RESOURCE MANAGEMENT FOR A ROTATING MULTI-FUNCTION RADAR

J.M.Butler[†,††], A.R.Moore[††], H.D. Griffiths[†]

[†] University College London, UK
[††]Defence Evaluation and Research Agency Portsdown, UK

1 INTRODUCTION

Due to cost limitations and the expense of phased array antennas, multi-function radars (MFRs) are often forced to utilise less than the 3 or 4 array faces required to give instantaneous hemispherical coverage. Instead, one or two faces are incorporated which are rotated to give full coverage over a scan time; usually of the order of one or two seconds. Although this increases the complication of mechanical construction and of the resource management there are also advantages.

This paper will address the issue of MFR resource management from the perspective of target tracking. It compares static and rotating MFR systems, outlining the main benefits that come from rotating the phased array antenna, and also highlighting the complications that arise in the control of the MFR. It then goes on to present a scheduling algorithm which deals with these complications in an efficient manner.

The work is based upon the research already undertaken for the MESAR experimental radar programme.

2 EFFECTS OF A ROTATING PHASED ARRAY

In a rotating MFR there are some significant complications to the radar control problem that do not exist in the case of a static face MFR, aside from the increased mechanical complexity. In light of this, it is worth pointing out some of the benefits that are accrued by rotating.

Firstly, and predominantly, using a rotating antenna allows full 360° azimuthal coverage with less than the minimum of three faces that are required for a static system. This gives a very significant reduction in the cost of the overall radar system.

Secondly, many of the MFR tasks, such as surveillance may be carried out on array azimuth broadside. The loss in gain and broadening of the beam is now only suffered in the elevation plane. This makes a significant difference to the occupancy (the percentage of the MFR time budget that must be devoted to a function) that is required for the surveillance function. The surveillance occupancy is governed by two factors; the number of beam directions required to search the volume, and the dwell time required in each surveillance beam direction. Fewer beams are required to search a given volume in the static case. However, longer dwell times are needed, since, for a uniform detection performance with azimuth, more pulses must be integrated to offset the loss associated with scanning away from array azimuth broadside.

Table 1 gives a comparison of the radar time that is required for several static and rotating MFR configurations to perform a uniform search over an elevation of 0°-60°. The example given assumes an MFR with phased array(s) tilted back 20° from vertical, and giving a 2.5° beamwidth. Nominally, a 1ms dwell time is assumed on array broadside, which is increased (assuming coherent integration of pulses) to offset a two way loss in gain of the array that varies with the cube of the cosine of the scan angle, φ (see section 2.2 below).

MFR Antenna Configuration	No of beams (per face)	Average beam dwell time	Radar time for search (per face)
1 face rotating	3380	1.17ms	4.0s
2 face rotating	1690	1.17ms	2.0s
3 face rotating	1127	1.17ms	1.3s
4 face rotating	845	1.17ms	1.0s
3 face static	963	2.03ms	1.9s
4 face static	774	1.55ms	1.2s

Table 1: A comparison of the radar time required to perform a search with static and rotating MFR systems

The average dwell time varies in the static case because the 4 faced system needs to scan only to ±45° in azimuth, where the 3 faced system must scan to ±60°, necessitating a greater compensation in dwell time.

Table 1 presents two interesting results. Firstly, comparing the 4 faced and 3 faced systems, it is found that the static systems require 20% (4 faced) and nearly 50% (3 faced) more radar time to execute the search than the rotating systems. More significantly, when comparing the 3 faced static system with a 2 faced rotating system, nearly the same amount of radar time must be dedicated from each of the 3 faces as is required from just 2 faces in the rotating case. Thus in this example, one of the 3 faces could be eliminated if rotation was employed with very little detriment to the search. This comparison is dependent on the search volume and the array tilt angle. It is interesting to note, however, that they are independent of the radar beamwidth.

