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Radar Sensitivity Budget Analysis for a Network of Skywave Over-the-Horizon Radars

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Abstract

We introduce a performance prediction methodology to address the challenge of designing a network of skywave over-the-horizon radar (OTHR). The approach can be used to optimise the number of radars, the location of each radar, the sensitivity of each radar, and the total network system cost, based on the chosen mission objectives. We demonstrate the method with a stylised example of a three radar network directed at the eastern region of Australia from radars located in New Zealand, Norfolk Island and New Caledonia. The network is evaluated for performance with respect to commercial aircraft flights operating between several major Australian cities and Sydney.

1 Introduction

Skywave over-the-horizon radar (OTHR) is a long-range beyond horizon radar technology that is presently employed by several nations for wide-area surveillance of aircraft and maritime vessels[5]. This radar class uses propagation via the ionosphere[3] to achieve radar energy propagation to and from the target region. The ionosphere is driven by the highly varying solar interaction with the Earth and this variability greatly influences the operational performance of a skywave OTHR. Considerable care in selecting radar operating parameters is required to achieve best performance.

The question naturally arises as to how one might design a network of OTHR. Significant design degrees-of-freedom include: the specific operational mission and definition of success; the number of radar and their physical locations; individual radar sensitivity and the operating parameter space of each radar; the network coordination strategy; and, of course, the total system cost.

In the paper we explore this question and propose a methodology for the performance prediction of skywave OTHR. In conjunction with the radar system and environmental modelling contained within our companion paper [2], we call this the *Radar Network Design Methodology*. Of secondary interest we note that our design philosophy has evolved over the past few decades with changing technology and communications possibilities. We are now interested in OTHR networks of many individual OTHR but where each radar is of lower sensitivity than existing systems and are sited to provide range and aspect diversity to the target region of interest. We contend that such netted-diverse-compact OTHR networks will achieve comparable performance to present day OTHR systems at lower total network cost and we are using the approach described herein to explore these possibilities.

To demonstrate the performance assessment method we consider the specific case of a three radar network located in New Zealand, Norfolk Island and New Caledonia and directed, with overlapping coverage, toward the eastern coastal region of Australia. Each notional coverage region has an azimuth extent of 90° and range of 1000 km to 3000 km. OTHR generally has a large potential coverage and so this particular network arrangement will have some capability against most of the eastern half of Australia. However, the instantaneous actual coverage is moderated by time-varying propagation support and the radar sensitivity as achieved in the chosen radar design.

In our approach there are a number of radar performance assessment metrics computed for each radar location that are then combined into a network performance assessment metric. For brevity only the network results are presented.

2 Characteristic mission performance

To assess the tracking performance of the radar network we must first select a relevant mission. Here we have chosen our mission to be the tracking of commercial aircraft flying into and out of Sydney (SYD) airport from Adelaide (ADL), Brisbane (BNE), Melbourne (MEL) and Hobart (HBA). Additionally, we wish to assess the tracking performance for aircraft circling Sydney airport in a typical holding pattern.

For each radar we perform the calculations described in our companion paper [2] to produce probabilities of target tracking over time of day, seasonal and solar activity variation. These calculations are for a reference base radar system. Using 90% probability of target tracking as the desired performance threshold we determine a multi-dimensional binary performance satisfaction map. There is a large parameter space when assessing performance so we condense the tracking performance into a small set of characteristic metrics introduced below.

The analysis with respect to our base-system design shows that there is almost no coverage at low solar activity and only some flight specific coverage for average solar activity. This base-system design is assessed as not satisfactory for the mission requirement of tracking flights to Sydney.

To investigate what scale of radar sensitivity within the network would achieve the desired mission we introduce a free variable, the marginal system gain ("system gain" for shorthand in what follows), as a radar design sensitivity modifier. We calculate the metrics described in the following section over a set of system radar sensitivity levels or system gain values. These sensitivity modifications can be distributed across the radar design, e.g. doubling of the transmit/receive array size or doubling of the transmitter power to achieve incremental 3dB improvements. We test an increased sensitivity above the base-system radar sensitivity of 0 to 30 dB, sampled at 1 dB increments.

