Entanglement-Based Quantum Radar: From Myth to Reality

David Luong, Defence Research and Development Canada; Carleton University
Sreeraman Rajan, Carleton University
Bhashyam Balaji, Defence Research and Development Canada

INTRODUCTION

Are quantum radars feasible? This fledgling field has attracted not a little attention lately, and it is natural to ask whether it is science or snake oil. We are happy to report that it is sound, sober science. In this article, we offer brief explanations of what quantum radars are? Why they work? How we can build one? What they can do?

What is a quantum radar? The short answer is that any radar which exploits phenomena unique to quantum mechanics to improve detection performance can be called a quantum radar. However, this is an extremely broad definition. In this article, we will focus on radars based on quantum entanglement, one of the most distinctive of quantum mechanical phenomena. The reason such radars are of interest is because they present a possible new solution to the question: how do we distinguish signal from noise? And this solution works at very low transmit power levels, where other radars might be swamped by noise.

Vast amounts of research and development have been devoted to the problem of distinguishing signal from noise. The strategy that a radar uses to solve this problem is heavily baked into every aspect of its design [1], [2], [3]. The radio waves it transmits are chosen to make the distinction easier; its measurement apparatus is designed to filter out unwanted signals; no component of a radar escapes the all-pervading need to combat noise. Research in this direction has never slackened since the invention of the radar itself, and there is every reason to believe that this work will continue for a very long time to come.

So where does quantum physics come into the picture? The fact is, most radars today are designed under the assumption that so-called “classical” physics holds. Examples of theories from classical physics include Newton’s laws of motions and Maxwell’s equations for electromagnetism—topics typically taught in undergraduate physics courses. However, these theories are known to hold only under circumstances typically encountered in everyday life. When one ventures outside those limits, these theories break down. Over the last century, scientists have developed a pair of theoretical frameworks, which account for all known physical phenomena: quantum theory and relativity. It is, therefore, possible that, if we search through this wider set of phenomena, we might hit upon something that might improve the radar performance.

In the case of quantum theory, research has shown that there are indeed certain phenomena, unexplained by classical physics, which have the potential to improve the radar performance [4], [5]. Chief among them is quantum entanglement, a potent weapon in the war of signal versus noise. At the inception of quantum physics, scientists did not have a firm grasp on such phenomena. The situation is very different today. Not only are these phenomena well-established, well-tested, and well-understood, researchers have realized that they can be exploited for practical purposes. In other words, quantum phenomena are no longer the exclusive preserve of scientists; they are also increasingly relevant to engineers.

The emergence of the field of the quantum radar in recent years is a recognition of the fact that, if we narrowly restrict ourselves to classical paradigms, we may miss out on valuable tools. It is, in large part, a response to the ongoing...
quest for better ways to identify genuine radar echoes amid noise. This is not the only aspect of radars that can be improved using quantum techniques, however. It is possible to develop quantum-enhanced receivers, for instance, which can detect signals at very low powers. Nevertheless, we will focus on the signal-versus-noise problem in this article because most work in the quantum radar has been in this direction.

One type of the entanglement-based quantum radar, called quantum two-mode squeezing radar (QTMS radar), has been experimentally demonstrated to be a feasible quantum range finder [6]. However, modern radars are not just range finders. They are rich in possibilities and capabilities, such as a synthetic aperture radar (SAR), adaptive array processing, and space-time adaptive processing (STAP) [3], [7]. Can a quantum radar do all that? In the case of QTMS radar, the answer is a definitive yes. This shows that there exists a definite path to a quantum radar, which can do everything modern radars can do. What is needed now is the will to follow that path.

The following is a largely heuristic discussion and is not meant to be exhaustive in terms of possibilities offered by quantum physics. A rigorous discussion would require material from quantum theory, which cannot be covered in a single article. We hope, however, that it gives a flavor for some of the possibilities of an entanglement-based quantum radar.

**HOW TO DISTINGUISH SIGNAL AND NOISE: MATCHED FILTERING**

The main function of a radar is to discriminate the signal of interest from the interference background, which comprises thermal noise, clutter, and intentional interference (jamming). Unlike other interference sources, thermal white noise cannot be suppressed via signal processing. Hence, distinguishing signal from noise is a fundamental problem in radar design. In order to understand what parts of a radar can be improved using quantum physics, it is helpful to have a basic idea of how radars actually deal with noise. (At this point, we will ignore other important practical issues such as clutter and interference. These will be discussed later). In order to keep the analysis simple, we will assume that the radar is attempting to detect a single, stationary target with a high radar cross section unless otherwise noted.

On a very basic level, the operation of many types of radars is based on matched filtering, which can be summarized as follows.

1) Produce a signal and transmit it toward a target. Retain a record of this signal.

2) Receive a signal, which may or may not contain an echo of the transmitted signal.

3) Correlate the received signal with the record of the transmitted signal.

4) If the correlation exceeds a preset threshold, declare that a target is present.