Finally, since many tasks may be scheduled on, or close to array azimuth broadside, they will produce the best azimuth plot accuracy; also, the beam will illuminate less clutter, and will be less susceptible to main lobe jamming.

It is concluded that rotation offers some significant benefits, even if 3 or more faces are available so that static operation remains an option. We now look at the complications that arise in the resource management.

2.1 Blind arcs in the MFR coverage

If full 360° illumination is not available from the MFRs array/s, (i.e. if less than 3 faces are present), then the MFR must contend with rotating blind arcs, where no tasks may be scheduled. This has the effect of limiting the maximum track update that may be sustained, depending on the azimuth scan capability of the MFRs phased array faces and the rotation rate of the arrays.

2.2 Scanning away from broadside

A heavy penalty may be paid for scheduling tasks away from array azimuth broadside unnecessarily. As Billeter[1] states, it is typical for the two way gain to decrease roughly in proportion with $\cos^3(\varphi)$, causing a decrease in the target signal to noise ratio. Secondly, the beam will broaden, in proportion to $1/\cos(\varphi)$. Thus there will be a two fold degradation in the estimate of the target angle, firstly due to a decreased signal to noise ratio, and secondly due to a broader beam.

Barton's[2] expression for estimating monopulse accuracy allows us to make an estimate of the expected degradation;

$$\sigma \approx \left(\frac{\theta_3}{2\sqrt{(snr).(n)}} \right)$$

where; σ = *monopulse accuracy (rads)*
θ_3 = *3db beamwidth (rads)*
snr = *signal to noise ratio*
n = *number of pulses*

Therefore, the factor by which the monopulse estimate of a beam degrades as the beam is scanned from broadside is given by;

$$\text{degradation factor} \equiv \frac{\sigma_\varphi}{\sigma_{bs}} \approx \left(\frac{1}{\cos^{5/2}(\varphi)} \right)$$

where; φ = *scan angle off broadside(rads)*
σ_{bs} = *monopulse acc. at array broadside*
σ_φ = *monopulse accuracy at scan angle* φ

This is significant for both surveillance and tracking tasks, giving a degradation of a factor of around 5.6 for a scan angle of 60°. Broadly speaking there are three potential courses of action that may be taken in response to this degradation;

i. accept the degradation in both detection performance and angular plot accuracy

ii. try to regain the original broadside detection performance, but accept a degradation in angular plot accuracy due to a broader beam

iii. try to regain the same angular plot accuracy achieved on broadside (in radians), therefore giving an increased detection performance

Option (iii), requires a very large increase in the dwell time. Using the equations above we derive the factor by which the dwell time must be increased to recover the broadside angular plot accuracy (assuming coherent integration of pulses) to be;

$$\text{factor by which to increase dwell time} \approx \left(\frac{1}{\cos^5(\varphi)} \right)$$

This suggests a dwell time 32 times the length of that on broadside would be required to give the same monopulse accuracy at a scan angle of 60°.

Thus we see that the penalties for unnecessarily performing tasks away from array broadside are large. They manifest themselves either in the form of degraded detection performance and plot accuracy, or in terms of increased dwell time for a task. The exact timing in scheduling of tasks is crucial in maximising the efficiency of the surveillance and tracking functions.

2.3 Non-uniform radar loading

The final complication due to rotation of the arrays occurs if the radar loading is not uniform with azimuth. In an operational scenario, very often targets of interest may be in a distinct angular region. It is possible that the total occupancy will be less than 100% for much of the angular coverage, but more than 100% in a smaller sector of it. In these circumstances a rotating MFR is able to behave differently to a static MFR.

Figure 1 compares a 3 faced static MFR system to a rotating system in the presence of a highly loaded sector.

