Book Review

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Book Review of "MIMO Radar: Theory and Application"

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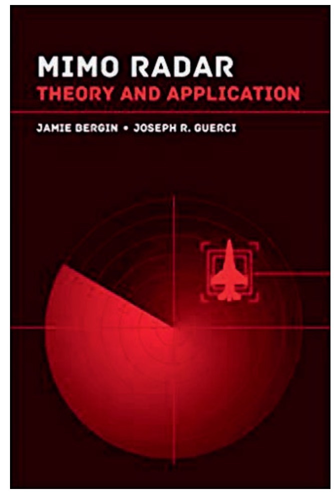
Review by Fred Daum, IEEE Fellow

MIMO radar is a very controversial hot topic. MIMO radar researchers have claimed 10 dB or 20 dB advantages relative to boring old phased array radars, but crusty old radar engineers have doubted such assertions and poked holes in their analysis. Ten years ago the Office of Naval Research (ONR) asked me to become embroiled in this debate, resulting in [5]. The authors of this new book tackle this problem head on. In particular, they say clearly and emphatically that: "The hype surrounding MIMO radar has come with a fair amount of skepticism. MIMO radar is not a cure-all for every radar problem…. Unfortunately, the benefits of MIMO radar have sometimes been overstated, which has created a cloud of controversy that has generally slowed its adoption for radar modes and applications where it could have great benefit. In this book we attempt to present a fair analysis of MIMO radar technology in a way that clearly highlights its benefits and pitfalls" (page 11). In this review, we shall see how well the authors have succeeded at this task. For example, on pages 72 to 75 there is a nice simple analysis of the bad impedance match of a typical MIMO antenna with free space, which results in a very poor radiation efficiency, and hence potential damage to the radar transmitter. That is, if the microwave energy is not radiated into free space, then it stays in the transmitter, which heats up and could suffer severe damage. That is, the typical MIMO antenna does not radiate efficiently like a boring old phased array radar or an extremely boring old dish radar. In fact, the MIMO radar transmitter might actually melt as a result. This is a simple fact of physics, first explained by Oliver Heaviside [9] well over one hundred years ago, and it is taught to every student of antenna design or electromagnetic physics. Unfortunately, the authors do not mention that there is a very simple solution to this problem: design the MIMO transmit pattern in beam space rather than element space, in which each beam is designed with high efficiency of radiation as explained in [3]. About 15 years ago a famous MIMO radar researcher (who will remain nameless) once visited us to extol the virtues of MIMO radar, and one of our smart aleck antenna designers in the back of the room pointed out that the MIMO transmitter would melt, to the eternal embarrassment of the famous professor.

Chapter 3 of this book gives a nice simple analysis of the extremely large computational complexity required for MIMO radars that have N^2 receiver channels rather than only a few receiver channels as in SISO radar or only N receiver channels as in SIMO radar. Likewise, this chapter explains the difficulty of actually calibrating all N^2 receiver channels, including all N^2 transmit-receive paths through the antenna, waveform generators, transmitters and receivers as well as the numerous propagation paths (through the troposphere or ionosphere) and possibly the radome, compared with the relatively simple task of calibrating a boring old phased array radar which has only a single propagation path. Also, this chapter explains the extra difficulty of collecting enough data samples for adaptive MIMO radar algorithms, considering that the number of required samples grows quadratically with the number of MIMO degrees of freedom. Obtaining enough data samples is especially challenging in real world clutter or jamming, which is typically highly heterogeneous and non-stationary, in contrast with textbook clutter or jamming found only in academic papers.



Chapter 5 gives a nice clear tutorial introduction to optimal MIMO radar, using the standard least squares approach for the general case of correlated MIMO waveforms, not just orthogonal MIMO waveforms. Unfortunately, almost all of the other chapters in this book assume N orthogonal MIMO waveforms, which suffer the maximum loss in signal-to-noise ratio relative to a boring old phased array radar (SISO or SIMO), owing to zero transmit antenna gain and the resulting omnidirectional transmit antenna pattern. Most serious MIMO radar experts today agree that orthogonal waveforms are a bad idea in practice, and that correlated MIMO waveforms should be used in essentially any application, as explained in [2]. Nevertheless, the academic literature as well as this book is still dominated by the assumption of orthogonal MIMO waveforms. Curiously, Chapter 5 fails to mention the most fundamental fact about optimal MIMO radars; namely, that the boring old phased array radar (SISO or SIMO) maximizes signal-to-noise ratio, and any MIMO radar is always suboptimal [12], assuming thermal front end noise and no clutter or jamming.