The rationale behind this scheme is that a genuine echo should be highly correlated with the originally transmitted signal. Therefore, an echo corrupted by noise may still be more strongly correlated with the original signal than pure noise. Note that the received signal does not need to be highly correlated with the recorded signal. For detection to succeed, it is only necessary that the detected correlation be distinguishable from zero correlation. But in order to achieve this distinguishability, the transmitted signal should be as strongly correlated with the recording as possible.

The quantum radar schemes that we consider in this article offer potential improvements in the fidelity of the record of the transmitted signal. In other words, quantum radars could produce transmitted and recorded signals, which are more highly correlated than any signals produced by a perfect “classical” source, irrespective of future technical advances in such classical sources. The reason this improves radar performance is that, the higher the correlation at the transmit side, the more room we have for noise to corrupt the received signal, yet still maintain detection performance.
This might seem like an odd place to improve. After all, could not we produce two exact copies of the same signal and keep one of them as a recording? In that case, the correlation would be 100%, and there would be nothing to improve. Unfortunately, this holds only in classical physics. Quantum physics tells us that at low signal powers, it is impossible to generate highly correlated signals using conventional techniques like splitting a signal. This would work only in the high-power regime. To achieve high correlations at low power, we require quantum entanglement. In the following section, we will see why this is so.

### ENTANGLEMENT

As mentioned above, entanglement is an important quantum phenomenon that could potentially improve the radar performance. We will see, in fact, that the most promising classes of the quantum radar all make use of entanglement. It is, therefore, important to have some sort of idea of what entanglement is all about. We do not propose to present an exhaustive review of quantum entanglement in this section; for that, the interested reader may refer to textbooks such as [8]. Luckily, we do not need all that to gain a basic working knowledge of entanglement as applied to quantum radar. All that is needed is an understanding of basic probability theory.

Before we talk about what entanglement is, however, it will be helpful to talk about what entanglement is not. Some people, in a well-intentioned attempt to simplify a difficult topic, explain entanglement in such a way as to give the following impression. “If one entangled particle interacts with something, its twin would react in the same way, even if it is far away.” This is unfortunate, because the statement is not true! One way to understand the falsity of this statement is to consider a pair of entangled pulses of light. Imagine sending one pulse through free space and the other at a wall. According to this incorrect description of entanglement, the first pulse would disappear into thin air as soon as the second hit the wall, violating the law of conservation of energy. This law is no less true in quantum physics than in any other physical theory, so the above-stated basic principle theory.

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Related to this misconception is the idea that it is possible to “read” what happened to one particle of an entangled pair simply by looking at the other, although they do not necessarily react in exactly the same way. This would imply that, if one of the particles were directed at a target, its interaction with the target could be inferred from its entangled twin without actually receiving a signal from the target. Einstein’s famous phrase, “spooky action at a distance,” would seem to support this interpretation. This too is untrue. It is impossible, according to the currently known laws of physics, to gain information about a target without receiving some sort of signal from that target.

In order to gain a more correct understanding of quantum entanglement, we must understand that entanglement is a statistical phenomenon [9]. Once we begin thinking in terms of random variables and probability theory, it is possible to have a better understanding of the implications of entanglement. In fact, statements about entanglement are statements about correlations between random variables. In addition, just as random variables can be broadly classified into discrete and continuous random variables, so entanglement can be broadly classified into discrete- and continuous-variable entanglement. (This is not a hard distinction, however). Many of the more striking and unusual properties of entanglement are best presented in the discrete case, but continuous-variable entanglement is more applicable to the quantum radar. It is also more easily understood without a background in quantum physics. Therefore, we will focus solely on continuous-variable entanglement.

### QUANTUM NOISE

Before continuing our discussion of entanglement, we must discuss the concept of quantum noise. Consider an electromagnetic signal of any kind, like a beam of light or a microwave pulse. If we measure the in-phase and quadrature voltages (I and Q) of this signal, we often find that in addition to the ideal waveform we expect it to have, it contains some amount of noise. This noise could be atmospheric noise or thermal noise, for example. According to classical physics, there is no reason why this noise cannot be entirely removed. In principle, we could eliminate the atmosphere or cool everything to absolute zero. Quantum physics tells a different story: even in theory, we cannot fully eliminate noise. That is to say, even in absolutely ideal conditions, quantum physics predicts that any I/Q measurement will contain a certain amount of noise. This residual noise is an example of quantum noise.

Figure 1 shows a comparison of the results we might obtain from measuring a beam of light under classical and quantum physics, both under ideal conditions. We can see clearly that, in the quantum case, the measurement result is noisy. The amount of noise here cannot be reduced under any circumstances; the theory of quantum physics forbids it.

Another property of note, not shown explicitly in the figure, is that this minimal amount of quantum noise does not change with the amplitude of the signal. Therefore, when signal powers are very high, the noise becomes negligible and is rightfully ignored in current radars. Conversely, when signal powers are extremely low, this noise can be a substantial confounding factor.
suggestions that one regime in which the quantum radar can have an immense impact is in the low-power regime—a suggestion supported by experiment, as we will see later.

The key takeaway from all of this is that we must regard $I$ and $Q$ voltages as random variables with nonzero variances. (As a matter of fact, this follows from the Heisenberg uncertainty principle, which sets a lower bound on the product of their variances.) The clean and noiseless waveforms of classical physics specify merely the average behavior of an electromagnetic signal; they do not quite tell the whole story, especially at low signal powers.

