precise time standard accurate to about 50 ns ($50x10^{-9}$ sec) relative to the US Naval Observatory master clock[2]. What they do care about is the geo-location of their system with the GPS constellation.

The benefits of GPS have proved themselves over the years. Prior to GPS, air and sea crafts used inertial navigation systems (INS) to provided all weather self-contained, i.e., on-board, system to determine position, speed, and altitude. The gyroscopes and accelerometers of the INS allowed for automatic navigation and rapid response to their host platform. This required the system to integrate gyroscopic and accelerometer data. INS systems are accurate for short times, but their accuracy degrades over time through the accumulation of system and instrument errors. Augmenting the rapid response of a platform's INS with GPS data provides continuous update of the INS. These GPS/INS systems can tolerate short interval GPS drop outs until the system reacquires GPS and reset the INS[3]. Current US platforms use GPS/INS for accurate PNT, but it is not ideal due to the open vulnerabilities the GPS receiver has to spoofing and jamming. The

[2] Data from USNO, General GPS Time Transfer Information, http://www.usno.navy.mil/USNO/time/gps/usno-gps-timing-data-and-information.

[3] Lawrence, Anthony, *Modern Inertial Technology: Navigation, Guidance, and Control*, pp 4 – 23.

ultimate INS would be self-contained and inherently accurate with little to no need of any external input for corrections. Elimination of the need for GPS data removes the key vulnerability of GPS/INSs, a critical requirement for future systems.

Future inertial systems will require the US to augment or replace GPS, and one of these future solutions is in its infancy and just as revolutionary as GPS. This new technology operates on the same basic principles as current inertial platforms through measuring and resolving rotations and accelerations. The key difference is on how the technology determines these forces. Normal mechanical accelerometers and gyroscopes measure the inertial or rotational force of a mass as it responds to external stimulus, i.e., movement of the host platform. Like laser based instruments, this new technology does not require a bulk mass. It obtains its measurements by resolving how the external stimulus changes the momentum of atoms in an atomic vapor. Precision comes from the sensitivity at the atomic level through quantum mechanics rather than the differential radio signals from satellites in a constellation. As farfetched as it might seem, this technology has already proven itself in the laboratory, and is ripe for development towards operational systems. It is "Cold Atom" technologies.

## Cold Atom Technology

Tremendous progress in physics has occurred over the last twenty years revolving around quantum theory and its applications. A key innovation was the ability to cool the atoms of a diluted gas down to a millionth of a degree Kelvin (i.e., $10^{-6}$ ºK or μK)[4]. The resultant population of "cold atoms" allows scientists to gain a deeper understanding of the quantum-physical behavior at the atomic level. The system formed by the cold atoms allows for

[4] The Kelvin scale is an absolute temperature scale where ºC=ºK-273.15. The lowest temperature is 0 ºK, or absolute zero. This a theoretical limit where all thermal motion ceases, and the system possess a zero-point quantum mechanical energy.

macroscopic measurement of quantum phenomena. A significant benefit to measuring atoms is the ability to exploit their quantum nature. Because the atomic quantum nature is invariant to time, it is inherently stable. Additionally, extremely sensitive instruments are capable using the cold atom de Broglie wavelength[5] to probe the atoms. These atomic matter systems are more sensitive, but they do not have the high particle flux found in laser systems. Nevertheless, the ability to measure with the de Broglie wavelength enables a system capable of identifying and conducting very sensitive measurements[6]. The cold atom community is just beginning to develop a variety of instruments for application outside of a laboratory environment that are over a factor of 10 better than laser based systems used in INS system today.

Quantum mechanics and thermal statistical physics form the basis of cold atom science. The molecules of air at standard temperature and pressure[7] are very active, and move at an average speed of approximately 4000 km/hr as described by the Maxwell-Boltzmann distribution. By cooling the gas sufficiently, it is possible to reach a state where the particles coalesce into a single "puddle" where the atoms are indistinguishable from each other and quantum effects dominate. At very low temperatures the spacing between individual particles is less than or equal to the de Broglie wavelength[8]. The system needs to cool in such a way as to avoid the gases freezing to form a solid. The gases will only condense into a liquid if they are

[5] The de Broglie wavelength is inversely proportional to the particle's momentum. A de Broglie wave is a wave of matter in quantum mechanics, and it has an associated de Broglie wavelength. These atomic wavelengths are typically $10^{10}$ – $10^{11}$ times smaller than typical wavelengths found in laser based systems.

[6] T.L. Gustavson, P. Bouyer, and M. A. Kasevich, "Precision Rotation Measurements with an Atom Interferometer Gyroscope", Phys Rev Letters, Vol 78, No 11, 17 Mar 1997.

[7] Standard Temperature and Pressure (STP) is a condition allowing comparison to experimental results. The National Institute of Standards and Technology defines STP by 1 atmosphere [atm] at 20 ºC. The International Union of Pure and Applied Chemistry (IUPAC) defines STP by 0.986 atm at 0 ºC.

[8] This quantum concentration occurs when the thermal de Broglie wavelength is greater than or equal to the cube root of the volume of the gas divided by the number of particles.

cooled in a high vacuum between $10^{-7} – 10^{-9}$ torr[9]. Performing this operation on free hydrogen reduces the speed to less than 1 km/hr (25 cm/s) at 1 µK.

Cooling the gas to extremely low temperatures to a liquid state is essential to enable the next transition where the quantum nature of the particles begins to dominate. As the gases cool, they lose energy and begin to settle into their lowest energy state. As the atomic spacing approaches the thermal de Broglie wavelength, the atoms begin to "sense" their neighbors as quantum mechanical objects. Macroscopic measurements of the atomic population are possible, once a large fraction of the atoms are in their lowest quantum state, resolving the individual quantum effects. The condensed gases will behave with a single wavelength identity with an associated quantum phase[10, 11]. Tuned lasers exploit the cold atoms by coherently creating a superposition of two atomic states. The quantum mechanical nature of the atoms dictates the probing and measurement of the homogeneous population of cold atoms. Data from the cold atoms comes about through the interference of atomic wave packets.

