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**14. ABSTRACT**

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The CNO and other DoD leadership have repeatedly stated that, "the United States is facing a return to great power competition." Specifically, the advancement of Russian and Chinese military technological capabilities is disrupting the global balance of power. In an effort to remain relevant as a global superpower, the United States must prioritize quantum capabilities that will enable unique military advantages against any potential adversary. This building of a *quantum-enabled force* is crucial and should be aggressively pursued.

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**NAVAL WAR COLLEGE**
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# The Weaponization of Quantum Physics: How Technology Is Transforming Warfare

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**Lieutenant, USN**

**A paper submitted to the Faculty of the Naval War College in partial satisfaction of the requirements of the Gravely Group Advanced Research Program.**

**The contents of this paper reflect my own personal views and are not necessarily endorsed by the Department of the Navy or the U. S. Naval War College.**

**Signature: _____/s/_____**

**15 February 2018**

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## Abstract

"We must look reality in the eye and see the world as it is, not as we wish it to be." [1] These words, spoken by SECDEF James Mattis, have never been more accurate than in today's challenging strategic environment. Multiple advancements are occurring continuously, mostly by Chinese researchers, in various scientific disciplines that utilize unique principles of quantum physics. The fields that have the highest potential for military applications are *quantum computing, quantum communications, and quantum sensing*.

Within these fields of study, new technology is allowing for the advancement of machine learning technology and artificial intelligence. Quantum communications through all mediums – optical cables, free-space air, and seawater – will progress to levels that will enable deployment of this ultra-secure capability on naval vessels, including aircraft, submarines, and munitions. Extremely capable sensors will unlock unprecedented levels of sensitivity in detecting changes in the physical environment that far exceed current technology; Quantum sensing will usher in an era of ubiquitous sensing of naval assets above, on, and under the sea.

The CNO and other DoD leadership have repeatedly stated that, "the United States is facing a return to great power competition." [2] Specifically, the advancement of Russian and Chinese military technological capabilities is disrupting the global balance of power. In an effort to remain relevant as a global superpower, the United States must prioritize quantum capabilities that will enable unique military advantages against any potential adversary. This building of a *quantum-enabled force* is crucial and should be aggressively pursued.


[1] James Mattis. *Nuclear Posture Review*. Washington DC, Office of the Secretary of Defense, 2018.
[2] John Richardson. *A Design for Maintaining Maritime Superiority*. Washington DC, United States Navy, 2017.

# Introduction

**As the landscape of global security is changing rapidly, progress in many fields of applied quantum physics has the overwhelming potential to completely redefine military operations in the 21st century.** Specifically, this paper will analyze the scientific advancements made in the recent years as well as the innovative and disruptive ways that quantum mechanical principles, applied to current warfare capabilities, will be the primary enabler of an otherwise elusive strategic military advantage in the 21st century.

Secretary of Defense James Mattis stated in the 2018 National Defense Strategy that the United States is officially focusing on the "great power competition." [3] In addressing this shift in priority, a key emphasis moving forward should be an intense effort in research and development of quantum capabilities that will provide the necessary capabilities to face any potential adversary. In a testimony to the SASC, Vice Chief of Staff of the Air Force, General Stephen Wilson stated that, "today's modernization is tomorrow's readiness." [4] When discussing the strained budgetary environment that the United States has operated under in recent years, advancing technology and research and development will gain substantially in readiness for each dollar spent.

As noted in ADM Harry Harris' Posture Statement for U.S. Pacific Command (PACOM), "China's military modernization program is transforming its forces into a high-tech military to achieve its dream of regional dominance, with growing aspirations of global reach and

[3] James Mattis. *Summary of the 2018 National Defense Strategy of The United States of America: Sharpening the American's Military's Competitive Edge.* Washington, DC: Department of Defense, 2018.
[4] Stephen Wilson, Testimony before Senate Armed Services Committee's subcommittee on Readiness and Management, February 14, 2018.

influence." [5] Though China's developments are not the primary focus of this paper, the following pages will directly validate ADM Harris' concerns showing specific advancements that have been demonstrated on a near-continuous basis in the field of quantum science.

With regards to avoiding war with China, Dr. Allison writes that the United States must "review all the strategic options – even the ugly ones." [6] It is along this same line of thinking that two distinct actions are proposed: Win the quantum race or be left behind wondering what happened. China has demonstrated a desire and capability to weaponize emerging quantum technologies, and if the United States is not prepared to undertake a similar course of action then the global power balance may already be upset beyond repair and remain that way for years to come.