**ENTANGLEMENT AS CORRELATED QUANTUM NOISE**

Suppose now that we have **two** electromagnetic signals. As explained above, each one must have a certain amount of quantum noise. If the quantum noise in each signal is independent of each other, it follows that the two signals can never be 100% correlated. This seems to put a hard limit on how strongly correlated the two signals can be, but that is not so. Quantum physics dictates that the two signals must be noisy; it does not say that the noise in each signal must be independent. Therefore, the “hard limit” does not exist. There does exist a level of correlation, however, beyond which the quantum noise in the two signals cannot remain independent. If the correlation is higher than this level, the two signals are entangled. This is depicted in Figure 2. Note that entanglement is not merely a statement that the quantum noise is correlated. Two signals whose quantum noise components are correlated, but exhibit low levels of “classical” correlation, are nevertheless not entangled. Only when the overall correlation is so high that the quantum noise is forced to be correlated can we say that the signals are entangled.

In summary, then, **if two electromagnetic signals are so highly correlated that their quantum noise cannot be independent, the two signals are entangled.** Although this description is very far from a comprehensive description of entanglement, it is all we need.

**CHALLENGES IN GENERATING ENTANGLLED SIGNALS**

The generation of entangled signals is a very deep topic, and it would be outside the scope of this article to enter into an extensive discussion of the details. Here, we cannot do more than touch on a few basic facts and show that entanglement generation is a nontrivial task. For further details, the reader may consult a book on quantum optics, such as that by Scully and Zubairy [12].

Naively, we might think that generating a pair of highly correlated signals should be straightforward. For example, we could use two arbitrary waveform generators to generate exactly the same signal, which would then be 100% correlated. This cannot work because arbitrary waveform generators cannot control the quantum noise in the signals. As a consequence, the generators cannot cause the quantum noise in the two signals to be correlated. Therefore, by definition, the two signals are not entangled.

Another idea is to generate **one** signal, then use a beamsplitter to split it in two. Perhaps in this way we could have 100% correlation? Unfortunately, beamsplitters cannot create entanglement out of classical signals such as sinusoidal waves. The reason is somewhat subtle. It turns out that, according to quantum optics, every beamsplitter must have...
two input ports. Of course a physical splitter may only have one input port built into it, but there is always a notional second input port which cannot be ignored in a quantum optical analysis. The reason why this second port is significant is because, at the very least, there is a vacuum in that port. It has been proven that if the inputs to a beamsplitter are classical, the outputs can never be entangled [13], [14]. A vacuum is certainly classical; it can be thought of as a signal with amplitude zero (though it still contains quantum noise which would be mixed into the output signals). We may conclude that any conventionally generated signal (from an arbitrary waveform generator, for example) cannot be split into two entangled signals using a beamsplitter.

One of the most common methods of generating entangled electromagnetic signals is to take a single signal and split it into two using some sort of optical nonlinearity. At optical frequencies, there exist nonlinear crystals that are suitable for entanglement generation. One such crystal was used for the experiment described in [15], for instance. At microwave frequencies, obtaining the necessary nonlinearity is substantially more difficult. We shall see in the following section, however, that it is by no means impossible.

However difficult it may be to produce two entangled signals, multipartite entanglement is much more difficult. After all, bipartite entanglement involves correlations between only two random variables. Multipartite entanglement implies correlations between three or more random variables, which is more difficult a fortiori. It is possible to have a quantum radar that exploits multipartite entanglement, but only bipartite entanglement is actually required. With quantum computers, multipartite entanglement is absolutely necessary. For this reason, it is far more difficult to build a quantum computer than it is to build a quantum radar [4].

BUILDING AN ENTANGLEMENT-BASED QUANTUM RADAR

As explained in the previous section, every electromagnetic signal must contain quantum noise. The correlation between any two signals will necessarily be limited so long as their quantum noise components are uncorrelated. This will always be the case for any pairs of signals created by methods based on classical physics. Therefore, there is a limit to how well a signal and the record of that signal are correlated—a limit that can be overcome by using entangled signals. This is the key insight that is exploited by quantum radars based on entanglement. Looking back on “How to Distinguish Signal and Noise: Matched Filtering” section, we can now appreciate how it is possible to improve the correlation between the transmitted signal and the recorded copy of it. If the signal and its copy are entangled, their correlation will go up and the matched filtering process can more easily pull the signal out of any background noise.

This discussion shows that only bipartite entanglement is necessary for an entanglement-based quantum radar. We require entanglement between the transmitted signal and its recorded copy. Multipartite entanglement, as required for quantum computers, is unnecessary.

So far, quantum theory suggests that entanglement can possibly lead to improvements in radar performance. The question now becomes: is it possible to generate entangled signals that can be used in radar applications? Luckily, the answer is yes.