The initial step for a cold atom system requires creating, cooling, and confining an atomic population. Once the system is stable and at vacuum, a reservoir generates a stream of source atoms to begin the process. The atomic cloud condenses to a liquid or optical molasses, nominally $10^6 – 10^9$ atoms, and is contained in a magnetic optical trap for subsequent use[12].

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[9] The torr is a unit of pressure equal to 760 mmHg or 1 atm. At 1 atm (760 torr) there is approximately $10^{20}$ molecules per $cm^3$. Between $10^{-7} – 10^{-9}$ torr there will be $10^9 – 10^7$ molecules per $cm^3$, respectively. Pressure in outer space ranges from $1x10^{-6} – 1x10^{-17}$ torr. The pressure within the Earth's thermosphere, 100 – 690 km above the Earth, ranges between $1x10^{-2} – 3x10^{-9}$ torr.

[10] The quantum phase of an object is a set of numbers that fully define the system. It is a mathematical construct enabling the ability to investigate the quantum behavior through the probability distribution of the system's wave function.

[11] Steve Miller, *Cold Atom Lab 2005-2007 Update*, pg 1.

[12] Royal Swedish Academy of Sciences, *Additional Background Material on the Nobel Prize in Physics 1997*.

## Cold Atom Applications

The advent of stable cold atom populations was clearly a boon to the scientific community. Scientists also realized they could make systems using de Broglie waves of atoms to conduct very sensitive and accurate measurements with applications extending well beyond basic science[13]. One use for the optical molasses is to form an atomic clock for precision timekeeping. An additional use is the construction of an ultra precise atomic interferometer based upon the de Broglie wavelength[14, 15]. Using interferometric techniques, the cold atoms can measure the acceleration of gravity, linear acceleration associated with motion, and rotation. It is through this capability of atom interferometery where the cold atom technology would comprise the main mechanism for a revolutionary and highly accurate INS.

Interferometery is a standard measurement and diagnostic technique to probe properties of two or more waves. When waves of the same frequency combine they interact through superposition, and the resulting new wave generates an interference pattern based upon the phase differences. This is akin to waves generated from a stone thrown in a pond where the water waves reflect upon a surface. The reflected waves interact with the incoming waves through superposition. When the waves are in phase, they will interfere constructively; however, the pattern is destructive when the waves are out of phase. The resulting interference pattern contains the data for the measurement.

Optical interferometers determine accelerations and rotations relative to their host platform. The basic setup has a beam light split by a beam splitter (Figure 1). The two identical beams travel along two separate paths ($L_1$ and $L_2$) only to recombine at the end in a loop. The resulting interference of the two beams can be detected ($D_1$ and/or $D_2$) to provide a measurement of the

[13] Bordé Ch. J., “Atomic Interferometry with Internal State Labeling”, pp. 10-12.

[14] Royal Swedish Academy of Sciences, *Additional Background Material on the Nobel Prize in Physics* 1997.

[15] C. J. Bordé, “Atomic Clocks and Inertial Sensors”, pp. 435 – 463.

path length difference traveled by each path.  The path lengths will begin to differ as the device rotates in the plane of the beams.  This causes a phase shift, measureable by the interference pattern, directly proportional to the rotation rate.  The sensitivity of the interferometer is proportional to the area enclosed by the loop of light.

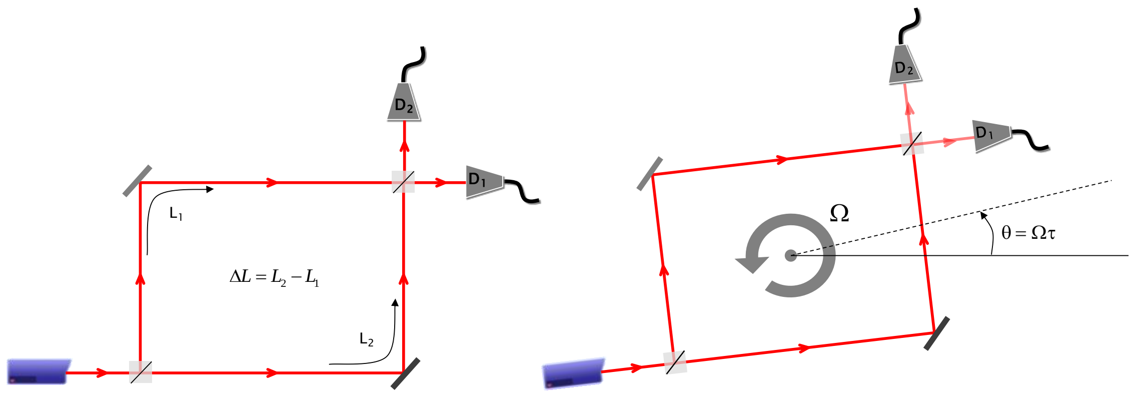


Figure 1:  Basic set-up of an optical interferometer to measure rotation[16].

An atomic interferometer operates along the exact same principle as an optical system, but it uses cold atoms instead of light.  There are no "mirrors" per se in the interferometer loop.  Tuned laser light acts as the loop mirrors to divide, deflect, and recombine the atomic stream to a detector to observe and make the interference measurements (Figure 2).  Atomic systems will not have the high particle fluxes and loop areas of optical systems.  This reduces some of the sensitivity of the interferometer, but they are still more sensitive than optical systems due to the use of the de Broglie wavelength[17].  What helps is that there is a large population of atoms at nearly the same identical state with very little variation, and it is this that makes this a viable technology for an ultra-precise INS.

[16] Figures from Dr Jamil Abo-Shaeer, DARPA/DSO.
[17] T.L. Gustavson, P. Bouyer, and M. A. Kasevich, "Precision Rotation Measurements with an Atomic Interferometer Gyroscope", pp. 2046 – 2049.