*If emerging technologies are not understood, countered, and most importantly, organically developed, how can the United States maintain global security dominance in the future?* **The way the United States' Joint forces operate will change significantly with the proliferation of applied quantum physics, specifically in the fields of *quantum computing, quantum communications, and quantum sensing*.** Described below, these emerging fields of study have generated key capabilities that will be vitally important to the national security of the United States. These technological gains will be seen in advancing computing power and machine learning effectiveness, unprecedented security in communications, and by way of ultra-sensitive radars and sensitive magnetometers enabling advanced navigation and magnetic sensing capabilities.

[5] Statement of Admiral Harry B. Harris, Jr., United States Pacific Command, 26 Apr 2017.
[6] Graham Allison. *Destined for War: Can America and China escape Thucydides' Trap?* New York: Houghton Mifflin Harcourt Publishing Company, 2017, Page 221.

Beyond the clearly defense-oriented analysis of quantum technology, this paper will briefly describe additional civilian sectors that will be greatly impacted by advancing these fields of study. Particularly, there are direct causational relationships that can be inferred as having a substantial effect in the fields of meteorology, finance, energy management, telecommunications, data security, and oil and gas. [7] Not fully explored here, future research should be done on the lasting effects of adopting quantum technology, with a particular focus on vital national infrastructure and economic sectors. It would be foolish to overlook this critical point of potential weakness in the overall United States defense strategy.

To establish and maintain a position of strength on the global scale, this paper makes several recommendations. These recommendations are not made to exacerbate the delicate security situation around the world, but rather to serve as a call-to-arms within the scientific circles of government, academia, and industry alike. The Commander of PACOM has said that the U.S. military is dedicated to "fly, sail, and operate wherever international law allows," [8] but without taking purposeful and definitive steps toward a quantum-enabled military force, the future of national security is bleak. **Leveraging advanced quantum technology, when enabled by the great minds of industry and academia and subsequently harnessed by the unrelenting warfighters of the U.S. Department of Defense, will enable continued peace and prosperity around the world.**

The conclusions and recommendations provided here agree with those by the Jamestown Foundation. In a comprehensive two-part article regarding technological and strategic implications of the rapid advancements of applied quantum physics. Their writings focus on

[7] Sir Peter Knight & Sir Mark Walport, The Quantum Age: Technological Opportunities, United Kingdom Government Office for Science, 2016.
[8] Statement of Admiral Harry B. Harris, Jr., United States Pacific Command, 26 Apr 2017.

Chinese advancements as the primary topic. [9] [10] If there is any hope to maintain our regional presence in the Western Pacific, let alone globally, the emerging technologies need to be understood, countered, and most importantly, organically developed. Developing quantum capabilities is a crucial step towards ensuring that United States diplomats always speak to potential adversaries from the position of overwhelming strength.

"We are convinced that we are at an inflection point – the early stages of a shift as profound as that brought on by the Industrial Revolution. Not only are the new technologies exponential, digital, and combinatorial, but most of the gains are still ahead of us." [11] The emergence of advanced computing, communications, and sensing capabilities is not new. innovation and adaptability provided key advantages in all the nation's wars. From submarines to radar to nuclear weapons to precision-guided munitions, the United States has adapted with evolving technology. Quantum science, though relatively immature as a warfighting technology, has the potential to disrupt every aspect of future warfare; This is only the beginning, but there is no time to lose. Without building a quantum-enabled force with competent and confident operators, the United States faces a future that is certain to place it behind China and even Russia as a global superpower.

[9] Elsa Kania and John Costello. "Quantum Leap (Part 1): China's Advances in Quantum Information Science. *The Jamestown Foundation: China Brief*, Volume 16, Issue 18. December 5, 2016. https://jamestown.org/programs/cb/china-third-offset/

[10] Elsa Kania and John Costello. "Quantum Leap (Part 2): The Strategic Implications of Quantum Technologies. *The Jamestown Foundation: China Brief*, Volume 16, Issue 19. December 21, 2016. https://jamestown.org/programs/cb/china-third-offset/

[11] Erik Brynjolfsson and Andrew McAfee. *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies.* New York: W.W. Norton & Company, Inc., 2016. Page 251.