At optical frequencies, generating entangled signals is relatively easy because nonlinear crystals suitable for such frequencies are available. In fact, quantum lidars have already been experimentally demonstrated [15], [16], [17], [18]. To date, no scientific publication has described a full experimental implementation of a quantum radar at microwave frequencies, so the question of the practicality of such a radar is—strictly speaking—still open. However, a recent experiment by Wilson et al. at the University of Waterloo’s Institute for Quantum Computing, in collaboration with Defence Research and Development Canada, strongly suggests that radars based on entangled microwaves are feasible [6], [19], [20]. Although these experiments are not a full implementation of a quantum radar, they come extremely close. Not only that, they show that performance gains are indeed possible, as we would expect from quantum theory.

In the following, we will focus on the University of Waterloo experiment mentioned above, which we call a QTMS radar. This is because it represents a clear technological route to a quantum radar. At the very least, it demonstrates all the necessary components of a quantum range finder. However, it has the potential to perform all the other tasks performed by current radars, including clutter suppression. Other routes to a quantum radar are possible as well, as we will see later.

QUANTUM TWO-MODE SQUEEZING RADAR

Figure 3 is a block diagram of the QTMS radar setup. The operation of the radar is more straightforward than the diagram may lead one to assume; the essentials are depicted in Figure 4. The key to the entire setup is the Josephson parametric amplifier (JPA), which generates a pair of entangled microwave beams. In other words, it generates a pair of signals that have a Pearson correlation coefficient higher than the classical limit depicted in Figure 2 and discussed in “Entanglement as Correlated Quantum Noise” section. Apart from the high-electron-mobility transistor, which is a low-noise amplifier, none of the other components inside the box marked “dilution refrigerator” actually affect the signals produced by the JPA. Once this is understood, we can summarize the operation of the radar as follows.
Figure 3.
Simplified block diagram of the QTMS radar setup.

Figure 4.
High-level schematic of the QTMS radar setup. The entangled beams are generated by a JPA residing within a dilution refrigerator. One of the beams is transmitted through free space; the other is recorded for later matched filtering.
1) Use the JPA to generate an entangled signal. Amplify both signals. Transmit one of them through free space. Perform a heterodyne measurement on the other and retain a record of the results in the form of time series of in-phase ($I$) and quadrature ($Q$) voltages.

2) Receive a signal. Perform a heterodyne measurement on it to produce time series of $I$ and $Q$ voltages.

3) Correlate the $I$ and $Q$ voltages of the received and recorded signals.

4) If the correlation exceeds a preset threshold, declare a detection.

If we compare this protocol to the generic one described in “How to Distinguish Signal and Noise: Matched Filtering” section, we can see that the QTMS radar protocol performs matched filtering just as described before. In this case, the record of the transmitted signal is obtained by measuring a signal, which was entangled with the transmitted signal. As described at the beginning of this section, we expect the use of entanglement to improve the fidelity of the record to the transmitted signal.

From this summary of the QTMS radar protocol, we can glean one important fact: the measurements performed on the signals are standard heterodyne measurements, and the results of the measurements are time series of $I$ and $Q$ voltages. Such measurements are very familiar to radar engineers and do not require complicated equipment. All the components required to perform such measurements are commercially available. This greatly increases the practicality of this scheme, especially as it means that standard radar signal processing can be applied. We may also note that the measurements on the received and recorded signals are independent. Other quantum radar schemes, such as quantum illumination (QI), require a joint and simultaneous measurement on the two signals, which is difficult to arrange.

Practically speaking, two of the most noteworthy components of this experimental design are the JPA and the dilution refrigerator within which it resides (Figure 5). The JPA is so important that we will devote the following section to it. The dilution refrigerator (which takes its name from the fact that it uses a mixture of helium-3 and helium-4) keeps its contents at cryogenic temperatures, a necessity for JPAs. The bias T and shot noise thermal junction are used only to calibrate the system when certifying that the JPA is indeed producing an entangled signal; they are unnecessary for the actual operation of a QTMS radar. As for the circulators, they prevent stray signals from entering the JPA and corrupting the entangled signals. The input port is not actually used in this experiment.

At present, this setup can only perform range finding, but later we will discuss extensions to other radar applications. Before that, though, we must note that there are two shortcomings, which prevent this experiment from being a full realization of a quantum radar or even a quantum range finder. The first shortcoming is that the experiment was only a one-way setup in which the transmitted signal was directly received at the receive horn; it was not reflected off a target. This, however, is easily remedied in future experiments; there is no reason why target detection would pose any significant problems.

