Three Special Sessions on Quantum Radar at IEEE Radar Conferences

Fred Daum

Quantum radar is a hot topic for several reasons, but especially because of the two recent experiments at X-Band as reported in [2] and [3]. A second reason is the story that microwave quantum radar was used in the real world by Chinese to track aircraft and missiles at 100 km range [5]. A third reason is the assertion that microwave quantum radar can defeat stealthy aircraft and missiles [5]. Such claims have been published by highly respected peer reviewed archival journals, such as Popular Mechanics, but most experts say that these assertions are highly dubious [7]. A fourth reason is that the taxpayers of China, Canada, Sweden, UK, USA, Italy, Austria and other countries have apparently spent a significant amount of money for research on quantum radars. Consequently, a special session on quantum radar was held (virtually) at the IEEE International Radar Conference on 30 April 2020, which did not occur at Washington DC. The five talks varied widely in perspective: three were upbeat but two were rather negative. Marco Frasca and Alfonso Farina presented a new idea to entangle atoms with photons, rather than the boring old method of entangling pairs of photons; the purpose here is to allow a greater number of photons to be usefully entangled for microwave quantum radar. Marco Frasca is a real physicist who deeply understands quantum mechanics, and Alfonso Farina is a famous expert in real radar systems. Han Liu, Amr Helmy and Bhashyam Balaji explained how to use temporal correlation of photons rather than boring old polarization entanglement to improve quantum radar performance by roughly 10 dB to 20 dB relative to a classical radar. A crucial point in this comparison is that the classical radar was not optimized, which is an important theme throughout all three special sessions. A third talk analyzed the benefits of using multiple quantum transmit devices in parallel; Marco Lanzagorta, who literally wrote the book on quantum radar [6], is the physicist on this team, and Jeff Uhlmann (who invented the unscented Kalman filter) is the engineer in this collaboration. All three of these talks were upbeat about the potential for quantum radar. In contrast, Jérôme Bourassa and Chris Wilson showed that a certain important class of quantum radars cannot beat the optimal classical radar if the transmit signal and the so-called “idler” (i.e., the other partner in the entangled photon pair) are amplified equally. This negative result is useful to know. Of course one wonders what happens with asymmetrical amplification of the transmitted signal and the idler, and this important question was answered at the special session on quantum radar at the IEEE Radar Conference in Florence Italy (September 2020), which we shall review later. Both Wilson and Bourassa are real physicists who have quantum mechanics for breakfast. The fifth talk, by Daum (not to be confused with the author of this note), was also rather negative. Daum showed that the cost of X-Band quantum radars is roughly ten orders of magnitude more than the corresponding classical radar with today’s technology. In the future, with the most optimistic assumptions, the relative cost can be reduced to only five orders of magnitude. During the Chat for this special session Professor Ravi Advi (the organizer of this special session) said that he was in tears after learning about this cost analysis, and these were not tears of joy. But one could put a positive spin on the huge cost of quantum radars, because companies typically make a profit of 10% to 20% on sales, and hence quantum radars would put them in clover. The Chat was continuously active throughout the entire two hour session. This allows for ten times more questions from people around the world than is typical at face-to-face meetings. Many participants said that virtual meetings were much better than face-to-face sessions, because they avoid the cost and time and inconvenience of travel, hotels, and parking. Michael Zatman, the Chairman of the IEEE Radar Conference, asked some good technical questions, and he said that this Chat was probably the best at the whole conference. Zatman asked about the assumptions used to compute 10 dB to 20 dB of improvement in performance for quantum radar relative to classical radar; as we shall see below, this is a recurring crucial question for all three special sessions.