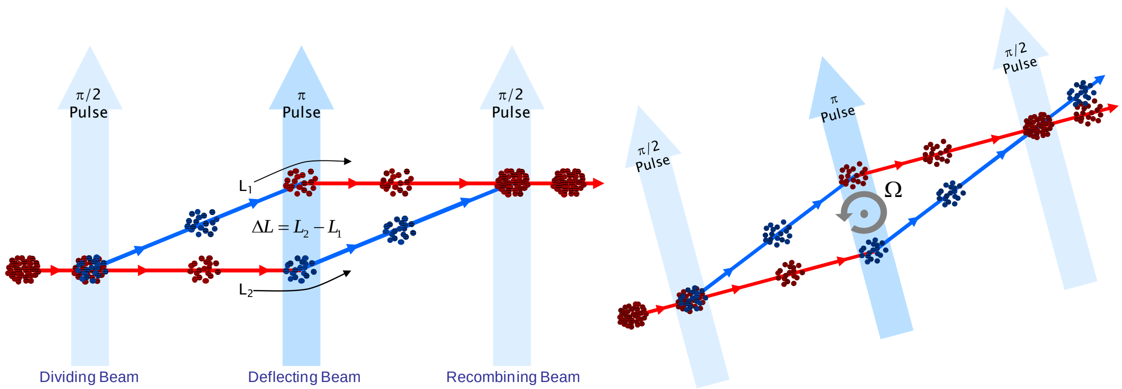


Figure 2: Basic principle of an atomic interferometer to measure rotation[18].

There are other aspects to the cold atom technology aside from their sensitivity and precision. The atom is in a near perfect inertial reference frame[19] where there will not be any spurious forces to degrade the measurement. This measurement is between the relative motion of the atoms (de Broglie waves) and the sensor case. As such, the measurements are uncorruptable through external measures, i.e., jamming. This opens up a vast possibility for the DoD to create very precise, stable, and accurate systems that an adversary will not be able to jam or spoof.

There are many applications using the cold atom technology for DoD. The ability to use the atoms for timing and accelerations make this an ideal construction for an inertial measurement unit (IMU) for an INS. A robust and accurate system using current technology requires compensation for the local effects of gravity or it must rely on a gravity map to adjust for the variance in gravity over the globe. A cold atom system would be robust and able to measure the local gravity and make corrections to the INS in real-time with more accuracy. Additionally, the sensitivity to measure the local gravity gradient allows a system to probe for anomalies. Such anomalies would occur with underground structures, facilities, or items (e.g., mines). This could

[18] Figures from Dr Jamil Abo-Shaeer, DARPA/DSO.
[19] An inertial reference frame describes a coordinate set that is invariant in space and time. The inertial frame is not accelerating with respect to the coordinate axes, and can be converted to a new frame through a mathematical transformation.

be a very useful tool to find, identify, and map underground structures for both manned and unmanned DoD mission areas for systems of all sizes. This additional capability provides a unique side benefit; but the main interest in the near-term is the development of the cold atom technologies for a highly accurate, autonomous, jam proof navigation system.

## Current Cold Atom Technology Readiness

There fortunately has been significant progress in cold atom technologies since its inception. The first systems were very large, and required a great deal of power and significant diagnostic equipment. This was required in the early stages of cold atom science, while scientists were trying to confirm the basic theory. Systems began to get smaller as the methodology and practice of generating and manipulating an optical molasses became more commonplace. Systems went from using multiple optical tables, usually 6'x20', within a laboratory down to only a portion of a single table[20]. Cold atom research occurs primarily at universities, government laboratories, or through a government-sponsored program. The majority of the work exists in the research and development phase at a Technology Readiness Level (TRL) of 3[21].

The most mature cold atom technology exists at a program run by the Defense Advanced Projects Agency (DARPA). The Precision Inertial Navigation System (PINS) had demonstrated a cold atom system measuring a rotation and acceleration on a single axis at TRL 5. The program has been successful in a laboratory demonstration system that has operated for over a year. This demonstration system measured a drift rate of less than 5 m/hr[22], and this rate is much less than the 1400 m/hr drift rate on current high-performance GPS/INS systems[23] by a factor of

[20] Dr Steven Miller, AFRL/RVBYM, interviewed by the author, 4 Oct 2010.
[21] TRL 3 consists of analytical and experimental critical function and/or characteristic proof of concept. DoD Technology Readiness Assessment, Jul 2009. See Apendix I for further clarifying information.
[22] Dr Jamil Abo-Shaeer, DARPA/DSO, interviewed by the author, 25 Oct 2010.
[23] DARPA PINS-HiDRA New Start brief (pre-decisional), 2009. Compares PINS-HiDRA to the Northrop-Grumman LN-250 and Honeywell HG9900.

280[24, 25]. The success of the PINS program has led to the PINS High Dynamic Range Atomic (HiDRA) sensor program. The first phase of the PINS-HiDRA plans to demonstrate a cold atom sensor cube measuring acceleration and rotation on each of the cardinal axes x, y, and z by the end of 2011. This first phase program goal shrinks the sensor to a size comparable to current high-performance aircraft IMUs at less than 8 L of volume; on the order of 10”x10”x5” with a drift rate of 20 m/hr. The associated system electronics would be contained in a separate equipment rack. The next program phase would incorporate the sensor and electronics into a form factor suitable to test on an airframe meeting the size, weight, and power constraints. If successful, the PINS-HiDRA program will achieve TRL 6 or 7 by the end of 2014[26], and be ready for a program of record.

A parallel cold atom effort is underway by the Air Force Research Laboratory Space Vehicles Directorate (AFRL/RV) at Hanscom AFB. This effort is less mature than DARPA’s PINS-HiDRA program. AFRL is working to build compact low power devices on a microchip to perform atom interferometery. AFRL is making steady progress, and has on-going efforts on theoretical understanding, microchip design, modeling, experimentation, and confirmation. Presently at TRL 3, program success could lead towards cold atom IMUs on small satellites and munitions which is a critical step to meet future Air Force future requirements.

Much work remains to operationalize either cold atom approach. A cold atom INS will have to fit initially into a legacy system or platform. This means there will be very stringent requirements on the size, weight, and power the INS can have, as well as requirements on the thermal and vibrational environment. The system will also have to demonstrate an increase in performance at a reduced life cycle cost or remove a key system vulnerability to make it

[24] Dr Steven Miller, AFRL/RVBYM, interviewed by the author, 4 Oct 2010.
[25] Dr Steven Miller, “Point Paper – Cold Atom Inertial Measurement Unit for GPS Contested Environment.”
[26] Dr Jamil Abo-Shaeer, DARPA/DSO, interviewed by the author, 2 Nov 2010.

palatable within DoD's fiscally constrained outlook. These constraints may pose some very stringent engineering hurdles prior to consideration for full development.