Figures 3.10 to 3.13 compare MIMO radar with so-called "conventional radar" performance, based on the Monte Carlo simulations reported in a 2009 IEEE Conference Proceedings paper that does not exist in the list of references at the end of this chapter, and hence we cannot learn exactly what kind of "conventional radar" the authors are talking about. It is not clear what the authors mean by "conventional radar"; is it a SISO radar or a SIMO radar? Was the SISO or SIMO radar designed by smart experienced antenna designers and radar system engineers or not? Was the design of the SISO or SIMO radar optimized to compete with the MIMO radar, or was it a stupid SISO or SIMO radar design, as we have seen so often in academic papers? Was the cost of the MIMO radar the same as the SISO or SIMO radar? After some digging, I guess that the actual source of these figures is [4], but that paper does not answer these questions either. Also, the analysis in Figures 3.10 to 3.13 is flawed, and it is definitely not a fair apples-to-apples comparison, because it assumes the same SNR for the MIMO and SISO or SIMO radars, whereas MIMO suffers an irretrievable SNR loss of a factor of N in track, where the SISO or SIMO radars have a transmit antenna gain that is a factor of N higher than the MIMO radar in track. Longer coherent integration time obviously improves the suppression of clutter for GMTI applications, and MIMO radar allows continuous integration of the targets and clutter owing to the omnidirectional transmit antenna pattern, but SISO and SIMO radars can also achieve long coherent integration times using pulse-Doppler waveforms; this elementary fact seems to have been ignored in the design of the strawman SISO or SIMO radars by MIMO radar researchers, as in [7]. Likewise, better suppression of clutter for GMTI can be achieved by using a larger receive aperture (to narrow the receive beam) for SISO or SIMO or MIMO, or a larger transmit aperture for MIMO radar, as in [7]. But why increase the transmit antenna size rather than the receive antenna size? It is generally less expensive to use a bigger receive antenna than a bigger transmit antenna, owing to the cost of power and cooling and high power microwave components. I discussed exactly such issues with Dan Bliss (the author of [7] and a MIMO radar expert at MIT Lincoln Lab) at the Orlando airport after the IEEE Conference on waveform diversity in 2009, and Dan agreed that these were valid questions. In summary, the analysis of the MIMO vs. non-MIMO for GMTI applications given in chapter 3 of this book is not a fair apples and apples comparison; see [5], [6] and [16] for details.

There are many important issues and topics that are not mentioned or not covered thoroughly in this book, including: (1) SIMO phased array radars (i.e., single transmit waveform but multiple receive channels to form multiple simultaneous receive beams); (2) correlated MIMO radar, which does not transmit orthogonal waveforms from distinct antenna elements, but rather transits correlated waveforms between distinct antenna elements, with the purpose of focusing the transmit energy in space (rather than forming an omnidirectional pattern with zero transmit antenna gain) in order to mitigate the loss of SNR (see [2] for details); (3) the useful area of range-Doppler space is reduced by a factor of N for MIMO radars with N degrees of freedom for any transmitted waveforms (see [1] for more details); (4) on page 50 the authors correctly note that the signal-to-noise ratio (SNR) for MIMO is a factor of N smaller than for the corresponding SIMO or SISO radar, but they then go on to say that this can be fixed by exploiting the longer time that the targets are illuminated by the fatter MIMO transmit beams; but this does not account for real world effects, as pointed out in [5], including the limited coherent integration time due to the lack of coherence of both the target and the propagation medium (i.e., troposphere or ionosphere); moreover, this attempt to compensate for the loss of SNR only makes sense for search, whereas for track, radar energy that is transmitted where there are no targets is irrevocably lost, to the severe detriment in MIMO radar performance; this is the main reason that hard boiled engineers do not use MIMO radars; (5) search performance for MIMO radar is clearly inferior to SIMO or SISO radars, owing to scan loss for any planar or linear array, despite the longer integration time allowed by MIMO radars (see [6] for a detailed analysis) assuming radar front end noise but no clutter or jamming; (6) the cost and risk of designing a MIMO radar is generally much higher than the corresponding SISO or SIMO radar, owing to the tight coupling between antenna design and waveform design for MIMO radar as noted in [5], larger system complexity of MIMO radars, difficulty of calibrating all the MIMO receive channels, novelty of MIMO radars, lack of real world experience with MIMO radars, etc.