The second and more important shortcoming is that the setup amplifies the entangled signals coming out of the JPA. This makes signal detection easier because the JPA output is at the very low power of $-145.43$ dBm (2.864 attowatts). However, the amplifiers add so much noise to the signals that, after the amplification process, the signals are no longer entangled. In general, if noise is added to an entangled signal pair, the correlation between the signals will fall. Once the correlation falls below the entanglement limit depicted in Figure 2, the resulting signal can be reproduced using classical devices and there is no need for an entangled signal generator. Therefore, in a pure quantum radar, any amplifiers in such a generator must not add so much noise that the correlation falls below the limit. The shortcoming of the experiment described above is that the amplifiers do add too much noise. The most obvious way to eliminate this noise is to simply remove the amplifiers: without amplifiers there is no amplifier noise. (Noiseless amplifiers are impossible [21].)
The challenge for the QTMS radar experiment is that, apart from amplifying the entangled signals, the amplifiers isolate the JPA from external signals, which might corrupt the entanglement generation process. However, this may be overcome by replacing the amplifiers with a series of circulators. These circulators would reproduce the isolation property of the amplifiers without adding noise. Another intriguing possibility is to amplify only one side of the entangled signal pair. As suggested in [22], the entanglement is more robust to amplifier noise in this case. In fact, in the extreme case of a so-called quantum-limited amplifier, which adds the minimum possible amount of noise consistent with quantum mechanics, the entanglement will not be broken even for arbitrarily large amplifier gains! This needs to be experimentally tested in the microwave regime. It may be of interest to note that, quite apart from its entanglement generation capabilities, an ideal JPA is a quantum-limited amplifier.

Despite these shortcomings, the QTMS radar experiment demonstrates almost all the ingredients required in an entanglement-based quantum radar, as listed in [23]:

1) an entangled signal generator (the JPA);
2) transmission of a signal through free space;
3) measurement and correlation of signals as required for matched filtering.

Even at this early stage, the experimental results are tantalizing. As described in [6], when the QTMS radar is compared to a classically correlated signal at the same power as the JPA output, which undergoes the exact same amplification process as the entangled signal, the latter reduces the required integration time by a factor of eight compared to the classical signal! Clearly, quantum radars have potential.

### Josephson Parametric Amplifiers

At the heart of the QTMS radar is a JPA, which is used to generate entangled microwaves. A JPA is essentially a microwave resonator with a variable resonance frequency. They have been used to generate “squeezed” quantum signals since at least 1988 [25]. The type of JPA used in the QTMS radar experiment consists of a resonant cavity with a superconducting quantum interference device (SQUID) at one end (see Figure 6). The resonance frequencies of the cavity can be modified by applying a magnetic field to the SQUID. If the magnetic field is modulated at a frequency corresponding to the sum of two resonance frequencies, the device generates a pair of microwave signals, one at each of the two frequencies. This modulation supplies the nonlinearity which, as noted in “Challenges in Generating Entangled Signals” section, can be exploited for entanglement generation. In the language of quantum physics, these two resulting signals are in the “two-mode squeezed vacuum state,” which is a specific type of entanglement wherein the I and Q voltages of the two signals are strongly correlated.

Unfortunately, JPAs are not yet available as off-the-shelf components. They have to be custom-designed and fabricated, which requires personnel with experience in nanofabrication and microwave circuit design. The specific JPA used in the QTMS radar experiment was fabricated in-house at the University of Waterloo except for a final evaporation step, which was performed at the University of Syracuse. (The evaporation can now also be done in-house). Luckily, this is the only major component in the QTMS radar that cannot be purchased commercially.

One major requirement for the operation of a JPA, as mentioned in the previous section, is that it must be cooled to cryogenic temperatures. In the QTMS radar experiment, the device was cooled to 7 mK. There are two major reasons for this: JPAs are superconducting devices that inherently require low temperatures to function, and JPAs are extremely sensitive to thermal noise. This means that JPAs require a significant amount of space and power to function. Luckily, JPAs themselves need not be large; the one used in the experiment was mounted on a printed circuit board approximately 3 cm long (see Figure 7). This means that multiple JPAs can fit into the same refrigerator (indeed, onto the same printed circuit board), a fact which will be important once we consider the possibility of building quantum radar arrays.

The JPA used in the QTMS radar experiment generated a pair of entangled microwave beams at 7.5376 and

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**Figure 6.**
Simplified diagram of a JPA, consisting of a resonant cavity with a SQUID at one end. This figure was reused from [24].

**Figure 7.**
JPA mounted on a printed circuit board. This picture was reused from [24].
Figure 8.
Receiver operating characteristic (ROC) curves for the QTMS radars and its “classical” counterpart, both operating at a power level of $-82$ dBm (after amplification), with an integration time of 80 ms.

6.1445 GHz, each with a bandwidth of 1 MHz. Only one of the beams is transmitted through free space, though either one could be easily chosen. In fact, it may be possible to build a system that switches between them. It is not possible to significantly change the frequencies on a JPA, but JPAs at various frequencies can be easily fabricated. It is also possible to build devices with larger bandwidths.

All this shows that the generation of entangled microwaves is absolutely feasible: JPAs can do the job. There are other possibilities as well, but we can state with certainty that there exists a device that can generate the desired signals.

PRACTICAL CONSIDERATIONS IN ENTANGLEMENT-BASED QUANTUM RADAR

No matter what type of radar we look at, there are multiple metrics to judge it with. A radar that scores very highly on one metric may score very badly on another. No radar is “optimal” in all respects. In this section, we give a brief overview of the various properties that an entanglement-based quantum radar might be expected to have, again taking the QTMS radar as a starting point.