Both DARPA and AFRL are looking to improve their systems while reducing the system size, weight, and power. Investment in vacuum technologies, laser diodes, electronic controls, heat removal/control, and mirrors are necessary for success[27, 28]. These areas will help reduce the INS to meet the needed size, weight, and power requirements. The first investment is associated with the cold atom system operating over a high dynamic range outside of a vibrationally isolated optical table in a laboratory environment. The second area deals with the integration of the sensor with the controls into a single package.

The realistic DoD operational requirement is a high-g dynamic environment, and any cold atom instruments must function over the relevant range for a given application. Instruments covering this range must be able to sample at a frequency sufficient to feed into a control system to be able to affect the platform. The cold atom systems to date have had comparatively long dwell times on the cold atom wave packets for their measurements. This has the effect of lowering the effective operating frequency in the single Hz range. A reduction in the sensor size will lead to shorter interrogation times of the atoms and a higher cycle time or repetition rate. This in turn can lead to better stability of the laser system due to shorter pulse lengths and the stringent frequency requirements. One of the areas that is least understood is how laser cooling and the optical molasses will behave in environments over 10 g. The system is doomed if it cannot create the optical molasses in this dynamic environment. The first phase of DARPA's PINS-HiDRA program will attack this problem in the coming year.

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[27] Dr Steven Miller, "Point Paper – Cold Atom Inertial Measurement Unit for GPS Contested Environment."
[28] Dr Steven Miller, AFRL/RVBYM, interviewed by the author, 4 Oct 2010.

No cold atom program will be successful if it cannot successfully integrate the sensor into a system. This is a daunting engineering challenge to package items normally found on an optical bench into a self-contained unit. Integrating the system will require a micro-optics bench, compact and efficient lasers, as well as control electronics. A housing structure is required for the sensor capable of holding an extremely high vacuum and able to keep the alignments on all of the mirrors. This effort requires optical-mechanical stability of precision machined and placed parts. These parts and the structure must be able to withstand a dynamic load in multiple axes simultaneously. Finally, any system measuring multiple axes, e.g., for an IMU, must retain its alignment and sensor-to-sensor orientation. The design and construction of a system to withstand the shock and vibrational will be the most stressing problem in the sensor integration[29,30].

The development of a cold atom INS/IMU may lead to engineering problems or issues due to the inherent sensitivity of the devices. The size, weight, and power requirements coupled with the thermal, shock, and vibration will require system tradeoffs to meet the overall system requirements. A cold atom IMU may be too sensitive for a reliable control system requiring a reduction in sensitivity for platform stability. Only continued development and systems integration will prove if this may or may not be the case. DARPA and AFRL/RV have investigated the potential sensitivity problem, and reached the same initial solution. The cold atom system architecture would consist of additional conventional accelerometers to help stabilize the system from growing dynamically unstable as well as lock the cold atom device in an area of maximum sensitivity. As the components mature, this problem becomes a key part of

[29] Dr Jamil Abo-Shaeer, DARPA/DSO, interviewed by the author, 2 Nov 2010.
[30] Dr Steven Miller, AFRL/RVBYM, interviewed by the author, 4 Oct 2010.

the systems engineering with the platform.  A conscious decision is required to early identify the first platform to receive a cold atom INS/IMU to guide the development and systems integration.

## Cold Atom Prioritization

Reality dictates a funding constrained environment, and prioritization of AF resources is required to obtain the maximum benefit of scarce resources.  There are three areas the AF needs to resource to ensure cold atom technologies continue to develop on a reasonable time line. AFRL needs to continue to fund basic research (6.1 funds) for cold atom technologies to ensure there is a solid foundation for future efforts in applied research (6.2 funds).  The second area consists of the early systems design to develop a functioning system, i.e., proof of concept (generally 6.3 funds).  The final category comprises programs of record designed to develop systems for operational fielding including all life cycle costs.

Given the current state-of-the-art for cold atom technologies, funding should be focused primarily in the 6.2 area, followed by 6.3 and continued 6.1.  The majority of the theory for cold atom is complete, and current efforts revolve around the design and development of practicable instruments and systems.  Yet the funding is well below what is required.  The vast majority of the AF funds should focus on the development of prototype systems.  This will include the required engineering to reduce the large systems into a manageable size.  Early allocation of resources enables efforts to study the integration of these systems with sensors and platforms. These studies are part of the development planning activities, and should support future developments by focusing on interfaces, design constraints, and anticipated operating environment for the host platform(s).

Early system studies are crucial to avoid the “Valley of Death,” and enable the right organizations to have the data they need to make and defend future budget decisions.  DARPA’s

PINS-HiDRA demonstration prototype by the end of 2012 should be the first step in a series of cold atom developments. The AF must conduct a platform study on the heels of PINS-HiDRA to identify the candidate airframe for a follow-on development program. The platform program office must lead the study to ensure a robust input, support in the POM, and potential inclusion into block upgrades. This opens up the potential for cost sharing with DARPA and other DoD organizations. Inherent in the initial studies are growth plans for other mission areas and platforms. A special examination for space and nuclear applications will have to determine if this technology is appropriate for these harsh and unforgiving environments.

## Cold Atom System Development

A confluence of developments in cold atom technologies will have a tremendous impact on the AF if properly managed (Figure 3). Based upon the current PINS-HiDRA research schedule, the program will have a decision point at the end of 2011 when Phase I concludes. Given success, this would be an ideal time for the AF to identify a platform for DARPA to test its Phase II device in 2014. In parallel, AFRL/RV would expect to have an operational microchip cold atom system by the end of the same year if properly resourced at approximately $6.5M per year[31]. Programmatic success lays the groundwork for the AF and DoD to develop and resource program using this technology for multiple mission areas. The programs of record will benefit by having two similar devices to perform tradeoffs during systems design and integration.

[31] Dr Steven Miller, "Point Paper – Cold Atom Inertial Measurement Unit for GPS Contested Environment."