## Quantum Physics: The Basics

To align the readers to the true purpose of this work, be reassured that the goal is not to delve into the advanced topics related to quantum mechanics. On the contrary, it is acknowledged that even with years of instruction, key concepts are difficult to understand or truly grasp. For simplicity and brevity, only the basic concepts will be introduced and explained. As they may not be wholly-scientific, these descriptions aim to move the discussion from theory to application.

Two distinct principles that should be understood are *superposition* and e*ntanglement*. *Entanglement* is a concept that is central to understanding much of applied quantum physics, particularly quantum communications and quantum radars. A commonly understood definition of *entanglement* says that particles can be generated to have a distinct reliance on each other, despite any spatial distance between the particles. This concept implies that as two (or more) particles are physically detached with no traditional or measurable linkages, what happens to one has a quantifiable affect on the other. [12] The ability to generate and manipulate pairs of entangled particles is at the foundation of many quantum technologies.

To briefly explain s*uperposition*, an example shared by Dr. Mark Johnson, D-Wave Systems Inc.'s Director of Research is useful. "Take the standard concept of flipping a coin to determine heads or tails. With the principles of quantum mechanics, your 'quantum coin' could be both heads and tails at the same time." [13] That is, particles have been confirmed to have two (or more) states at any given time.[14] A more relatable description lies in the field of quantum

[12] Marco Lanzagorta and Jeffrey Uhlmann. *Quantum Computer Science*. Morgan & Claypool Publishers, 2008.
[13] Personal Interview with Mark Johnson, Director of Research at D-Wave Inc., August 29, 2017.
[14] Michelle Starr. "Physicists prove Einstein's 'spooky' quantum entanglement," *CNET*. November 19, 2015. Accessed June 8, 2017. https://www.cnet.com/news/physicists-prove-einsteins-spooky-quantum-entanglement/.

computing. Classical computers process information in a collection of bits where each bit has a value of either zero or one. Quantum computers differ in that the quantum bits, or qubits, can have a value of zero, one, or both simultaneously. This is counterintuitive to the general understanding of classical physics, but this property has repeatedly been proven in many credible scientific experiments. This allows for the computational power to increase from a nearly linear progression in classical computers to an exponential progression in quantum computers.

With these basics briefly described, the remaining discussion will focus on the specific technological advancements made possible by this science. To demonstrate the capabilities, the following pages will highlight recent efforts of researchers in various disciplines of applied quantum physics. Though Chinese advancements are not the focus, many examples can be seen coming out of China due to their vigor and national emphasis on advancing quantum sciences. The limitless and coordinated approach the Chinese have taken should cause concern for the budget-limited US Department of Defense. [15]

[15] Tim Johnson. "China speeds ahead of U.S. as quantum race escalates, worrying scientists." *McClatchy DC*. Updated October 23, 2017. Accessed October 23, 2017. http://www.mcclatchydc.com/news/nation-world/national/national-security/article179971861.html

## Quantum Computing

In his chapter entitled "Weird Science: What's Next," Dr. James Canton, CEO and Chairman of the Institute for Global Futures, highlights the impact of quantum computing. Specifically, described here are several causes relating to advanced computing power (both classical and quantum) that will lead to truly intelligent machines and the "awakening of the internet." [16] The capability to run classical algorithms at an unprecedented speed will unlock even more advances in artificial intelligence and machine learning technology.

MIT Professor Dr. Max Tegmark references the King Midas paradox while describing the inherent problems faced by programmers and computer scientists when communicating "our goals" to super-intelligent AI. [17] The current security environment is dominated by discussions surrounding the rising age of cognitive computing and deep learning; The proliferation of practical quantum computers will undoubtable assist in solving these problems – providing the super-fast computing speeds that can be used to capture true deep machine learning. Though it is another issue completely to analyze how military operations will be affected by artificially intelligent technology, the aim here is simply to draw a connection from quantum computing to the development of advanced AI.

Moore's Law was stated in 1965 by Gordon Moore, an American engineer and co-founder of Intel Corporation. Oversimplifying, this profound observation basically states that the number of transistors that can be placed on a silicon chip will approximately double every two

[16] James Canton, Ph.D. *The Extreme Future: The Top Trends That Will Reshape the World for the Next 5, 10, and 20 Years.* New York: Dutton, Penguin Group Inc., 2006. Pages 245-260.
[17] Max Tegmark, *Life 3.0: Being Human in the Age of Artificial Intelligence*. New York: Penguin Random House LLC, 2017. Pages 260-261.

years.[18] Through the last several decades this law has been surprisingly resilient, maintaining pace (and even sometimes exceeding it) with the most recent advances in computing technology. The implication of Moore's Law continuing to hold true is the creation of a world where computing power will exceed that of the human brain. If true, this will have applications that are world-changing.