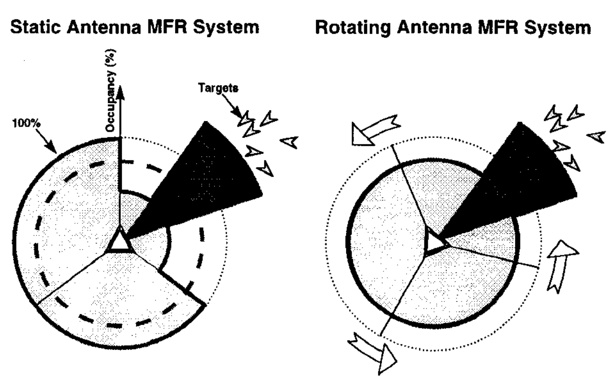

Figure 1: A comparison of the surveillance degradation of static and rotating MFR systems in the presence of an overloaded azimuth sector

In general MFRs are designed to meet a surveillance detection range requirement, using a fraction of the total available occupancy - the surveillance occupancy. This is depicted in figure 1 by the thick dashed line, showing that a nominal 80% of the MFR time budget is allocated to surveillance. The remaining fraction, which we will term the tracking occupancy, is to be used for tracking and other functions.

In the static MFR, two of the arrays are not facing in the direction of the high load angular sector. These array faces will have less than a 100% total occupancy due to the low tracking occupancy. In a static system it is usual for the surveillance occupancy to expand to use the extra available radar time, giving a surveillance detection performance in excess of the requirement (shaded area). Conversely, the array that is facing in the direction of the high load angular sector has a total occupancy in excess of 100%, and thus the surveillance occupancy is contracted to accommodate the extra tracking tasks (small shaded area). Thus the detection performance for this array face will be degraded below the requirement in order to free radar time for higher priority tracking functions. Unfortunately, this is likely to be just the direction where a good search performance is desired.

In the rotating MFR the unequal loading with azimuth angle does not necessarily translate to an unequal loading between the MFR array faces as it does in the static case. It is possible to spend more radar time in some azimuth directions, and less in others by performing tasks ahead of, or behind array azimuth broadside. This is termed *forward* and *back-scanning* of the tasks.

By utilising forward and back-scanning efficiently, the rotating MFR should be able to sustain a uniform detection performance, and allocate extra radar time to service a highly loaded sector. However, forward and back-scanning should be avoided wherever possible due to the penalties associated with performing tasks away from broadside. This suggests that the rotating scheduler algorithm is likely to be required to monitor the MFR radar time loading and act appropriately to allow efficient task scheduling.

3 A BEAM SCHEDULING ALGORITHM FOR A ROTATING MFR

In an MFR the beam is rapidly switched between many tasks to provide the functions of volume surveillance, horizon surveillance, track maintenance, missile uplink etc. The task schedulers job is to maximise the use of radar time, whilst matching it to the most appropriate tasks.

Several task schedulers have been developed for static phased array radars such as those for the SPY, PATRIOT and MESAR[3,4] radar systems. A scheduler algorithm for a single array faced rotating MFR[5] has also been described, based upon the use of a queue to store volumetric search tasks which cannot be performed in a scan due to the presence of tracking tasks.

Here, an algorithm is proposed for a rotating MFR, with one or more array faces, that is designed to cope with the complications of;

i. *rotating blind arcs*
ii. *constraining tasks to array broadside where possible*
iii. *distributing the MFR radar time efficiently with azimuth angle*

The algorithm is centred around the idea of scanning surveillance tasks forward or behind array azimuth broadside (where they would normally be scheduled). This allows radar time to be made available to higher priority tasks such as tracking tasks, which are at a different angle, even if the MFR becomes overloaded. Surveillance will gradually scan forwards in directions where the total desired occupancy is less than 100%. Conversely, surveillance will gradually scan behind array azimuth broadside where the desired occupancy is greater than 100%.

The algorithm attempts to schedule tasks as close to their desired time as possible; typical in a static MFR task scheduler. Additionally, the rotating scheduler algorithm uses the concept of *windows of opportunity*. These are angular limits, relative to array azimuth broadside, which tasks must be within to be scheduled. These windows may be discrete, hard limits, or they may be 'fuzzy', giving soft constraints with angle. For surveillance tasks, they are used to control the amount of forward or back scanning.

