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Foreword to the Special Issue on Quantum Radar—Part 2

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QUANTUM physics has had a large impact on our everyday life. Relevant examples range from transistors and Monolithic microwave-integrated circuit, or MMIC,[1] that make most of our technological society, as well as to nuclear energy, and to the science of materials. Some of these technologies have met with indisputable success while others have not proven to be useful to date. It should be remembered that the idea of a clean energy coming from nuclear fusion is an unfulfilled promise: such technologies have always involved a change of paradigm that made them quite different from known expectations. Note that Von Neumann machines, the foundations of our computers, are based on hardware made from quantum mechanics effects but they are otherwise easy to understand. A quantum computer is a rather different object and not so easy to comprehend unless an extensive knowledge of quantum physics is achieved. The same applies to the quantum radar (QR), the main topic of this special issue, which is quite different from a classical radar, both in terms of the working principles and the kind of hardware to realize it. The today's radars are based on the propagation of electromagnetic waves of the classical (nonquantum) physics. The QR promises to be a radical change. It should be said that we are yet at a pioneering stage and we cannot be certain yet if a goal will be achieved nor in what form we will see it, though, R&D is progressing.

One of the central tenets of quantum aspects is that observation inevitably disturbs the object being observed. This is especially well understood for microscopic objects. In radar applications, one is interested in sensing macroscopic objects. This leads to the natural questions: is there a role for quantum physics to improve the sensing of macroscopic objects, and where is the role of radar (as observer) with respect to the target (the observed object)?

An initial view might be that quantum physics is not relevant for macroscopic applications. It is true that quantum coherence has macroscopic manifestations, such as in a superconductor or with liquid helium. The very nature of such states that are to maintain quantum coherence for a long time is strongly linked to the way such states are prepared. For all practical purposes, the most possible preparations of a quantum state will yield quite swiftly a classical state. This can be due to interaction with the environment but also due to a beautiful theorem by Lieb and Simon that makes most many-body quantum states intrinsically fragile [1], [2], [3]. This has been experimentally observed with nuclear magnetic resonance (NMR) techniques [4].

However, as pointed out by Quantum sensors program [5] (with prescient insights from Lloyd [6] and Sacchi [7]), the benefits of fragile quantum property of quantum entanglement can survive in sensing applications even though entanglement is broken. This naturally leads one to consider what other possible routes of enhancement are possible from quantum physics.

What is a QR? There has been a taxonomy proposed in the literature (summarized in the Harris report on Quantum Sensors [5]), with an emphasis on the "quantum" aspect. We believe it is also important to emphasize the "radar" aspect.

The first important criterion is that a QR proposal should be buildable and ideas testable. A proposal that aims to be a QR should have the ingredients needed to build a primitive variant of the idea. Some parts of the proposed radar may require an expensive and specialized fabrication facility, but as long as the only limiting factor is investment, it is a potentially interesting idea that should be explored.

As every radar engineer knows, a radar performs a multiplicity of functions. Apart from ranging, radars are used to estimate radial velocity via Doppler processing. Furthermore, range-independent high resolution is possible by radar signal processing using synthetic aperture radar processing. Multichannel radars have been developed that are able to suppress clutter (via space-time adaptive processing), and direction finding and jammer suppression (array processing).

Therefore, a second criterion is that a QR proposal should clearly identify what it can/cannot do among the wide variety of functions. It is possible that a novel QR proposal will only be able to do a subset of the functions, for example, limited to

[1]Recently, some research has been carried on microwave quantum devices based on the Josephson junction properties, namely to implement low-noise amplifiers and mixers.

a range finding application. Such ideas should be explored if it can perform only a subset of the functions it does provide gain in the functions. It is important that due consideration is given to the decades of work done by radar scientists/engineers. On the other hand, it would be too limiting to reject all ideas that do not fully conform to what is currently thought of as a radar, in much the same way that it would be too limiting to reject ideas that are not "fully quantum." Many such theoretical radar proposals may not be amenable to advanced radar signal processing (clutter suppression, array processing, etc.), but it may still be useful as a less featured remote sensor (range finding).

Third, an important point is that it exploits practically a novel quantum aspect in the transmit and/or receive sides, and that is not being exploited in current radars. This could be entangled photon pair generation, quantization of energy, quantized transitions (Rydberg), etc. Papers exploring such concepts are in the first issue.

Fourth, cost, size, weight, and power considerations are of course important in practice. However, these considerations should not limit whether an idea is explored. It is likely that an initial prototype might have too many drawbacks to be relevant for practical applications. However, the concept should not be equated with the initial technological implementation. After all, the initial implementation of the computer (Charles Babbage and Ada Lovelace's Analytical Engine, or later on the vacuum tube-based ENIAC) was not very "practical."