As noted in 2012 by the world-renowned theoretical physicist Michio Kaku, the issue with Moore's Law is that this exponential growth is limited if silicon chips and standard transistors are used in the future. [19] Using "standard silicon technology" will result in an end of Moore's Law, but that same rate of exponential growth in computing power can still be achieved with the advent of quantum computers.[20] The world population has grown accustomed to advancements of this magnitude in computer technology, and thus industry will find a way to continue to deliver – this time with quantum computers.

China has unmistakably realized that the quantum future of computing is an issue that deserves the highest national attention. Despite their efforts thus far however, progress in this relatively new field of study is difficult. The South China Morning Post reported in May of 2017 that "A team of scientists from eastern China has built the first form of quantum computer that they say is faster than one of the early generation of conventional computers developed in the

[18] "Moore's Law." *Encyclopedia Britannica.* Accessed online February 3, 2018. https://www.britannica.com/topic/Moores-law.
[19] Matt Peckham. "The Collapse of Moore's Law: Physicist Says It's Already Happening." *Time.* May 1, 2012, Accessed October 3, 2017. http://techland.time.com/2012/05/01/the-collapse-of-moores-law-physicist-says-its-already-happening/.
[20] Ibid. Though somewhat similar, Moore's Law is sometimes described improperly by referencing computing power. Gordon Moore clarified that the 18-24 months doubling time of computing power was championed by Intel's David House.

1940s." [21] Though this development might seem impressive at first glance, this same article also notes that, " The Chinese team admit that their machine is of no practical use as it only carries out this one highly complex form of calculation, but it highlights the future potential of quantum computing." [22] This example makes clear two important facts. One is that China is not years ahead of the United States in quantum computing. And the other is that this technology, despite the intense research and development efforts, might still be many years away from practical applications.

Delving deeper into the different styles of quantum computing will reveal a bit more about the future of this technology. The process pursued here by the Chinese is likely very similar to that used by D-Wave Inc., a Canadian quantum computing company. This approach is called 'quantum annealing,' and it is not the 'world-changing' technology sought in the pursuit of practical quantum computers. The real applications for quantum computers are better suited for ones operating under the 'universal gate model.' Again, sparing the details, this method is much more difficult to utilize and remains many years away.

According the MIT Technology Review in April 2017, *quantum supremacy* is quickly being approached by Google and IBM. [23] Quantum supremacy refers to the point where quantum computers exceed the capability of classical computing technology. Once quantum supremacy is reached the true implications of practical quantum computers will be the efficient use of two fundamental quantum algorithms. Shor's Algorithm can be used to break standard

[21] Stephen Chen. "China hits milestone in developing quantum computer 'to eclipse all others'." *South China Morning Post.* Updated June 12, 2017. Accessed September 26, 2017. http://www.scmp.com/news/china/policies-politics/article/2092635/china-hits-milestone-developing-quantum-computer.
[22] Ibid.
[23] Tom Simonite. "Google's New Chip Is a Stepping Stone to Quantum Computing Supremacy." *MIT Technology Review.* April 21, 2017. Accessed October 17, 2017. https://tinyurl.com/y7g3oszn

encryption and Grover's Algorithm for faster and more efficient search. [24] [25] The impact of these algorithms can be found in literature abound, and there are clear applications to the military.

[24] Peter Shor. "Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer." *SIAM Journal on Computing, 26(5)*, 1997. Pages 1484-1509. https://arxiv.org/pdf/quant-ph/9508027.pdf
[25] Andris Ambainis. "Quantum Search Algorithms." *SIGACT News, 35 (2)*, 2004. Pages 22-35. https://arxiv.org/pdf/quant-ph/0504012.pdf

## Quantum Communications

Quantum communications is the developing field of study that uses principles of quantum physics to transmit information with unprecedented security and speed. The protocols tested and proven thus far use quantum key distribution (QKD), along with a classical electro-magnetic communications path to provide two-way communications. Quantum communications utilizes the quantum principle of entanglement to ensure ultra-secure exchange of quantum keys, while utilizing a classical communications path to transfer information. Experiments have been conducted proving the viability of quantum communications through three critical mediums, each of which can be exploited for distinct strategic advantages.