An example of a surveillance window of opportunity is shown in figure 2. The window has a hard limit of ~10° ahead of array broadside and a limit behind array broadside set to the extreme of antenna coverage. This allows a maximum forward-scan of surveillance of 10°, but back-scanning is allowed to the extreme scan angle.

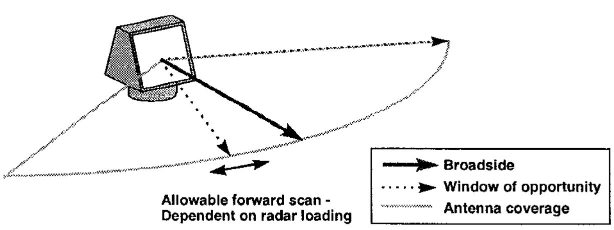

Figure 2: A surveillance task window of opportunity

The amount of forward scanning may be modified by moving the forward limit of the window, in relation to the MFR loading conditions. In under-loaded conditions the window should be set very close to azimuth broadside to ensure surveillance is performed with the maximum efficiency. When an angular region becomes overloaded with tasks the window of opportunity is moved ahead of broadside to allow more forward-scanning of surveillance to occur.

3.1 Forward and back-scanning of surveillance

In principal surveillance may be scanned forward or back to the full azimuth scan limit of the array. This would allow 100% occupancy to be dedicated to tracking tasks for the duration that the loaded sector is within the array coverage sector (whilst still maintaining the surveillance occupancy over a complete scan). However, the detection performance degrades when forward or back-scanned. To maintain a uniform surveillance detection performance, the surveillance dwell times, and thus the surveillance occupancy, must be increased as scan angle increases. The angle of forward and back-scanning is thus constrained; no further forward scanning will occur when the surveillance occupancy reaches 100%. This occurs dependent on the original array azimuth broadside surveillance occupancy chosen. This theoretical limit is shown in figure 3.

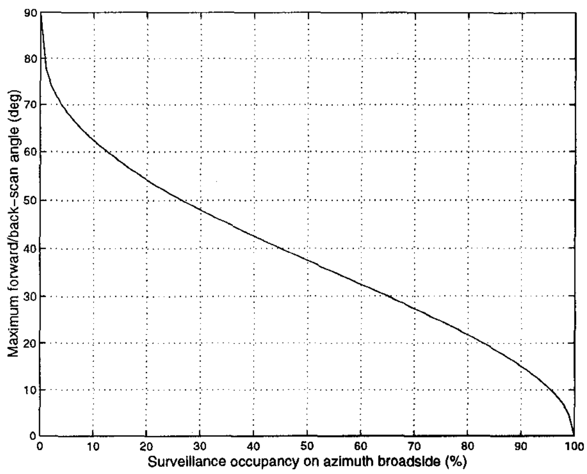

Figure 3: The limit of forward and back scanning from array azimuth broadside, as a function of the design surveillance occupancy.

The maximum radar time that may be dedicated towards tracking functions in an overloaded angular sector through the use of forward and back scanning of surveillance, t_{max}, before the onset of any surveillance degradation, is given by;

$$t_{\max} = \frac{2.\cos^{-1}\left(\sqrt[3]{occ_{surveillance\_bs}}\right)}{\omega}$$

where; $occ_{surveillance\_bs}$ = *surveillance occupancy on array az broadside*
ω = *antenna rotation rate*

3.2 Results

Computer simulations of an MFR using this scheduling algorithm have been undertaken. The results are presented here.