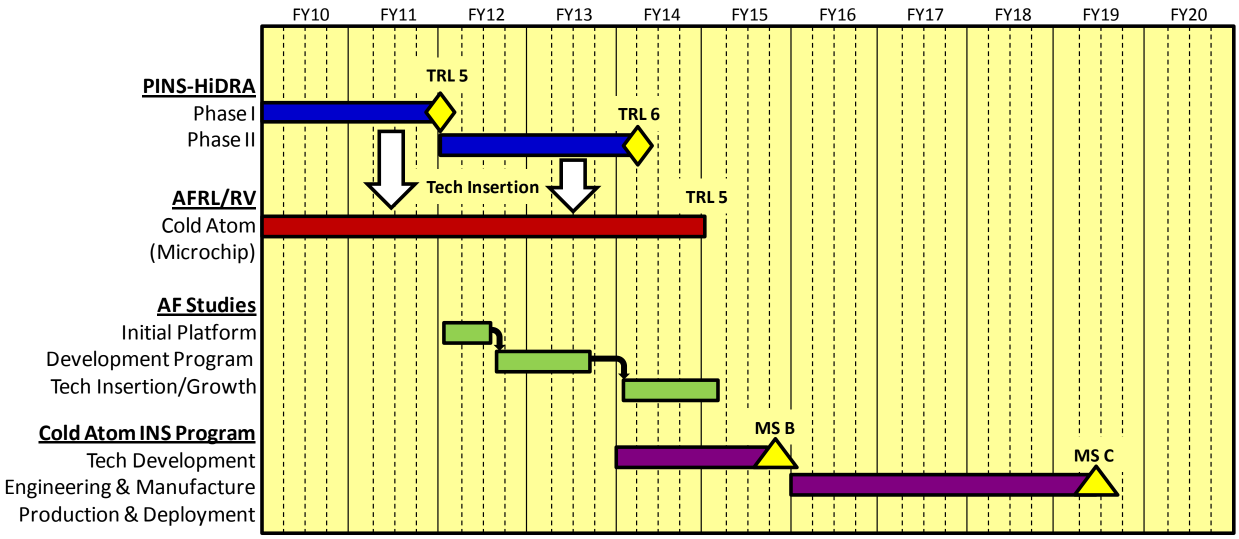


Figure 3: Cold Atom Development and Timeline.

Parallel development of associated technologies will enable a rapid transition to operational platforms. Design of a prototype IMU is possible once the AF identifies a candidate airframe. This decision will feed both the DARPA and AFRL/RV developments to meet the desired operational envelope and characteristics. It will also set the size, weight, and power requirements for the of both the sensor and control electronics. The system requirement will flow down and drive not only the cold atom system but also all of the control electronics. All of these efforts will reduce the development timeline to enable the production of the first operational system near 2020.

There are multiple ways to transition the cold atom technology to operational platforms. The least risky plan would be to begin by developing a cold atom system IMU for a large aircraft. A large aircraft would have more room to enable the development and ringing out of a cold atom system. If proven feasible and effective, a spiral development can begin to look at smaller and faster platforms. The initial development would perform the necessary nonrecurring engineering, and begin standardization of parts and logistics. The development would progress from large aircraft, to medium aircraft, fighters, and then look towards RPVs and munitions (Figure 4). This tiered approach would allow the development, acquisition, and operational community to understand the technology and develop the best and most cost effective plan for its growth.

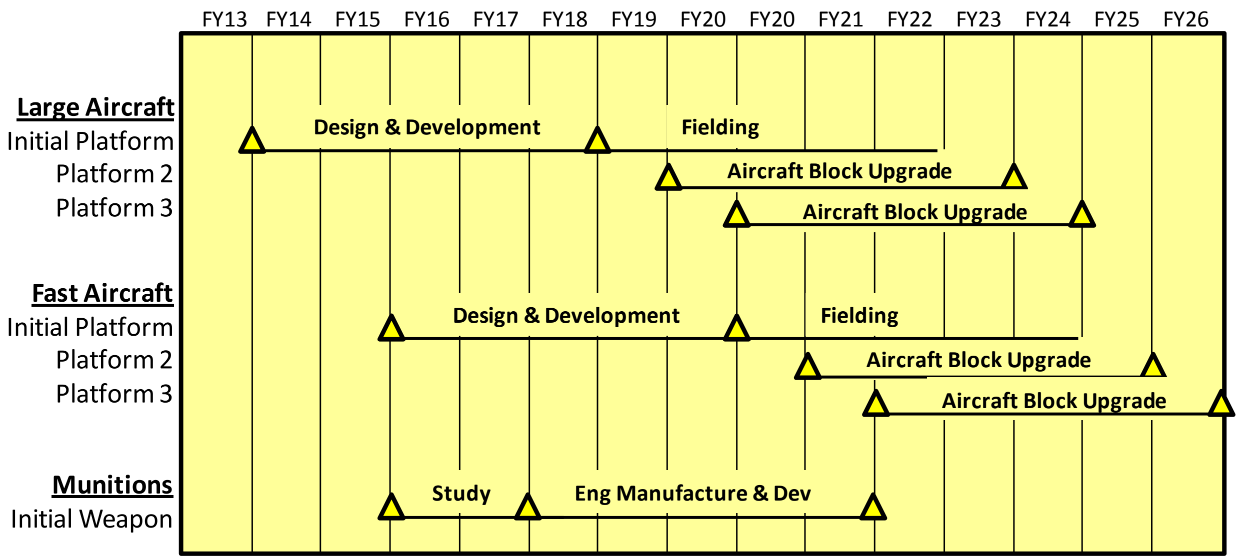


Figure 4: Cold Atom System Development and Deployment Construct.

The development of cold atom systems will require programmatic off-ramps if the technology is not feasible while also providing growth opportunities. If the large aircraft cold atom development progresses according to the development plan, it will enable growth to airframes with much more stringent operational envelopes. The staggered program approach allows time to determine feasibility and identify any technology needs necessary for the next evolution. As the initial development for each airframe class progresses towards production, the program offices in conjunction with the using command can identify cold atom as an item for insertion into a pre-programmed block upgrade. This provides stability in funding, avoiding the "valley of death," as well as a known construct for incremental platform updates. Additionally, it allows flexibility to cost share with other platform needs. The ultimate desire would be to develop a cold atom INS that would constitute a one-for-one swap with current navigation systems.