Still dwelling on the definition of a "QR," one of the Associated Editors (A. Farina) remembers the interesting paper [8] because it was previous to his paper [9] at the same symposium during the inaugural plenary session. Reading again the paper [8], the following points seem interesting to quote in this foreword. "A radar is said to be a QR if at the detection level we have insufficient RF target photons density to invoke classical physics by means of the Gaussian central limit theorem [8]." Indeed, this definition of QR deserves to be reiterated. Continuing to quote the authors of [8]: "The RF frequency electromagnetic waves are comprised of discrete photons. However, the energy of these photons is much weaker than at visible frequencies; thus, the quantum nature of these signals is generally discounted, without deleterious effects. At RF frequencies, the thermal noise is much larger than the energy of a single photon and so in general by the time one sees a radar signal the law of large numbers has kicked in and quantum effects becomes invisible."

Continuing with [8], the authors note: "As radar systems work with longer integration times, larger apertures, and smaller noise figures we can no longer necessarily ignore the photon nature of RF energy." The authors show that the quantum effects arise in the area of phased arrays verses dishes in particular for radio astronomy application where quantum effects might become substantial. An explanatory simulation of a "photon starved" phased array of 128 by 128 elements is compared to a dish of equal aperture. The authors show that the array loses $m = 128^2$ photons compared to the dish. The authors' interpretation of this result is that the array pays a price for the ability to measure where across the aperture the photon arrived. Knowledge always comes at a price in quantum theory and we see here that the price is one photon per element. As a practical example, the authors reported the imaging of the 216 Kleopatra asteroid by the Arecibo radio telescope in Puerto Rico (https://news.cornell.edu/stories/2000/05/radar-shows-giant-bone-shaped-asteroid). They conclude that in general arrays would underperform dishes in low-noise environment. In short, these are some lesson learned from [8].

The increased importance of quantum technologies is testified by the choice of *IEEE Aerospace and Electronic Systems Magazine* to introduce a new category: Quantum Technologies for Aerospace. This will be managed by one of us (M. Frasca) as an Associate Editor.

This special issue on QR contains five interesting papers that reflect both the radar engineer as well as the quantum physics viewpoints.

F. Daum raises some practical, system engineering aspects "Quantum Radar Cost and Practical Issues." He notes the many challenges in developing a practical system based on breadboard radar used in experimental investigations carried out in the laboratory to date. QR scientists seeking to develop practical systems would do well to satisfactorily address the issues raised in the paper.

A. Karsa and S. Pirandola carry out a quantum information theoretic analysis of a quantum illumination radar architecture with a phase-conjugating receiver, and derive the SNR in terms of signal and idler energies and their cross-correlations. This analysis helps them identify regimes such a radar may offer a performance benefit over a classical radar.

In “Evolution of Quantum Radar Concept to Noise Radar Concept,” leading noise radar researcher K. Lukin turns the idea of QR on its head. He proposes the application of stepped-frequency concept to the design of QR. The paper concludes by noting that while QR is unrealistic for long-range radar applications, QR could be a promising approach in extremely near-field applications and extremely high frequencies.

M. Lanzagorta and J. Uhlmann present a back-of-the-envelope and implementation-agnostic analysis of QR that suggest that in some contexts QR can be expected to offer realizable practical advantages over classical alternatives.

C. Wilson and J. Bourassa discuss the current situation of microwave quantum illumination in view of the prototype that was realized to show the working principle. The main difficulties to be overcome yet are on the transmission and amplification of entangled photon pairs without destroying quantum coherence. In principle, it appears feasible, if not in view yet, a fully superconductive QR with the current technology.

The research on QR among the radar community appears to be gaining momentum. There was a special issue on QR at the IEEE International Radar conference in Washington, DC, USA, in April, 2020. In September, 2020, IEEE Radar Conference in Florence, Italy (https://www.radarconf20.org/) features a special session on QR. The following year will feature a double session at IEEE Radar Conference 2021 at Atlanta, Georgia, USA (https://ieee-aess.org/conference/2021-ieee-radar-conference), including a public debate on the topic, moderated by F. Daum. The articles at Florence extend past work in interesting directions, in particular:

Quantum Radar: Real World Experiments and New Theory, Chairs: B. Balaji, F. E Daum

– S. Barzanjeh, S. Pirandola, D. Vitali, J. Fink, “Microwave Quantum Illumination with a Digital Phase-Conjugated Receiver.”

– N. Messaoudi, A. M. Vadiraj, J. Bourassa, B. Balaji, Christopher M. Wilson, “Practical Advantage in Microwave Quantum Illumination.”

– R. S. Jonsson, R. Di Candia, M. Ankel, A. Strom, G. L. Johansson, “A Comparison Between Quantum and Classical Noise Radar Sources.”