Figure 4 demonstrates forward and back-scanning of surveillance tasks for an MFR with a broadside surveillance occupancy of 80%. In the interval 0-1s, no tracking tasks are present. Forward scanning from 0° at the simulation start, to the limit of around 22° in the first quarter of a second. In the interval 1-2s, a large number of long tracking tasks is introduced over a 30° sector, causing a desired occupancy from the MFR in that sector in excess of 100%. Surveillance is temporarily suspended in this case, due to the extremely high tracking load, and is reinstated some 18° behind array azimuth broadside. It is also important to note that the tracking tasks are performed as close as possible to azimuth array broadside with this method.

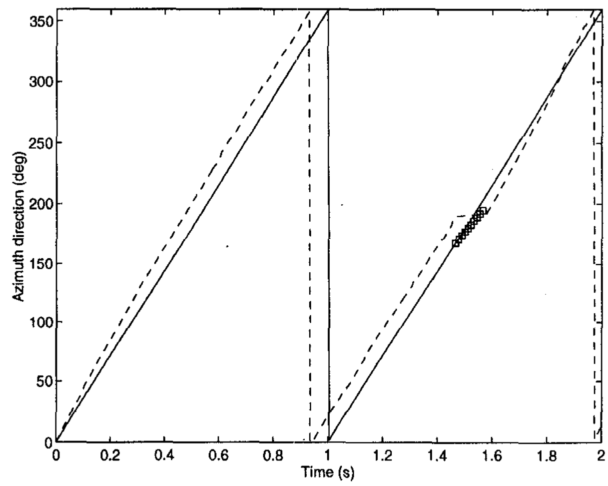

Figure 4: A comparison of the array pointing direction with the azimuth direction of surveillance and tracking tasks. Solid line shows array pointing direction. Dashed line shows surveillance task direction. Square markers show track task direction.

Figure 5, below, shows the desired occupancy from the MFR, needed to service the surveillance and tracking tasks as a function of azimuth. Since the tracking tasks lie within a 30° sector, the desired occupancy over most of the coverage is simply that required by surveillance (80%).

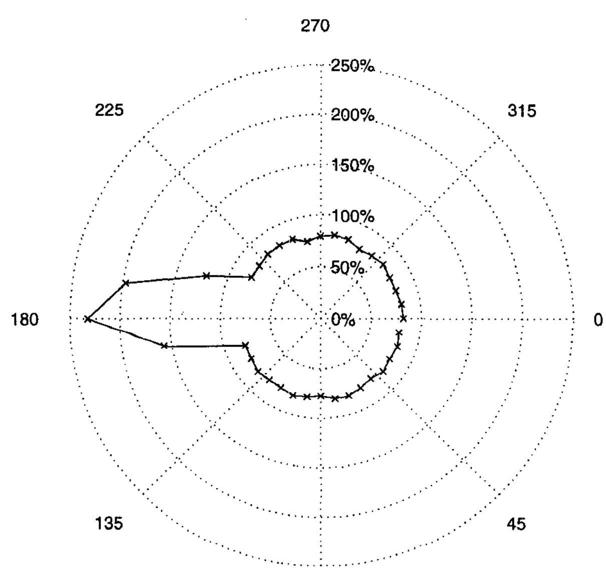

Figure 5: Total desired occupancy of surveillance and tracking tasks as a function of azimuth

The desired occupancy shown in the loaded sector is only around 95% of the theoretical maximum that is suggested from the limit of forward/back-scanning shown in figure 3. The limitation arises from the time taken to go from fully back-scanned surveillance to fully forward-scanned surveillance. Since this must be achieved by the next rotation, the theoretical maximum desired occupancy in the loaded cannot be achieved.

Figure 6 shows the actual occupancies of surveillance and tracking that were needed to service the desired occupancies of figure 5. In regions where only an 80% occupancy was desired, 100% of the occupancy was devoted to surveillance to allow forward scanning to occur.