2.1 Spatial hours coverage

We represent the spatial performance of the radar network coverage through the hours of coverage for the given mission. This is the hours of a day for the given environmental conditions that the mission is satisfied. The highly variable and undesirable performance of the base-system design is shown in Figure 1, where colour represents performance and is overlaid on the geographic flight path. By comparison when a system gain of 6dB is added the flights are covered better in both hours and consistency as seen in Figure 2.

This representation highlights that the radar network performance against all the flight paths vary spatially along each path. In particular, the Brisbane flight has almost no track coverage. The difficulty with tracking the BNE-SYD flight is due to the aspect geometry of all of the three radars. The aircraft in this flight path are either tangential to each radar in the radar network (i.e. lost in the ground clutter) or have poor target scatter due to the aspect dependency of target RCS.

2.2 Mostly-at-least hours coverage

The second metric we use is the spatial median of hours of coverage for the target missions evaluated for each season and solar activity. This metric allows us to condense the hours of radar network coverage for an entire flight path down to a single value. This value indicates that most of the target flight path will be covered by the minimum probability of achieving tracking for at least the stated amount of hours. This enables identification of the conditions that do not satisfy a particular system requirement of target coverage, or more generally speaking are outside the system performance expectations. This performance metric for the scenario is displayed in Table 1.

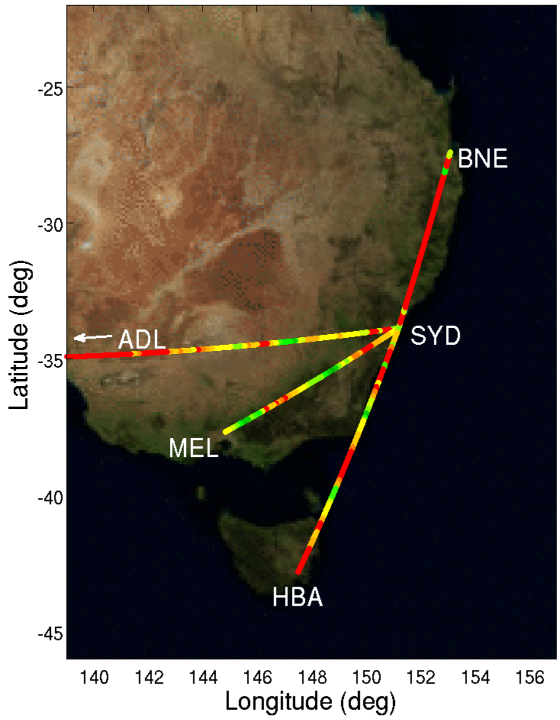

Figure 1. Map of eastern Australia. Shows flight routes colour coded with the predicted hours of radar network coverage for inbound to Sydney flights in December at low SSN for a radar network designed to the base-system design. Red translates to no track coverage, while green is 10+ hours of coverage a day, and yellow patches are around 5 hours of coverage.

SSN	Month	ADL-SYD	BNE-SYD	MEL-SYD	HBA-SYD	SYD holding
20	MAR	6	0	9	6	12
	JUN	3	0	5	3	9
	SEP	0	0	0	0	3
	DEC	11	0	12	10	16
70	MAR	19	1	19	18	21
	JUN	11	1	12	11	13
	SEP	17	0	18	16	20
	DEC	20	0	20	20	23

Table 1. Radar network spatial median hours (out of 24) coverage results for a radar network designed to +6dB with respect to the base-system design.

3 Radar system optimisation

The radar network design methodology discussed makes a great many assumptions and simplifications (for example, the use of climatological models of the ionosphere[1]). We consider it important to include an assessment of the robustness of our radar network design. For instance, will a small error in our choice of radar sensitivity (and hence the individual radar configuration) mean overall network performance is compromised, or is there some margin for error?