Receiver operating characteristic (ROC) curves—plots of probability of detection versus probability of false alarm—are one of the most important metrics because they are directly related to what one sees on a radar screen. A false-alarm probability of 1 in 1 000 000 means that we would expect roughly one spurious blip on a display with 1 000 × 1 000 pixels. An example of these ROC curves is given in Figure 8, which compares the QTMS radar with a source of correlated but unentangled microwave beams. The latter corresponds to the point marked “Max classical correlation” on Figure 2. The JPA and the “classical” source operate at the same power, their signals undergo the same amplification, and the received signals are treated in exactly the same manner: an apples-to-apples comparison. The ROC curves show that the probability of detection is markedly higher for the QTMS radar compared to its classical counterpart. The difference in the curves corresponds to a change by a factor of eight in integration time: in effect, the classical radar would have to dwell on a target eight times longer to achieve the same detection probability as the QTMS radar [6].

A recent paper [26] states that the QTMS radar cannot outperform a classical radar when the power of the transmitted signal (not the received signal) is significantly lower than that of the reference signal retained within the radar. While intriguing theoretically, there does not seem to be a wide application space for this result.

By necessity, many types of entanglement-based quantum radars emit signals at very low powers because it is difficult to generate entangled microwaves quickly. This means that such radars are strong candidates for covert radars; it would not be easy to determine whether such a radar is operating. In theory, certain types of quantum signals have a distinctive nonclassical “signature,” which could theoretically be detected even at low signal powers, but this is not true of all entangled signals. Any radar based on two-mode squeezed vacuum, such as QTMS radar and QI radar, do not display any such signature so long as only one of the two entangled beams is transmitted. (This is the case for both types of radars when operating normally.) Their transmitted signals would look exactly like thermal noise, indistinguishable from background noise in the atmosphere. QTMS radar is a good example of a quantum covert range finder.

The fact that QTMS radar signals look like noise suggests a connection with noise radar, which has already been studied by radar engineers. In fact, a QTMS radar is essentially a noise radar with an entanglement source instead of a pseudorandom generator. (In [19], the QTMS radar was actually called a quantum-enhanced noise radar.) This means that QTMS radars inherit many of the properties of noise radars: low probability of intercept, low probability of detection, efficient spectrum sharing, and more [27], [28], [29]. A QTMS radar would be applicable wherever any of these properties are required, such as short-range medical sensing, medium-range smart home monitoring, and long-range UAV detection. Moreover, a QTMS radar would possess enhanced resiliency against noise at low signal powers compared to a noise radar. It also means that, as a first approximation, QTMS radar can be understood as an enhanced noise radar and all noise radar signal processing techniques can be ported over to QTMS radar.

One of the downsides of JPA-based QTMS radars is that they require cryogenic cooling. The refrigerator, helium tanks, and other paraphernalia used in the experiment described above requires about as much space as a large car, though this could be reduced by a dedicated engineering.
Effort. The power consumption is not trivial, either: approximately 15 kW. Although this is quite high compared to conventional radars, it is not an insurmountable obstacle. These considerations suggest that ground- or ship-based QTMS radars are feasible. Given that cryogenics have already been incorporated into spacecraft [30], space-based QTMS radars may also be possible. JPA is sensitive devices but not extraordinarily, so if mounted inside a ruggedized dilution refrigeration, heroic measures against disturbances would not be necessary. Moreover, as we will discuss later, JPA are not the only approach to generating entangled microwaves.

Cryogenically cooled radar receivers have been a topic of interest for some time [31], but it is important to note that the QTMS radar employs cryogenic cooling only for the radar transmitter. Its receiver is entirely conventional, is not cooled, and has nothing specifically “quantum” about it. In theory, QTMS radars and classical radars stand to gain equally by using cryogenically cooled receivers, so the possible use of such enhanced receivers does not form part of our analysis. From a practical point of view, it may not be impossible to cool both the JPA signal source and the receiver in the same refrigerator, resulting in enhancements at both transmit and receive.

It is worth noting that, in terms of detection capability, QTMS radars reduce to the performance of conventional radars at high transmit powers and high signal-to-noise ratios (SNRs). For applications where adverse SNRs are not a problem, therefore, it may not be worth the effort to switch to a quantum radar. By the same token, the performance of a QTMS radar does not drop below that of conventional radars at high SNR and high power, so an operational QTMS radar does not need to be supplemented by a conventional radar in order to operate in this regime. However, there are extremely important applications in the low-power, low-SNR regime, where QTMS radars could bring a benefit, such as long-range detection, improved low-probability-of-intercept capability, and ease of spectrum sharing.

FUTURE DIRECTIONS IN ENTANGLEMENT-BASED QUANTUM RADAR

There are two major directions for the continued development of the quantum radar, roughly corresponding to “quantum” and “radar.” The first category comprises such topics as entanglement generation methods, types of entangled signals, and measurement techniques. The second category involves topics like quantum radar arrays and signal processing. There are many areas to explore in both of these directions, and there is naturally some overlap between the two. Together, they represent a vast region of unexplored territory. Here, we can do no more than give a brief overview of the possibilities.

FUTURE DIRECTIONS: QUANTUM

Under this heading, we may list the following topics.