There is not enough data now to identify a cost for the development of a cold atom INS. The AF needs to conduct the platform study to inform the budget process. There are many unknowns with regard to the extent of developmental and operational testing required. Additionally, if this development requires a change in the operational flight program or system software, this will become a major cost driver. If successful, cold atom INSs will become more affordable and the development time will shrink as more platforms/systems obtain this capability. The operational requirement for such a system is so compelling that funding should be made available. It will revolutionize US force employment and remove a key vulnerability.

## Placement within the AF for Successful Development

The development of cold atom technology to date has mainly been in academia, and the AF needs to identify who should lead the development. Key stakeholders need to be involved to lead the technology out of the lab environment to an operational system. This will require a single entity to lead this development and not leave it up to chance. Cold atom is in a grey area, it is too early to be lead out of a platform systems program office and it can easily die if it does not progress through the labs.

A step-wise approach needs to be considered. The AF S&T planning process has created Flagship Capability Concepts (FCCs) collaboratively developed by MAJCOMs, Product Centers, and AFRL. These capabilities, commissioned through the S&T Governance structure (Figure 5), address a documented and prioritized MAJCOM capability gap. The benefit of an FCC is that it has been vetted, a lead Product Center for transition is assigned, initial systems engineering and development planning is initiated, a MAJCOM is identified, and transition funding is committed two years prior to the S&T completion[32,33]. The FCC process protects program funding, and it aligns the technology with the acquisition process to avoid the "Valley of Death."

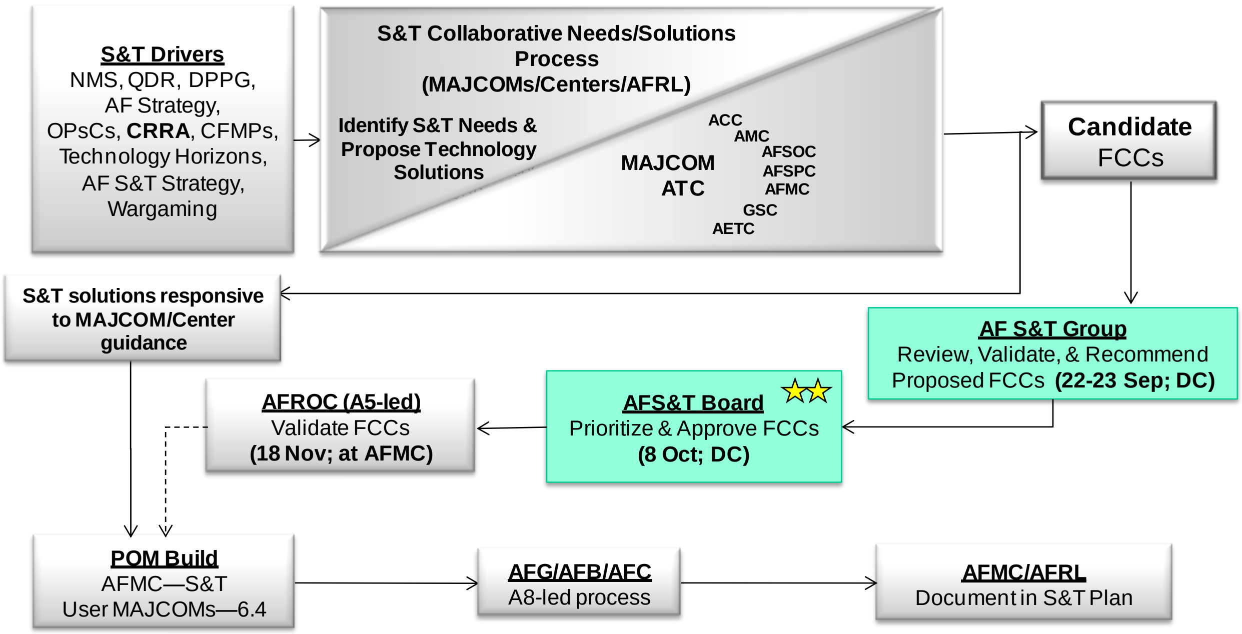


Figure 5: AF S&T Planning Process[34].

The proper development of the cold atom technology would benefit if selected as an FCC. The applicability of this technology would cut across several MAJCOMs and Product Centers. The ideal selection of the Aeronautical Systems Center (ASC) as the transition Product Center and Air Combat Command (ACC) as the MAJCOM transition manager would fit the incremental development approach listed above. This would lead to the best integration across large and small platforms. ASC would take ownership of the graduated cold atom FCC. They would facilitate the transition from aircraft cold atom systems to the development of munitions based systems with the Air Armament Center (AAC). Continuity would exist between the MAJCOM

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[32] Maj Jay Kucko, AF/A8XC, interviewed by the author, 10 Nov 2010.
[33] AF/A8XC Brief, Flagship Capability Concept and AF S&T Governance Process, 2010.
[34] Taken from AF/A8XC Brief, Flagship Capability Concept and AF S&T Governance Process, 2010.

user (ACC), the platform program office (ASC), and the munitions program offices (AAC). This would be a seamless transition from laboratory, to Product Center, to an operational user. Success depends upon the engagement and involvement of all parties.

## Summary

The promise of an ultra-precise and non-corruptible INS/IMU for DoD applications appears to lie in the realm of cold atom technologies. Successful development of this technology will remove a key vulnerability to the current reliance on GPS data. There are several steps necessary to ensure proper development of this technology. First, the AF must increase their involvement with DARPA's PINS-HiDRA program. The AF must conduct a platform feasibility study at the conclusion of Phase I of PINS-HiDRA to help focus DARPA's Phase II and subsequent follow-on AF programs. Secondly, the research into cold atom microchip devices must receive robust funding to accelerate the technology base. This will help to provide risk reduction in the technology development for aircraft and munitions. The parallel development will symbiotically help each effort as they both push the technology base for common components. The most important piece of the development is the assignment of an executive agent to oversee the overall cold atom development. This technology has the ability to revolutionize the AF and DoD, but it cannot help if it never leaves the laboratory. The advocacy and programming must begin now for success prior to when GPS has been removed by an outside actor. Time is now on our side, but it can easily slip away if we fail to act.