We use a marginal system gain with respect to the sensi-

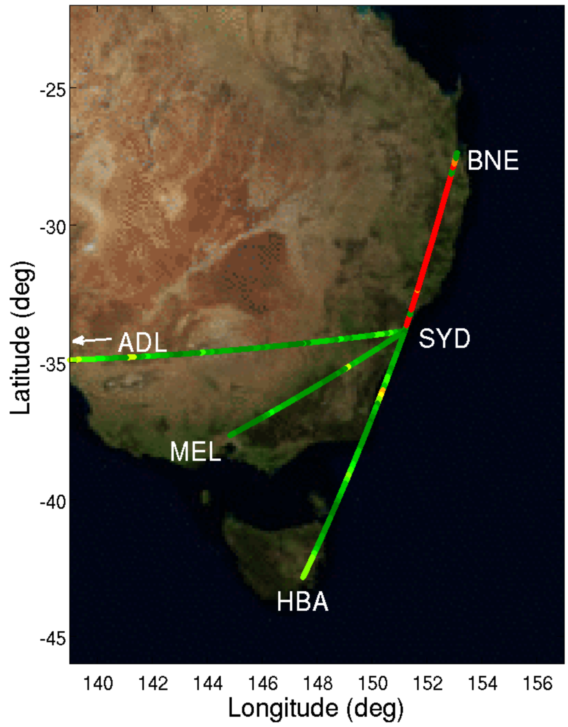

Figure 2. Map of eastern Australia. Shows flight routes colour coded with the predicted hours of radar network coverage for inbound to Sydney flights in December at low SSN for a radar network designed to +6dB of base-system design. Red translates to no track coverage, while green is 10+ hours of coverage a day, and yellow patches are around 5 hours of coverage.

tivity of the base-system as an independent variable over which to optimise the performance to the design budget. What we seek in our optimisation is to select a radar design specification that meets the desired outcome, but is far from any performance "cliff" and hence under-designed, nor indeed in a performance "plateau" with some cost savings possible as the radar is over-designed and hence too expensive. The former case could result in a complete loss of capability from day-to-day variability with respect to the climatological environmental models used. The latter cases result in an over specified radar network which would lead to higher than necessary total network cost.

In order to optimise the design we require the absolute and comparative performance across the marginal system gains. The absolute performance is represented in tables like Table 1. To compare performance we statistically test if two additional marginal system gains produce statistically equivalent mean hours of coverage. This test incorporates the variance of performance values and will test if greater marginal system gain provides greater benefit.

The statistical approach we take is that of a two sample t-test with unequal variance [4]. This determines the probability that the mean of two distributions are equal. We perform the statistical tests for each combination of the 0 to 30 dB additional marginal system gain performance distributions.

We introduce the concept of "equivalent performance gain" to represent the maximum radar sensitivity that produces performance distributions for which the t-test has not rejected the null-hypothesis of equivalent mean values. We reject the null hypothesis of equivalent mean performance for less than 10% probabilities. This equivalence represents a lack of significant change in the performance outcomes between levels of radar sensitivity. We average the probabilities across the season and solar states to incorporate environmental variations, as these variations are shared across all system gains.

We may then plot the equivalent performance gain value against the additional marginal system gain for the temporal and spatial performances. Figure 3 demonstrates the equivalent performance gains for each flight temporally.

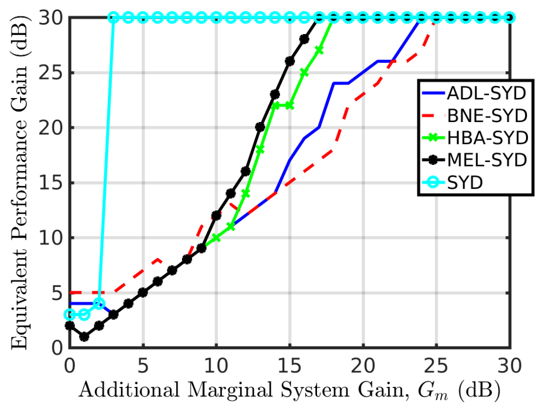

Figure 3. The temporal performance system gain equivalence for the radar network from 0 to 30dB values of system gain.