1) Increased transmit powers. We have already seen that JPA represent one method for generating entangled microwaves, which has been demonstrated to work. However, the signal power generated by a single JPA is very low: for the QTMS radar experiment, it was $-145.43$ dBm or $2.864$ attowatts. If the transmit power is low, the received power after target reflection would be very low indeed. This may pose a problem for long-range sensing, because any measurement apparatus has limits to its sensitivity. This is an important practical problem that needs to be solved for any type of quantum radar and reflects the difficulty of generating entangled signals in general. With JPA-based quantum radars in particular, we could increase the output of the JPA (by “pumping” it harder) or amplify the signal emitted by the JPA. The biggest problem with the first option is that if JPAs are pumped too hard, excess heat or other effects may degrade the output signal. This may be overcome by developments in JPA engineering. As for the second option, excessive amplification of an entangled signal will break the entanglement. A judicious use of low-noise amplifiers, however, would degrade but not break the entanglement. In fact, JPAs can be used as amplifiers (as their name implies), and in this role they would add the least amount of noise possible under quantum mechanics.

2) Transmitter arrays. The most promising method of increasing transmit power is to build an array of transmitters. This would also be useful for signal processing applications. Luckily, JPA-based QTMS radar is scalable. It would be practically impossible to create an QTMS radar array if we required one refrigerator per JPA, but that is not the case. JPAs themselves are very small, and multiple JPAs can fit onto a printed circuit board like the one shown in Figure 7. Therefore, multiple entangled signals can be created within the same refrigerator; the incremental cost of adding a JPA is small once a refrigerator is already available. This means that there exists at least one technological route to entanglement-based quantum radar arrays.

3) Frequency, bandwidth, and polarization. If quantum radars were restricted to certain frequencies, their applications would be limited. Luckily, JPAs can be engineered at a wide variety of microwave frequencies. Similarly, any radar must have a high bandwidth for most practical applications. The JPAs used for the QTMS radar experiment had a relatively narrow bandwidth of approximately 1 MHz, but it is possible to engineer JPAs (or banks of JPAs) with increased bandwidth. Polarimetry is another important function...
of many radars and should be carefully studied in the quantum context.

4) Other entanglement generation methods. JPAEs are not the only conceivable method of generating entangled microwaves. Another proposal involves optical-to-microwave conversion. This exploits the fact that entanglement is easier to generate at optical frequencies; it can be done at the room temperature without cryogenic refrigeration. Optical-to-microwave conversion could be achieved, for example, using an electro-optomechanical converter, which relies on a mechanical resonator [32]. It may also be possible to generate polarization-entangled microwaves using a Josephson mixer [33], [34].

5) Other types of entangled signals. Two-mode squeezed vacuum, the type of entanglement used in the QTMS radar, is not the only continuous-variable entangled signal that could be used in a quantum radar. There are other types of entanglement, which have been proposed for the use in radars. One proposal uses photon-subtracted two-mode squeezed states (PSTMSS) [35]. This type of the entangled state is different from the two-mode squeezed vacuum that is used in the QTMS radar. The authors of [35] show that “QI with PSTMSS appreciably outperforms its classic correspondence in both low- and high-noise operating regimes, extending the regimes in which QI is optimal for target detection.” In other words, it may provide gains even at high SNRs, contrary to the expectation that quantum radars would not offer a significant gain over conventional radars in this regime. PSTMSS is more difficult to generate compared to two-mode squeezed vacuum, but experimental designs have been proposed at least for optical frequencies [36], [37]. Another type of entangled signal that could find use in quantum radars are the so-called NOON states, which also offer a gain in parameter estimation at high SNRs [38], [39].

6) Other quantum radar protocols. QI is one of the most important quantum radar schemes to be proposed to date. Although it has never been implemented at microwave frequencies, QI-inspired experiments have been performed at optical frequencies [15], [16], [17], [18]. In fact, QI was an inspiration for the QTMS radar. The principal difference between pure QI and QTMS radar lies in the measurements being performed on the signals. In the QTMS radar, one of the entangled beams is immediately measured using heterodyne detection; the received signal is measured separately. In QI, the entangled beam, which remains within the system, is not measured immediately; instead, it is retained so that it can be measured jointly and simultaneously with the received signal. In a sense, a physical signal is used to perform matched filtering of the received signal. According to quantum theory, this should yield better results compared to the separate measurements used in the QTMS radar. However, it seems practically quite difficult to set up a system whereby the retained signal is held until the moment the corresponding transmitted signal arrives at the receiver. Other quantum radar schemes may overcome this challenge.

FUTURE DIRECTIONS: RADAR AND SIGNAL PROCESSING

Radar have to contend not only with noise, which was the main focus of the preceding sections, but also with other sources of interference. In particular, they have to deal with clutter and jamming. In conventional radars, such interference can be tackled via signal processing, such as STAP [7]. In order for a quantum range finder (like the current incarnation of the QTMS radar) to progress to a full-fledged quantum radar, and in order for future quantum radar proposals to be truly practical, the following are some of the topics we must consider.

1) Doppler processing. At present, the QTMS radar setup is only a quantum range finder. In order to estimate velocity, Doppler processing is important. In the case of QI, highly sophisticated (but not currently practical) techniques for velocity estimation have been proposed [40]. On the other hand, the QTMS radar can be understood as an enhanced noise radar. It, thus, inherits all the capabilities of the noise radar, and classical Doppler processing is certainly possible.