Nevertheless, there are certain niche applications where MIMO radar actually might make sense, including HF over the horizon radars, where we can adaptively null spread Doppler clutter, as explained in the superb paper by Gordon Frazer [11]; unfortunately, this book only spends one page on this important application of MIMO radar. GMTI radar is another important niche application of MIMO, and the bulk of this book is focused almost exclusively on that single application. This book gives many nuts and bolts technical details about how to make MIMO radar work for GMTI applications in the real world. The authors do a good job explaining this topic, using intuition and nice simple easy to grasp analysis. GMTI is a good application of MIMO because the target speeds are very low and the range interval is small, because the targets are on the ground (by definition). That is, the slow moving ground targets are in a very small area of range-Doppler space. This means that MIMO does not suffer very much from the reduction in usable range-Doppler space (by a factor of N compared with SIMO or SISO); see [1] for details. Second, GMTI radar system performance is generally limited by clutter and jamming rather than thermal noise, and hence MIMO does not suffer very much from the reduction in SNR by a factor of N relative to SISO or SIMO [5]. Thirdly, GMTI radars typically operate in a track-while-scan mode rather than a track mode. It is curious that this book does not explain why GMTI is a good application for MIMO in contrast to many other potential bad applications of MIMO. The theoretical result proved in [1] is fundamental for MIMO radar performance; it is like Ohm's law in electrical engineering. It is curious that the results in [1] are not mentioned in this book.

Recall the quote at the beginning of this review (from page 11 of the book) which blamed the slow adoption of MIMO radars in the real world (in contrast with paper radars in academic papers) on "a cloud of controversy." As an alternative explanation of the lack of real world applications of MIMO radar, is it possible that smart experienced hard boiled antenna designers and radar system engineers have actually done a quantitative cost and risk tradeoff between MIMO radar vs. boring old phased array radars, and concluded that MIMO radar is too risky and too expensive relative to properly designed boring old SISO and SIMO radars? There is no such cost analysis or credible cost model mentioned in this book. Without a credible cost model it is impossible to decide whether MIMO radar is better than boring old phased array radars. On the other hand, rumor has it that MIMO radar has indeed been adopted for automobiles in the real world (e.g., see [17] and [18]). This application apparently makes sense for MIMO radar because it is extremely short range with very non-stealthy slowly moving targets and hence very low cost radars, and therefore the severe loss of SNR (of MIMO relative to SISO or SIMO) is not so important relative to the improved spatial resolution with a constrained antenna size. But alas, this book only devotes one and one-half sparse pages to this important real world application of MIMO radar. The potential market for such MIMO radars on cars (human driven cars or robot driven cars) is huge, and this is not exactly a "niche" application; I am grateful to an anonymous reviewer of my book review for emphasizing this point.

Over ten years ago I was asked by the Office of Naval Research (ONR) to provide an independent analysis of the efficacy of MIMO radar compared with boring old phased array radars (SIMO or SISO), and my paper [5] summarizes this evaluation. At that time one of the world's experts on MIMO radar told me that 95 percent of the papers on MIMO radar were snake oil, but that he could not say that in public, and he could not publish such a blunt appraisal. How do these papers on MIMO radar get published by the IEEE in archival journals? Almost all such papers on MIMO radar have been published in the IEEE Transactions on Signal Processing, rather than the IEEE Transactions on Antennas and Propagation. The reviewers for the latter journal know that one must design radars with high radiation efficiency, otherwise the transmitter might melt, whereas reviewers for the IEEE Transactions on Signal Processing apparently don't know such important facts about antennas. Sadly, they also do not understand how boring old phased array radars actually work by exploiting time diversity in search and track rather than exclusively using waveform diversity [5]. Both MIMO as well as boring old phased array radars can exploit spatial diversity, but this fact is often suppressed in the MIMO literature, as explained by Professor Chernyak [15]. Obviously the use of multiple simultaneous beams on receive (using SIMO radar or MIMO radar) enhances the efficiency of networks of multiple spatially diverse antennas for transmit and receive; this fact is also often suppressed in the MIMO papers, as explained very clearly by Professor Chernyak [14]. What is not said in books and papers is often more important than what is actually said, and this book is no exception.

Long ago and far away on a planet in another galaxy MIMO radar was invented before SISO radar or SIMO radar. But after the invention of SISO and SIMO radars, it was discovered that these non-MIMO radars had the following advantages over MIMO radar: (1) SISO and SIMO radar maximize SNR, whereas MIMO does not; (2) SISO and SIMO radar give significantly better search performance compared with MIMO for operation in radar front end noise and no jamming or clutter; (3) SISO and SIMO radars give vastly superior track performance compared with MIMO radar, which wastes most of the transmit energy using omnidirectional antenna patterns, whereas SISO and SIMO focus the transmit energy where the targets actually are using the knowledge of target location from tracking; (4) SISO and SIMO radars were much simpler to design than MIMO radars, because the antenna design was decoupled from the waveform design; (5) SISO and SIMO radar transmitters did not melt, unlike many MIMO radars; (6) SISO and SIMO radars were much easier to calibrate, owing to many fewer receiver channels; (7) adaptive SISO and SIMO radars required many fewer samples than MIMO radars, owing to many fewer degrees of freedom; (8) SISO and SIMO radars were lower cost and lower risk than MIMO radars; and (9) Skolnik's radar handbook (intergalactic edition) does not mention MIMO radar, and hence radar engineers lacked a canonical source of wisdom to guide them. ◆

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