# Appendix I: DoD Technology Readiness Levels

Data taken from DoDI 5000.2-R, Appendix 6, 5 Apr 2002, pages 204 - 205.

| **Technology Readiness Level** | **Description** |
|---|---|
| 1. Basic principles observed and reported. | Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties. |
| 2. Technology concept and/or application formulated. | Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies. |
| 3. Analytical and experimental critical function and/or characteristic proof of concept. | Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. |
| 4. Component and/or breadboard validation in laboratory environment. | Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory. |
| 5. Component and/or breadboard validation in relevant environment. | Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components. |
| 6. System/subsystem model or prototype demonstration in a relevant environment. | Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment. |
| 7. System prototype demonstration in an operational environment. | Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft. |
| 8. Actual system completed and qualified through test and demonstration. | Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications. |
| 9. Actual system proven through successful mission operations. | Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission |

| | |
|---|---|
| | conditions. |

The DoDI further clarifies the following:

BREADBOARD: Integrated components that provide a representation of a system/subsystem and which can be used to determine concept feasibility and to develop technical data. Typically configured for laboratory use to demonstrate the technical principles of immediate interest. May resemble final system/subsystem in function only.

"HIGH FIDELITY": Addresses form, fit and function. High fidelity laboratory environment would involve testing with equipment that can simulate and validate all system specifications within a laboratory setting.

"LOW FIDELITY": A representative of the component or system that has limited ability to provide anything but first order information about the end product. Low fidelity assessments are used to provide trend analysis.

MODEL: A reduced scale, functional form of a system, near or at operational specification. Models will be sufficiently hardened to allow demonstration of the technical and operational capabilities required of the final system.

OPERATIONAL ENVIRONMENT: Environment that addresses all of the operational requirements and specifications required of the final system to include platform/packaging.

PROTOTYPE: The first early representation of the system which offers the expected functionality and performance expected of the final implementation. Prototypes will be sufficiently hardened to allow demonstration of the technical and operational capabilities required of the final system.

RELEVANT ENVIRONMENT: Testing environment that simulates the key aspects of the operational environment.

SIMULATED OPERATIONAL ENVIRONMENTAL: Environment that can simulate all of the operational requirements and specifications required of the final system or a simulated environment that allows for testing of a virtual prototype to determine whether it meets the operational requirements and specifications of the final system.

The above data refers to both hardware and software. DoD further clarified the definitions in the DoD Technology Readiness Assessment (TRA) Deskbook (Jul 2009) by breaking out hardware and software. The following two tables are taken from Appendix H of the DoD TRA Deskbook .

| Hardware TRL Definitions, Descriptions, and Supporting Information | | |
|---|---|---|
| **TRL Definition** | **Description** | **Supporting Information** |
| **1**<br>*Basic principles observed and reported.* | Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties. | Published research that identifies the principles that underlie this technology. References to who, where, when. |
| **2**<br>*Technology concept and/or application formulated.* | Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies. | Publications or other references that outline the application being considered and that provide analysis to support the concept. |
| **3**<br>*Analytical and experimental critical function and/or characteristic proof of concept.* | Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. | Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed. |
| **4**<br>*Component and/or breadboard validation in a laboratory environment.* | Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory. | System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals. |
| **5**<br>*Component and/ or breadboard validation in a relevant environment.* | Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components. | Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals? |
| **6**<br>*System/subsystem model or prototype demonstration in a relevant environment.* | Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment. | Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level? |
| **7**<br>*System prototype demonstration in an operational environment.* | Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space). | Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level? |
| **8**<br>*Actual system completed and qualified through test and demonstration.* | Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications. | Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design? |
| **9**<br>*Actual system proven through successful mission operations.* | Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions. | OT&E reports. |

| Software TRL Definitions, Descriptions, and Supporting Information | | |
|---|---|---|
| **TRL Definition** | **Description** | **Supporting Information** |
| **1** *Basic principles observed and reported.* | Lowest level of software technology readiness. A new software domain is being investigated by the basic research community. This level extends to the development of basic use, basic properties of software architecture, mathematical formulations, and general algorithms. | Basic research activities, research articles, peer-reviewed white papers, point papers, early lab model of basic concept may be useful for substantiating the TRL. |
| **2** *Technology concept and/or application formulated.* | Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies using synthetic data. | Applied research activities, analytic studies, small code units, and papers comparing competing technologies. |
| **3** *Analytical and experimental critical function and/or characteristic proof of concept.* | Active R&D is initiated. The level at which scientific feasibility is demonstrated through analytical and laboratory studies. This level extends to the development of limited functionality environments to validate critical properties and analytical predictions using non-integrated software components and partially representative data. | Algorithms run on a surrogate processor in a laboratory environment, instrumented components operating in a laboratory environment, laboratory results showing validation of critical properties. |
| **4** *Module and/or subsystem validation in a laboratory environment (i.e., software prototype development environment).* | Basic software components are integrated to establish that they will work together. They are relatively primitive with regard to efficiency and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues. Emulation with current/legacy elements as appropriate. Prototypes developed to demonstrate different aspects of eventual system. | Advanced technology development, stand-alone prototype solving a synthetic full-scale problem, or standalone prototype processing fully representative data sets. |
| **5** *Module and/or subsystem validation in a relevant environment.* | Level at which software technology is ready to start integration with existing systems. The prototype implementations conform to target environment/interfaces. Experiments with realistic problems. Simulated interfaces to existing systems. System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment. | System architecture diagram around technology element with critical performance requirements defined. Processor selection analysis, Simulation/Stimulation (Sim/Stim) Laboratory buildup plan. Software placed under configuration management. Commercial-of-the-shelf/government-off-the-shelf (COTS/GOTS) components in the system software architecture are identified. |
| **6** *Module and/or subsystem validation in a relevant end-to-end environment.* | Level at which the engineering feasibility of a software technology is demonstrated. This level extends to laboratory prototype implementations on full-scale realistic problems in which the software technology is partially integrated with existing hardware/software systems. | Results from laboratory testing of a prototype package that is near the desired configuration in terms of performance, including physical, logical, data, and security interfaces. Comparisons between tested environment and operational environment analytically understood. Analysis and test measurements quantifying contribution to system-wide requirements such as throughput, scalability, and reliability. Analysis of human-computer (user environment) begun. |
| **7** *System prototype demonstration in an operational high-fidelity environment.* | Level at which the program feasibility of a software technology is demonstrated. This level extends to operational environment prototype implementations, where critical technical risk functionality is available for demonstration and a test in which the software technology is well integrated with operational hardware/software systems. | Critical technological properties are measured against requirements in an operational environment. |
| **8** *Actual system completed and mission qualified through test and demonstration in an operational environment.* | Level at which a software technology is fully integrated with operational hardware and software systems. Software development documentation is complete. All functionality tested in simulated and operational scenarios. | Published documentation and product technology refresh build schedule. Software resource reserve measured and tracked. |
| **9** *Actual system proven through successful mission-proven operational capabilities.* | Level at which a software technology is readily repeatable and reusable. The software based on the technology is fully integrated with operational hardware/software systems. All software documentation verified. Successful operational experience. Sustaining software engineering support in place. Actual system. | Production configuration management reports. Technology integrated into a reuse "wizard." |