One may ask, *why does this technology matter*? The answer to that question requires only basic understanding of tactical security and military operations. As many classical theorists explain, information can win wars. For example, Carl Von Clausewitz's *On War* tells military strategists that removing the 'fog and friction' during a conflict could lead to victory where otherwise impossible.[26] History shows that with the ability to intercept and understand enemy communications, a distinct advantage can be gained. This is shown famously by the breaking of the enigma code of Nazi Germany, tapping of underwater cables of the Soviet Union, and the interception of Japanese plans at Midway during World War II. It follows that maintaining secure communications should remain a top priority for every nation in times of peace or war.

The first medium for quantum communications is between two ground stations via an optical cable. The capability to conduct secure quantum communications between two locations will ensure a nations ability to maintain integrity of its' most sensitive information. There is a

[26] Carl von Clausewitz. *On War*. Translated and edited by Michael Howard and Peter Paret. Princeton: Princeton University Press, 1976.

1,243-mile fiber-optic cable that connects Beijing and Shanghai ground stations. [27] This link provides a test platform for fast-failure and high-velocity learning in the field of quantum communications.

The second medium for quantum communications is between a ground station and an airborne platform. This capability has been demonstrated by the world's only quantum satellite, *Micius*, owned and operated by the Chinese. [28] This satellite operates multiple photon transmitter and receivers to send and receive entangled photons from ground stations. Here too, China has achieved a distinct advantage in the field of experimental quantum communications.

The third, and most important, medium for quantum communications is through seawater. Though relatively immature, this field of study has rapidly progressed in recent years. In August of 2017, Chinese researchers reported having tested and proven the feasibility of seawater as a medium stating, "[this] represents the first step towards underwater quantum communication." [29]

Separately, these three capabilities – quantum communications via optical cables, through free-space, and through seawater – have the potential to be disruptive in an environment where strategic communications are needed for operations that may be vital to a nation's security. Together however, they provide an unprecedented capability to completely secure all required communications from all national assets. The synergy and maturity of this technology requires further research and should be examined at the highest possible levels.

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[27] Tim Johnson. "China speeds ahead of U.S. as quantum race escalates, worrying scientists." *McClatchy DC*. Updated October 23,2017. Accessed October 23, 2017. http://www.mcclatchydc.com/news/nation-world/national/national-security/article179971861.html

[28] Ibid.

[29] Ling, Ji, et. al. "Towards quantum communications in free-space seawater" *Optics Express. 25, (17),* August 21, 2017. https://doi.org/10.1364/OE.25.019795.

One viable model of synthesis for these technologies can be seen in the following example. A Chinese submarine conducting local operations has the need to communicate on a periodic basis. Remaining submerged, underwater quantum communications could be conducted through the seawater-air interface between the submarine and *Micius*, the quantum communications satellite. That secure communication can be received and retransmitted to a ground station in Beijing. That communication could then be transmitted to a command center for submarine operations. Once received, a message could be sent in the reverse direction using the same protocols for security and transmission paths. Thus, from cradle to grave, a submarine could have the capability to communicate while operating completely submerged (without a communications antenna out of the water).

Though covered more in the below, one urgent recommendation would be to highlight this technology as a priority for research and development. Primarily through appropriated funding and collaboration between government and academic institutions, this field of study can be matured rapidly to an operational level. Secure communication with a submarine operating at speed and at depth (meaning without a limitation on remaining slow and shallow with a communications antenna out of the water) is a critical capability that should be developed. Without clear, deliberate progress in the field of quantum communications, via all mediums, China will gain the ability to conduct uninhibited submarine communications while the United States plays catch-up.

## Quantum Sensing

*Quantum sensing* is an emerging field of study that has gained more notoriety in recent years. Cappellaro, Degen, and Reinhard describe quantum sensing as "the use of a quantum system, quantum properties or quantum phenomena to perform a measurement of a physical quantity." [30] Simply put, this science aims to provide extremely sensitive sensing capabilities that cover many different spectrums. Three technologies that will be discussed here: advanced quantum radar systems as well as, "GPS-free global navigation and cryogen-free high-precision magnetometry." [31]

### Quantum Radar

The military impact of the proliferation of quantum radar technology is tremendous. The fundamental science of this technology is completely different than traditional radar as most understand it. P. W. Singer and Jeffery Lin offer a great description of these differences:

> While conventional radars transmit radio waves to reflect off of targets, a quantum radar instead uses entangled photons, via fiber couplers, quantum dots or other methods. The entangled photons bounce off of the targeted object back to the quantum radar, which can extrapolate the position, radar cross section, speed, direction and other properties of the targeted object from the return time of the photons. Also, attempts to spoof the quantum radar would be immediately noticed, since any attempt to alter or duplicate the entangled photons would be detected by the radar.[32]

This, like other concepts within quantum physics, is difficult to understand but very easy to realize the military implications.