We interpret these curves by identifying the performance cliffs and plateaus. These can be seen in Figure 3 as a cliff of 0dB to about 3dB, and a plateau for greater than 17dB for all the flights except for just SYD. In order to determine that theses are cliffs and plateaus the actual performance values must be checked in the form of the equivalents of Table 1 for the respective additional marginal gain values.

We describe the minimum system gain equivalent to higher gains of satisfactory performance as being "sweet spots", where we have designed the system such that any further improvement would have statistically no benefit. This is observed in Figure 3 for the MEL-SYD flight for additional marginal system gains of 10-16dB. For example the 12dB marginal system gain performance is equivalent to 4dB greater marginal system gain. The equivalent results to Table 1 should be used to decide on the median level of performance desired. If the table shows that 10dB additional marginal system gain provides satisfactory performance for the desired radar network mission then this is a good performance to design cost choice.

Another consideration to the choice of optimal system gain value is the stability of performance. If the radar network is to overcome environmental variability we must increase the system design above the minimum requirement as the day-to-day propagation power may decrease or noise may increase with respect to the monthly median environment. One method of ensuring performance stability is to choose an additional marginal system gain with a margin above any performance cliffs.

We identify 6dB as being the minimum system gain to achieve reasonable network performance for all but the BNE-SYD flight. The 6dB system gain could be reasonably realised through the doubling of two of either the transmit array, receive array, or transmitter power.

3.1 Radar utility

It is also useful to examine the *marginal utility* of each radar within the network to determine how they contribute to the overall network mission. This provides a straightforward means of assessing the relative importance of each radar in the network for each mission and can provide guidance as to, for example, the order in which the radars within the network are constructed. We introduce the metric "radar utility" to inform marginal utility.

Radar utility is calculated as the percentage of space/time that a particular radar is superior in the network conditioned on achieving the mission for the given operating environment. We demonstrate the radar utility for an additional marginal system gain value of 6dB in Table 2. This allows the ordering of priority of radar tasking when tracking each flight. New Caledonia performs well for most flights, however New Zealand is superior for ADL-SYD in winter as expected, being physically closer in weaker propagation conditions.

Informed by this, one may then reasonably adjust the mission planning of each radar. We may task the Norfolk Island radar to cover westward flights, the New Zealand radar the northern flights, and the New Caledonia radar the southern directed flights so simply break the region up while attempting to maximise the utility of each radar.

Radar	Month	ADL-SYD	BNE-SYD	MEL-SYD	HBA-SYD	SYD holding
New Caledonia	MAR	38	5	49	64	52
	JUN	20	0	43	60	62
	SEP	27	0	63	80	100
	DEC	35	3	46	63	52
New Zealand	MAR	31	90	21	19	22
	JUN	46	100	19	22	22
	SEP	52	0	0	20	0
	DEC	35	96	25	18	28
Norfolk	MAR	31	5	31	18	26
	JUN	34	0	38	18	16
	SEP	20	0	37	0	0
	DEC	30	1	29	19	20

Table 2. Percentage radar utility for a radar network designed to +6dB with respect to the base-system design for the case of low SSN.

Alternatively, a radar may be removed with a reduced network mission scope or radar systems may be added to add diversity to the geometry of propagation and flights. We may use the radar utility to prioritise the overall importance of a particular radar in the network. The radar utility may also guide maintenance schedules or the delivery order of building new radars.

4 Conclusion

We have considered the problem of designing a network of OTHR. We have assumed that the radars within this network have overlapping coverage and aspect and range diversity with respect to the region of network coverage and a defined operational mission. The radar network design methodology generates estimates for the median number of hours per day of effective radar performance and extends these for the total network performance. An estimate of the performance as a function of time-of-day can also be determined. Finally, a radar marginal utility metric is computed, and this is useful for understanding the relative contribution of each radar within the network. We have applied the approach for a hypothetical three-radar network and examined network performance for various radar sensitivity levels. In our example the base-system design is shown to be poor while higher sensitivity designs improve network performance in specific ways.

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