## Bibliography

AF/ST-TR-10-01-PR, *United States Air Force Chief Scientist (AF/ST) Report on Technology Horizons: A Vision for Air Force Science & Technology During 2010-2030,* Vol 1, 15 May 2010.

Bandi, Thejesh N., Cold Atom Physics: Trapping Methods and Detection Schemes, Cork Institute of Technology, Masters Thesis, 2008.

Bandi, Thejesh N., et. al., "Atom microtraps based on near-field Fresnel diffraction", *Physical Review A,* Vol 78, Jul 2008.

Barbour, N. and Schmidt, G., "Inertial Sensor Technology Trends," *IEEE Sensors Journal*, Vol. 1, No. 4, pp. 332-339, 2001.

Bordé Ch. J., "Atomic Interferometry with Internal State Labeling", *Phys. Lett*., A140, 1989, pp. 10-12.

Bordé, Ch. J., "Atomic Clocks and Inertial Sensors", *Metrologica*, Vol 39, Issue 5, 2002.

Curcic, Tatjana, AFOSR/RSE (PM for Atomic and Molecular Physics), interview by the author, 9 Sep 2010

DoD 5000.2-R, Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System Acquisition Programs (MAIS), 5 Apr 2002.

DoDI 5000.02, Operation of the Defense Acquisition System, 8 Dec 2008.

Gauguet, A., et. al., "Characterization and limits of a cold atom Sagnac interferometer", *Physical Review A,* Vol 80, Issue 6, Dec 2009.

Gustavson, T. L., et. al., "Precision Rotation Measurements with an Atom Interferometer Gyroscope", *Phys. Rev. Lettr,* Vol 78, No. 11, pp. 2046 - 2049, 17 Mar 1997.

Hussey, Thomas, AFOSR/Chief Scientist, interview by the author, 7 Sep 2010.

Kasevich, Mark, "Science and technology prospects for ultra-cold atoms", CAMOS brief, Stanford University, Nov 2002.

Kasevich, Mark and Chu, Steven, "Atomic Interferometry Using Stimulated Raman Transitions", *Phys. Rev. Lettr,* Vol 67, No. 2, pp. 181 –184, 8 Jul 1991.

Kasevich, Mark, "Cold Atom Navigation Sensors" , Position Navigation and Timing Symposium Brief, http:// scpnt.stanford.edu/downloads/14.%20Kasevich_PNT-Symposium.pdf.

Kohel, James M., et. al., "Generation of an intense cold-atom beam from a pyramidal magneto-optical trap: experiment and simulation", *J. Opt Soc. Am. B*, Vol 20, No. 6, pp. 1161 – 1168, Jun 2003.

Lawrence, Anthony, *Modern Inertial Technology: Navigation, Guidance, and Control*, Springer-Verlag, Dec 1992.

Ménoret, V., et. al., "A Transportable Cold Atom Inertial Sensor for Space Applications", International Conference on Space Optics, Oct 2010.

Miller, Steven M., *Cold Atom Lab 2005-2007 Update,* AFRL-RV-HA-TR-2007-1125, 20 Nov 2006.

Miller, Steven, AFRL/RVBYM, interviewed by the author, 4 Oct 2010.

Miller, Steven, "Point Paper – Cold Atom Inertial Measurement Unit for GPS Contested Environment", AFRL/RVBYM, 6 Oct 2010

Morris Ed, et. al., <u>A Day Without Space: Economic and national Security Ramifications,</u> The George Marshall Institute, Washington D.C., Oct 2008.

Pace, Scott et al., *The Global Positioning System: Assessing National Policies,* RAND Report MR-614-OSTP, RAND Corporation, 25 Jan 1996.

Peters, A., et. al, "Precision atom interferometry", Phil. *Trans. R. Soc. Lond. A,* Vol 355, pp. 2223 – 2233, 1997.

Royal Swedish Academy of Sciences, *Additional Background Material on the Nobel Prize in Physics* 1997, 15 Nov 1997, http://nobelprize.org/nobel_prizes/physics/laureates/1997/back.html.

Royal Swedish Academy of Sciences, *Advanced Information on the Nobel Prize in Physics* 2001: *Bose-Einstein Condensation in Alkali Gases, Oct 2001*, http://nobelprize.org/nobel_prizes/physics/laureates/2001/adv.html.

Schmidt, George T., "INS/GPS Technology Trends", NATO Research and Technology Organisation, RTO-EN-SET-116, pp.1 – 18, May 2009.

Technology Readiness Assessment (TRA) Deskbook, Jul 2009.

Tompkins, Stefanie, "Precision Inertial Navigation Systems", DARPA, http://www.darpa.mil/dso/thrusts/physci/newphys/pins.

Zhan, Mingsheng, et.al., "Cold Atom Interferometry", J. *Phys Conf Ser*. No. 80, 2007.