2) Parameter estimation. Range, bearing, and elevation estimation strongly impact target tracking and data fusion. For the QTMS radar, a good initial indication of its capabilities in this direction would be provided by existing noise radar work.

3) Array processing and STAP. A quantum radar needs to be compatible with current array processing and STAP algorithms for interference suppression, or it must be able to emulate these capabilities using quantum-inspired techniques. Not all quantum radars can do this. For example, QI requires a sophisticated joint measurement between the received signal and its entangled counterpart, which was retained within the radar. The outcome of this measurement may not be immediately usable in any of the algorithms developed to date, and QI-specific interference suppression techniques have not yet been developed. This is not to say, however, that quantum radars are categorically incompatible with STAP or other signal processing techniques. The QTMS radar, for example, would be amenable to these techniques because it performs
standard heterodyne measurements, resulting in $I/Q$ data just like most regular radars. Therefore, it is relevant to practically any radar application, including STAP. By reducing the effect of white noise with superior matched filtering, such a quantum radar would improve the outcome of signal processing. (To modify a well-known phrase: less garbage in, less garbage out.) STAP reduces the effects of clutter and jamming to the noise floor; a quantum radar would actually lower that noise floor. Monopulse QTMS radars are just as feasible as monopulse noise radars [41], and perhaps most practical in the short term.

4) **Pulsed signals.** The QTMS radar, as well as most other quantum radar proposals, such as QI, assume continuous-wave operation. In some radar applications, pulsed operation may bring advantages.

5) **Radar image processing.** One of the most important applications of the radar is imaging, including SAR and inverse SAR. These capabilities have been demonstrated for noise radars [42], [43], which means that the QTMS radar can perform the same tasks.

6) **Multistatic and MIMO capability.** Quantum radars that rely on performing joint measurements between a received signal and its entangled counterpart, such as QI, are constrained to have equal numbers of transmitters and receivers, because each transmitted signal is physically entangled with only one counterpart within the radar. Other designs, such as the QTMS radar, have no such constraint and can be used in multistatic or multiple-input multiple-output (MIMO) configurations.

7) **Radar phenomenology.** As a first approximation, we can treat the QTMS radar as a noise radar for the purpose of estimating radar cross sections, polarization effects, antenna patterns, and the like. However, detailed experimental work is required to confirm how well this equivalence holds. If other quantum signals (such as PSTMSS or polarization-entangled states) are used, experimental work will also need to be carried out to verify whether intuitions from conventional radars hold for such signals.

8) **Possibly of interception.** We have already stated that any radar based on two-mode squeezed vacuum, such as QTMS radar, do not broadcast any distinctive quantum signature. As long as only one of the beams is transmitted, it looks exactly like thermal noise. This does not entirely preclude interception of a quantum radar beam. Anisotropies in environmental noise, for example, may be exploited to infer the operation of a QTMS radar. Interception may also be made considerably easier if access to the internal measurement record of the radar were available [44].

### CONCLUSION

Quantum radars are feasible. That is the message; all else is commentary. From this commentary, we learned that quantum radars exploit unique quantum phenomena to enhance the radar performance, that entanglement in particular does this by providing a better way of distinguishing signal from noise (via improved matched filtering), that JPA-based quantum radars are very close to experimental reality, and that quantum radars can—in principle—do practically anything that a conventional radar can. The QTMS radar is an example of a quantum technology that can be developed into a proper radar as understood by radar engineers. The discussion in this article was heuristic and does little more than scratch the surface when it comes to the possibilities offered by quantum science. We hope this overview will spur research and development of better quantum radars!

One point needs to be emphasized: there exists an entanglement-based quantum radar design, namely QTMS radar, which is amenable to all known radar signal processing techniques. This dramatically lowers the barrier for research and development from a signal processing perspective. This fact could help shape the design of future generations of QTMS radars. We believe that, going forward, other quantum radars should be designed with an eye to signal processing capabilities.

To move beyond quantum range finding, the support of government and industry stakeholders is essential. The quantum radar has clear potential, and it would be wise to explore it further. Developing entanglement-based quantum radars demands far less money and effort compared to quantum computers. The one requires entanglement only between two signals; the other requires multipartite entanglement among a plethora of qubits. Billions of dollars have already been spent on quantum computing; compared to this, a few million dollars to develop a field-testable QTMS radar does not seem extravagant. With the evidence before us, it seems worthwhile to make a modest effort to understand the possibilities of quantum radars more thoroughly.

Finally, a dedicated effort by both physicists and engineers is necessary. The quantum radar is, as the name implies, an interdisciplinary field: a cross between quantum physics and radar engineering. No researcher, research group, or research program will achieve success by focusing on one to the exclusion of the other. A sound understanding of ROC curves is no less important than a sound understanding of entanglement. There must be collaboration and cooperation between both sides. The piecemeal approach is inefficient and far from ideal. If we adopt a holistic mindset, however, we have every reason to be optimistic about the future of the quantum radar.
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