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[30] P. Cappellaro, C. Degen, & F. Reinhard. "Quantum Sensing." June 7, 2017. https://arxiv.org/abs/1611.02427.
[31] Ibid. *Quantum Magnetometry* implies a magnetic sensor sensitive enough to detect extremely small variances in traditionally weak magnetic fields.
[32] Jeffery Lin, P.W. Singer. "China Says It Has Quantum Radar: What Does That Mean?," *Eastern Arsenal*, September 27, 2016. https://www.popsci.com/china-says-it-has-quantum-radar-what-does-that-mean. (Accessed 8 October, 2016)

China is currently developing a quantum radar with a range of 100-km that could defeat the advanced stealth technology utilized by fifth-generation aircraft (e.g. the coveted advanced strike fighter, F-35).[33] This will further complicate fighter jet and aircraft carrier operations in the PACOM AOR, even more than is already being done due to the Chinese Anti-Ship Ballistic Missile (ASBM) Program.[34] If PACOM assets, specifically aircraft carriers and the embarked airwings, will continue to operate wherever international law allows, then an effective counter-technology to quantum radars needs to be developed in parallel with U.S. quantum capabilities.

Further reaching there is open literature suggesting that China seeks to use this technology to counter U.S. stealth platforms. In a recent article in South China Morning Post, *ghost imaging* technology was discussed to detect covert take-offs of stealth bomber aircraft that usually occurs at night. [35] This technology is not susceptible to weather effects or darkness that would preclude conventional collection methods. This science will continue to develop in the coming years, furthering the divide in capabilities if the United States does not properly invest in research and development of quantum radar technology.

## Quantum Navigation

In May 2014, the British Ministry of Defence started investing in the development of *quantum compass* that could eventually remove the overreliance on GPS technology for nautical navigation.[36] This game-changing technology is extremely effective when applied to submarine

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[33] Ibid.
[34] Andrew S. Erickson, *Chinese Anti-Ship Ballistic Missile Development: Drivers, Trajectories, and Strategic Implications* (Washington, DC: Jamestown Foundation, 2013).
[35] Stephen Chen. "Could ghost imaging spy satellite be a game changer for Chinese military?" *South China Morning Post.* November 26, 2017. Accessed January 28, 2018. http://www.scmp.com/news/china/society/article/2121479/could-ghost-imaging-spy-satellite-be-game-changer-chinese.
[36] Ryan Whitwam, "UK military creates quantum compass that could be the successor to GPS. *Extreme Tech*, 23 May 2014. https://www.extremetech.com/extreme/182973-uk-military-creates-quantum-compass-that-could-be-the-successor-to-gps. (Accessed 15 Jun 2017).

navigation. Without constant GPS updates, a submarine's Inertial Navigation Systems could be off by about one kilometer per day.[37] With a *quantum navigation system* uncertainty could be reduced by 1000x to approximately one meter.[38] The technical details are beyond the scope of this paper, but advancements in quantum compasses operate with extremely sensitive measurements of traditionally weak magnetic fields, which enables this distinct jump in capabilities. This technology is still being developed, but once it has been perfected it will end reliance on space-based assets, adding an extremely secure way for the U.S. Navy to operate without the threat of a 'GPS-Denied Environment.'[39]

In an ever-increasingly cluttered environment, U.S. Navy ships need reliable navigation tools that are not susceptible to disruption. Though the importance to a submarine is demonstrated, this technology could be applied to surface ships, aircraft, and even precision-guided munitions and missiles. Acquiring this technology through aggressive research and development, along with rapid integration into the current force will continue to ensure freedom of navigation throughout an increasingly contested global commons. Likewise, the risk of lagging in utilizing this technology severely hampers safety and security of forward-deployed naval forces around the globe while allowing an adversary to operate uninhibited.