– D. Luong, B. Balaji, S. Rajan, “Simulation Study of a Detector Function for QTMS Radar and Noise Radar.”

– M. Frasca, A. Farina, “Multiple Input-Multiple Output Quantum Radar.”

In this special issue, we have focused on quantum technology for radar. Quantum technology is of course also applicable to other topics of interest to our audience, such as electronic warfare, position, navigation, and timing (PNT)[2] as well as communication. The impact of quantum technology on electronic warfare demands attention in parallel to QR. However, in some cases, such as PNT and communication, quantum technology is more near-term than QR. A recent example is the demonstration of entanglement in the optical regime on a nano-satellite, which is an important step for quantum key distribution using nano-satellites [10], as compared to the considerable challenges, such as need for dilution refrigerators, for some approaches to microwave QRs [11].

In summary, we believe that for research in QR (paraphrasing Richard Feynman) “it is necessary both to accept and to reject the past and explore the future, with a kind of balance that takes considerable skill.” We are supremely confident that the readers of this special issue have the requisite skill!

Finally, not all the progress in science and technology takes place in isolation. Understanding of quantum physics and relativity happened in the midst of World Wars and difficult times in between. These days humanity is facing severe challenges as well, that challenges us all. We wish the readers best and hope the *fratelli e sorelle ingegneri* radar (radar and engineer brothers and sisters) are inspired to come up with even more exciting ideas in the future.

[2]D. Corey in his presentation entitled “Quantum Showcase,” December 5, 2019, at the University of Waterloo, Canada, discussed the use of early quantum technology, a first sensor with a quantum control element, based on birefringence of calcite, late 10th century navigation of Viking. This interesting topic has been the subject of the following recent publication by D. Száz and G. Horváth, “Success of sky-polarimetric Viking navigation: revealing the chance Viking sailors could reach Greenland from Norway,” *Royal Society, Open Science*, pp. 1–10, Mar. 6, 2018. Available: http://dx.doi.org/10.1098/rsos.172187.

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REFERENCES

[1] E. Leib and B. Simon, "Thomas-Fermi theory revisited," *Phys. Rev. Lett.*, vol. 31, pp. 681–683, 1973. [Online]. Available: https://authors.library.caltech.edu/85914/1/PhysRevLett.31.681.pdf.

[2] E. Leib and B. Simon, "Thomas-Fermi theory of atoms, molecules and solids," *Adv. Math.*, vol. 23, pp. 22–116, 1977. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0001870877901086

[3] M. Frasca, "Thermodynamic limit and decoherence: Rigorous results," *J. Phys., Conf. Series*, vol. 67, 2007, Art. no. 012026. [Online]. Available: https://iopscience.iop.org/article/10.1088/1742-6596/67/1/012026.

[4] P. R. Zangara and H. M. Pastawski, "Loschmidt echo in many-spin systems: A quest for intrinsic decoherence and emergent irreversibility," *Phys. Scripta*, vol. 92, no. 3, 2017, Art. no. 033001.

[5] "Quantum sensors program," Harris Corporation, Sponsored by DARPA, Melbourne, FL, USA, Final Tech. Rep. AFRL-RI-RS-TR-2009-208, Aug. 2009. [Online]. Available: https://apps.dtic.mil/dtic/tr/fulltext/u2/a506209.pdf.

[6] S. Lloyd, "Enhanced sensitivity of photodetector via quantum illumination," *Science*, vol. 321, 2008, Art. no. 1463, [Online]. Available: https://science.sciencemag.org/content/321/5895/1463).

[7] M. F. Sacchi, "Entanglement can enhance the distinguishability of entanglement-breaking channels," *Phys. Rev. A*, vol. 72, 2005, Art. no. 014305. [Online]. Available: https://journals.aps.org/pra/abstract/10.1103/PhysRevA.72.014305.

[8] A. Steinhardt and J. McCrabe, "Radar in the quantum limit," in *Proc. IEEE Int. Symp. Phased Array Syst. Technol. [Plenary Session Invited Talk]*, Boston, MA, USA, Oct. 14–17, 2003, pp. 31–34.

[9] M. Cicolani, A. Farina, E. Giaccari, F. Madia, R. Ronconi, and S. Sabatini, "Some phased array systems and technologies in AMS," in *Proc. IEEE Int. Symp. Phased Array Syst. Technol. [Plenary Session Invited Talk]*, Boston, MA, USA, Oct. 14–17, 2003, pp. 23–30.

[10] A. Villar et al., "Entanglement demonstration on board a nano-satellite," *Optica*, vol. 7, pp. 734–737, 2020.

[11] M. Zheng et al., "A brief review of dilution refrigerator development for space applications," *J. Low Temp. Phys.*, vol. 197, pp. 1–9, 2019.