A second special session on quantum radar was held virtually at the IEEE Radar Conference on 22 September 2020, which unfortunately did not happen at Florence Italy. The five talks at this special session were also a mixture of positive and negative results. An experiment on X-Band quantum radar was reported by Shabir Barzanjeh, David Vitali, Stefano Pirandola and Johannes Fink, a powerful team of physicists from Italy, Iran, UK and Austria. The results of this seminal experiment, performed at Vienna Austria, were in good agreement with theory for this special class of quantum radar, which uses digital receivers and digital signal processing. Marco Frasca and Alfonso Farina quantified the benefits of using multiple quantum transmit devices in parallel for a quantum MIMO radar, rather than using boring old phased array radars. Another strong team of physicists and radar engineers from Sweden and Finland explained that a certain important class of quantum radars could not beat the optimal classical radar using any version of amplification of the transmitted signal and the idler, even assuming ideal quantum processing in theory. This team consists of Robert Jonsson, Anders Ström, Roberto Di Candia, Martin Ankel and Göran Johansson. Another negative result was reported in a paper by Nizar Messaoudi, Chung Wai Sandbo Chang, A. M. Vadiraj, Jérôme Bourassa, Bhashyam Balaji and Chris Wilson, which shows the limitations of an important class of quantum radars due to amplification of the transmitted signal and the resulting destruction of entanglement of the photon pairs. On a positive note, David Luong, Bhashyam Balaji, and Sreeraman Rajan computed the ROC curves for a certain class of quantum radars using both Monte Carlo simulations and Gaussian approximations to obtain simple formulas. This quantum radar gives substantially better performance than a classical noise radar, but it does not beat the optimal classical radar, as explained in [1], [8] and [9]. Daum talked about a radically different quantum radar design which does not use any cryogenic dilution refrigerators, and hence reduces the cost by many orders of magnitude; however, this talk was theoretical and highly speculative, with no experimental results. Daum generates the desired electromagnetic field using the square root of a huge covariance matrix multiplied by thermal noise rather than boring old entanglement of real physical photons [9]. This idea was greeted skeptically by most real quantum mechanics, but no mathematical flaws were exposed in this surprising and counterintuitive idea.

However, the real drama of this special session played out during the reviewing process of the papers. All of the reviewers were world class experts in quantum radar. But the reviews of many papers varied widely from definite reject to definite accept. Apparently there is substantial disagreement among the world experts on quantum radars. One heroic reviewer wrote four reviews that were twice as long as the papers being reviewed with original research and improved results as part of the reviews. This reviewer was extremely reluctant to review any papers, but somehow or other we were able to twist his arm by pointing out that, owing to COVID-19 strictures, he was not allowed to leave his house, and there were no classes to teach at his school, and all restaurants, museums, concerts, plays, movies and bars were closed, removing nearly all distractions from the important task of reviewing papers.

A third special session on quantum radar is planned for the virtual IEEE Radar Conference in May 2021, which will not be held at Atlanta Georgia. This will consist of eight talks plus an hour long panel discussion, which will actually be a debate about the crucial open questions in quantum radar, including: how much better is a quantum radar than the optimal classical radar? The opinions about this issue vary widely: 6 dB, 3 dB, 10 dB to 20 dB, zero, as well as BT, in which BT is the time bandwidth product of the transmitted waveform. Here we compare radar performance in terms of equivalent SNR for a ROC curve. For a special class of quantum radars the correct answer is 6 dB quantum advantage in effective SNR at low photon flux per mode, assuming equal transmit power for the quantum radar and the classical radar (see [1] for details). This analysis also assumes Gaussian states and optimal quantum detection and very little amplification of the signal and idler, and no sampling of the idler, with constant RCS target (and exactly known range, azimuth, elevation, polarization, amplitude and phase of the target). This 6 dB quantum advantage further assumes that the classical radar does not exploit the known polarization of the target; it also assumes that we have a lossless analog quantum (arbitrarily large) memory for the idler (see [1] for details). However, for non-Gaussian states of photons and entanglement of more than pairs of photons and polarization entanglement jointly with squeezing of the quantum vacuum and other more general assumptions, the jury is still out. Moreover, the current analysis uses the boring old Schrödinger equation, whereas the correct analysis would use the Belavkin-Zakai equation. The debate at Atlanta will be among the world's experts in quantum radar, and we will strictly enforce the quantum Marquess of Queensberry rules, including: no entanglement, no squeezing and no tunneling. Essentially all experts now agree that the two experiments reported in [2] and [3] are not actually quantum radars, owing to the amplification of the transmitted signal and the idler, and hence they do not offer any quantum advantage relative to the optimal classical radar with the same transmit power, as explained in [1], [8] and [9]. This is not debatable; it is a mathematical fact. Some researchers think that quantum radar today is like the Wright Brothers' airplane. But for the airplane we had an existence theorem: birds can fly. Also, the Wright Brothers only required improving the engine efficiency and lift-to-drag ratio and stability margins by less than one order of magnitude relative to the state-of-the-art. In contrast, the cost of quantum radar is ten orders of magnitude more than optimal classical radar, and we cannot fix this problem using amplification [9]. This is not debatable; it is a mathematical fact. But hope springs eternal in the breasts of some quantum radar researchers, who dream of new technology and much more general methods of entanglement as well as new clever ideas and new physics yet to be discovered.

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