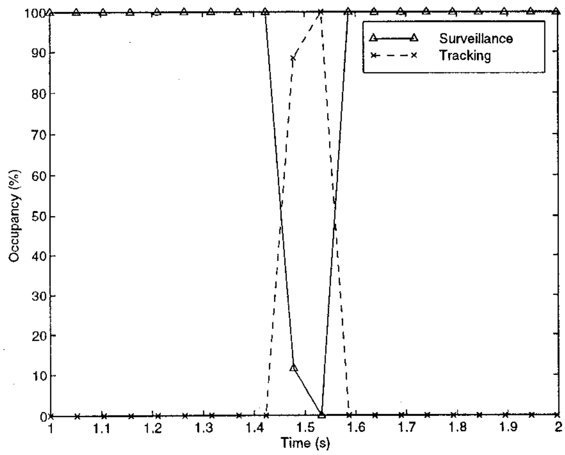

Figure 6: Surveillance and tracking occupancies used to service the desired occupancy shown in figure 5

3.3 Strategies to adopt in case of under or over loading of the MFR

Currently the algorithm only performs forward scanning of surveillance in azimuth angular sectors where the radar loading is less than 100%. It may be desirable to forward scan surveillance even when the loading in an angular sector exceeds 100%, i.e. to degrade surveillance performance in order to dedicate still more time to tracking. Also, mechanisms for freeing or using extra radar time are necessary for the occasions that the MFR is under-loaded or overloaded. In an under-loaded situation, surveillance will reach the forward boundary of its window of opportunity since it will be set close to array azimuth broadside, and the MFR may be faced with no tasks for a period. When overloaded, surveillance may reach the backward boundary of its window of opportunity, possibly requiring the unfavourable option of dropping surveillance beams.

The following are examples of action that may be taken to use or free extra occupancy in the case of under-loading or overloading of a rotating MFR;

i. *increase or decrease surveillance frame times in some regions.* This must be done in multiples of the rotation period of the antenna.

ii. *increase or decrease the surveillance dwell times.* Two methods exist for achieving this; firstly, the number of pulses in a given direction may be increased or decreased to modify the dwell time. Another method is to modify the PRFs of the surveillance waveforms adaptively, extending or decreasing the unambiguous range.

iii. *increase or decrease the surveillance beam spacing.* This is an effective alternative to changing the surveillance frame time or dwell times significantly. A disadvantage is that if the beam spacing is increased too much, then there may be regions in the surveillance coverage with large dips in detection performance. This may be alleviated by utilising scan interlacing[6,7].

iv. *increase tracking data rate or dwell times.* This applies only in the case of under-loading, since our main aim is to avoid decreasing these factors in the case of overload.

5 CONCLUSIONS

An algorithm has been presented for the scheduling of tasks in a rotating MFR that copes with the problems of,

i. blind arcs in the antenna coverage
ii. constraining jobs to array azimuth broadside wherever possible
iii. a non uniform loading of radar tasks with azimuth (as is likely to be the case in practice)

It is highly efficient in distributing the radar occupancy to the angular sectors which require it most. It will automatically adjust from a situation in which tasks are uniformly distributed throughout the MFR coverage to a situation in which the threat may come from a particular angular sector, so that many of the MFR tasks are concentrated in a small azimuthal sector.

REFERENCES

1 "Multifunction array radar design", *D.R. Billeter, Artech House, 1989*

2 "Modern radar system analysis", *D.K.Barton, Artech House, 1988, p393*

3 "Real-time control of a multifunction electronically scanned adaptive radar (MESAR)", *W.K.Stafford, IEE Colloquium, 12 June, 1990*

4 "Software architecture for real-time control of the radar beam within MESAR", *M.Wray, Proc. Radar '92*

5 "An improved scheduling algorithm for a naval phased array radar", *A.Barbato and P.Giustiniani, ALENIA Defence Systems, Proc. Radar '92, October 1992*

6 "Parameter Optimisation in phased array radar", *E.R. Billam, Proc. Radar '92, October 1992*

7 "Beam shape loss and surveillance optimisation for pencil beam arrays", *P.M. Hahn and S.D. Gross, IEEE Trans. vol. AES-5, 1969*