## Quantum Magnetometry

Following the same science that allows *quantum navigation*, the ability to detect very small changes in magnetic fields has also led to the use of *quantum magnetometers.*[40] The

[37] Ibid.
[38] "British MoD works on 'quantum compass' technology to replace GPS. RT, 27 Jun 2014. https://www.rt.com/uk/159256-uk-defense-gps-compass/. (Accessed 10 October 2017).
[39] 'GPS-denied environment' is self-explanatory and is a term commonly used when talking about the problems facing an adversarial Anti-Access, Area-Denial (A2AD) approach.
[40] Michael Schirber. Synopsis: Quantum Sensing of Magnetic Fields. https://physics.aps.org/synopsis-for/10.1103/PhysRevLett.119.043603 (Accessed 27 September, 2017)

military importance of this can be seen in the use of Magnetic Anomaly Detection (MAD) devices aboard naval aircraft. MAD-equipped aircraft can fly at low altitudes to detect changes in the earth's magnetic field, potentially revealing a hidden submarine. The low-profile flight pattern is not compatible, however, with a Navy P-8's traditional high-altitude search routines.[41] Instead of sacrificing the advantages that MAD systems bring to the ASW mission, drones could be used to cover the gap. Here, quantum magnetometers could enhance MAD so that it can be used at high-altitude with even greater accuracy than low-altitude operations with traditional sensors.

The most prevalent form of quantum magnetometer is a superconducting quantum interference device (SQUID). [42] Stephen Chen, a reporter for *South China Morning Post,* was surprised when Chinese breakthrough hailed by the Chinese Academy of Sciences "vanished" from news reporting after the link was drawn between these extremely sensitive magnetometers and submarine detection. [43] There is additional open literature about China's plans to use this and other disruptive technology to build an, "Underwater Great Wall." [44] There is no mistake that these sensors will be used by military forces once matured, it is just a matter of who will get there first.

With increased utilization of newer detectors built on the principles of quantum mechanics, submarines will no longer be able to operate freely under the blanket of stealth due to

[41] John Keller. "BAE Systems to develop MAD ASW drone to help Navy P-8A find submarines from high altitudes," *Military & Aerospace.* 14 January 2015. Accessed October 11, 2017. http://www.militaryaerospace.com/articles/2015/01/bae-subhunting-drone.html.
[42] David Hambling. "China's quantum submarine detector could seal South China Sea." *New Scientist.* August 22, 2017. Accessed October 27, 2017. https://www.newscientist.com/article/2144721-chinas-quantum-submarine-detector-could-seal-south-china-sea/
[43] Ibid.
[44] Sarosh Bana. "China's Underwater Great Wall." *The Washington Times*. August 30, 2016. Accessed February 13, 2018. https://www.washingtontimes.com/news/2016/aug/30/chinas-underwater-great-wall/.

the establishment of a **magnetically transparent ocean**. Equipping aircraft with new *quantum magnetometers* will allow high-altitude flights to yield better Intelligence, Surveillance, and Reconnaissance (ISR) collection, as well as constant ASW mission accomplishment. Though not yet developed, equipping satellites in Low Earth Orbit (LEO) with these ultra-sensitive sensors could further erode the stealth enjoyed by all submarines across the globe.

## Much More Than the Military

Though the focus of this paper is to demonstrate the technical advantages that are gained by the development of quantum capabilities, it should be clear that these technologies will directly benefit a nations' infrastructure, security, and economic strength. In other words, if the military advantages are not enough to spur research and funding for these technologies, the potential impact on civilian sectors also add to the importance.

Advances in quantum computing has clear and sweeping effects on many sectors, not least of which will be consumer electronics and all versions of e-trade, e-commerce, or online based services. Cloud computing, utilizing quantum computers, could replace the need for bulky and expensive home computers – allowing all the processing power to be held in the cloud could provide a new version of home computing that enables small and inexpensive thin-client type systems.

Likewise, quantum communications that are unhackable will provide network security to organizations that suffer instances of cyberattacks or corporate espionage. Quantum clocks, not discussed here, have implications for all industry sectors that rely on current atomic clocks today, namely financial institutions and GPS which is used by the world's shipping fleets.

Advances in quantum magnetometers could be used in resource mining operations to locate previously undiscovered nodes of rare earth metals. Additionally, these sensors could be used in search and rescue operations for ships, submarines, or aircraft that are lost at sea. These quantum magnetic sensors also have clear applications to the medical field. These sensors could offer more capable detection of various diseases and heart conditions. [45] Additionally, these sensors don't rely on "bulky and expensive equipment" that is present in medical establishments today. [46]

## Getting There First

Despite the clear examples of advancing quantum technology, some critics say that these capabilities are more distant than this analysis assumes.[47] While some advancements are slow-going and overhype might occur, nothing in this paper is science fiction. The technologies described above are real advancements being studied in the best universities in the world. To say that proliferation of quantum technologies for military use isn't on the precipice of occurring is woefully negligent. Quantum technologies are going to change the strategic environment. The real question is: *How would the United States handle a quantum-equipped China without the ability to compete or even counter its new capabilities?* **The United States must raise awareness of this threat by highlighting the strategic implications within published posture statements and testimonies to U.S. Congress.**

[45] Sir Peter Knight & Sir Mark Walport, *The Quantum Age: Technological Opportunities,* United Kingdom Government Office for Science, 2016.
[46] Ibid.
[47] James Wootton. "Quantum Computing Is Not As Close As You Might Have Heard," *Medium* (21 Sep 2017), https://tinyurl.com/y72zjhd3. (Accessed 6 Oct 2017)

Countless institutions and organizations are researching applied quantum physics, but Massachusetts Institute of Technology (MIT) – Lincoln Laboratory (LL) is perhaps America's leader in advancing *quantum sensing* capabilities. As their "Quantum Information Science" program goals state, "*Quantum sensing* at Lincoln Laboratory focuses on devices that exceed the capability of their classical counterparts." [48] The idea of adapting existing capabilities and enhancing them through new quantum sensors is not new, but it is extremely valuable. **The future of national security in the United States depends on the government's ability to foster collaboration and cooperation between industry, academia, defense, and other state entities.**

A whole-of-country approach must be taken to ensure America's quantum future. This means that the U.S. should also show urgency to this course of action with allocated spending on research and development, as well as testing, procurement, and integration into the current military force structure. A model to follow is that of Britain's creation of the *National Quantum Technologies Programme,* a multi-discipline, multi-industry program that is funded to "capitalise on [Britain's] comparative advantage."[49] **Without budgetary priority aimed to further R&D, the United States will fall further behind in the Quantum Race.**

The day the globe wakes up to various quantum technologies with real-world applications, everything changes. This is not science fiction. This is real, and it is a potentially devastating group of technologies that we could use to destroy any adversaries in the near and far

[48] "Quantum Information and Integrated Nanosystems." MIT Lincoln Laboratory: Advanced Technology: Quantum Information and Integrated Nanosystems. (Accessed 1 Oct 2017). https://www.ll.mit.edu/mission/electronics/qiin/quantum-info-science/quantum-info-science.html.
[49] Sir Peter Knight & Sir Mark Walport, *The Quantum Age: Technological Opportunities,* United Kingdom Government Office for Science, 2016. This report shows UK's wholistic approach to further research of quantum technologies for economic and domestic benefit. This would be a useful model to follow for a country attempting to accomplish similar advancements.

term or used against us with the same results. If no action is taken to secure a quantum future, the U.S. is settling for the second place in a deadly game of winner-take-all.

## Future Research Recommendations

Research is owed in all fields of applied quantum physics. The following is a list of recommended topics to pursue with particular attention paid to national security concerns:

**Quantum Computing:**

1. How will quantum computing affect the planning of military operations?
2. If artificial intelligence technology could be integrated into a ship's control systems, how could saved man-hours be recapitalized?
3. What human analysis tasks that occur within the Department of Defense could be better performed by highly capable computers?

**Quantum Communications:**

1. How will submarine employment change *when* communications are achievable while operating at speed and depth? Will this lead to more or less missions expected of submarines?
2. What additional infrastructure will be required to achieve truly end-to-end quantum communications between submarines and shore facilities?
3. Though extremely secure, how resilient will quantum communications be in times of conflict between global superpowers?
4. As the future will likely have a mix of classical and quantum communications, what applications will benefit from traditional methods? In other words, what will remain the same after the wide adoption of quantum communications?

**Quantum Sensing:**

1. Are quantum magnetometers sensitive enough to detect a submarine operating beneath the ocean's surface when deployed from a satellite? If so, how will this change employment tactics?
2. What additional capabilities will be gained once naval shipboard sensors reach a *quantum* level of accuracy.
3. Can the required components for quantum navigation sensors be miniaturized enough, at an acceptable cost, to be placed on missiles? What are the follow-on effects of non-satellite reliant missile systems?
4. What will the resolution be on quantum imaging systems that are employed from satellites in LEO, GEO?
5. What short-range capabilities could be gained from advances in quantum imaging? Specifically, how can the U.S. Army and Marines utilize quantum sensing technology?
6. How will quantum sensing affect a commander's ability to maintain an accurate operational picture during naval operations?

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