Design Criteria for a Multifunction Phased Array Radar integrating Weather and Air Traffic Control Surveillance

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Abstract — **Cost reduction for Transmit/Receive modules makes phased array radar of potential interest to civilian users. An integrated target/weather surveillance at medium range, i.e. for Terminal Manoeuvre Area in the frame of ATC and regional weather monitoring, is made possible by MPAR (Multifunction Phased Array Radar) techniques, allowing a single technology to satisfy different requirements. The main design criteria and tools are outlined, as well as the preliminary guidelines for a detailed system design, needed for a future cost/benefit analysis. The key techniques needed to achieve the required performance are (a) interleaving of functions by careful scheduling, (b) digital beam forming for target surveillance and (c) fast (electronic) scanning for the weather surveillance. Using these techniques it is possible to design an architecture in which the Transmit/Receive module (TRM) may operate with a rated low peak power, compatible with the low-cost requirement.**

I. INTRODUCTION

MPAR (Multifunction Phased Array Radar) architectures for civil use have recently gained a significant interest, see e.g. [1] – [5]; as an example, in [1] it is shown that the present situation in the USA concerning Air Traffic Control and weather radar, i.e. 510 radars with a mechanically rotating antenna, being of 8 different types, each type being single mission, requiring multiple maintenance, logistic and training programs, may be substituted by 334 radars with an electronically steered antenna, single type, scalable architecture, with common logistics and training programs. Doc. [5] refer to the Next Generation Air Transportation System Integrated Plan by the USA Joint Planning and Development Office where it is said that MPAR can provide the greatly reduced scan times, high resolution, and multifunction capability required for the enhanced severe weather prediction and aircraft. An example of emerging requirements for ATC radar surveillance is shown in Table I.

II. SURVEILLANCE REQUIREMENTS

In this work we consider four functions: *ATC* functions at short and medium range, and *Weather* functions at short and medium range. Table II shows the assumed requirements for the four functions in term of the coverage area and the update time (time request to revisit a range bin) [3].

TABLE I
EMERGING REQUIREMENTS FOR ATC RADAR SURVEILLANCE

Coverage requirement	60 – (80) NM : 110 – (150) km
Target Characteristics	Swerling 1, RCS 1 m^2
Antenna Rotation	12 rpm or 15 rpm
Probability of Detection	better than 80 %
False Alarm Rate	10^{-6}
Maximum elevation angle	40° (50°)
Maximum height	40000 feet (12 km)

For an European-type environment, the application of MPAR to Terminal Area (TMA) surveillance (up to 60 Nautical Miles, NM) is considered more important than the Airway Surveillance (up to 200 NM) and the present study is related to TMA and to Airport Surveillance, with a sensor much smaller and having less Transmit-Receive-Modules than the one outlined in [5].

TABLE II
ATC AND WEATHER FUNCTIONS AND REQUIREMENTS
(SR = SHORT RANGE, MR = MEDIUM RANGE)

Functions	R_{MAX} (km)	Height (km)	Azimuth x Elevation	Update time T_F (s)
ATC SR	55	12	90° x 50°	1
ATC MR	110	12	90° x 40°	4
Weather SR	55	12	90° x 26°	150
Weather MR	110	12	90° x 15°	300

III. MAIN ARCHITECTURES CONSIDERED FOR THIS MPAR STUDY

MPAR architectures can be subdivided in two classes. The first class, in order to cover the radar volume, uses large beams in transmission, while in reception, by Digital Beam Forming (DBF), employs many simultaneous narrow beams. The second class uses beam forming to scan the coverage volume both in transmission and in reception. In this study we consider the first type of MPAR with Digital Beam Forming to permit a quick revisit time and an optimal coverage of the surveillance volume, [6], [7]. Moreover in this preliminary study we limit ourselves to non-adaptive functions, where the scan time do not depend on the observation.

A simplified scheme of the array [10], [11], [12] is shown in Fig. 1; groups of elements, spaced each other by half wavelength, are combined by an analog network in subarrays (the rough order of magnitude of the number of subarrays is the square root of the total number of elements); the analolg-to-digital conversion is executed at the subarray output in order to perform digitally beam-forming and other array processing functions. The architecture has a narrow beam at low elevation with DBF at high elevation, as well as a variable number of pulses in the beam: from 16 (groups, or CPI each of 8 pulses) at low elevation up to 2 pulses at high elevation.

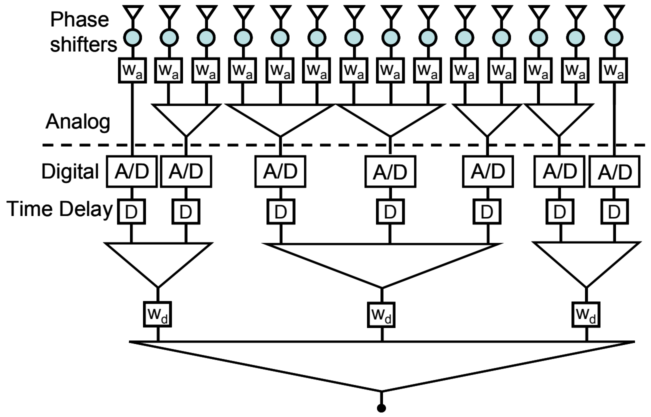

Fig. 1 Array architecture with subarrays, Digital Beam Forming and digital True Time Delay.

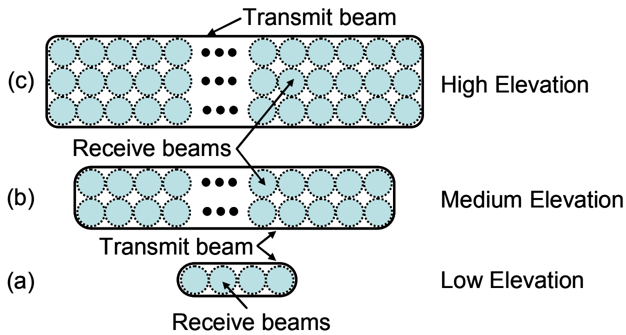

Fig. 2 General view of transmitted and received beams (DBF).

In such a way the optimal distribution of radar resources (power, time) is achieved to obtain the desired coverage in elevation. A typical grouping of receiving beams with DBF is shown in Fig. 2 with the elevation of 0.35° to 8.05° (case *a*), 12.45° (case *b*) and 19.05° (case *c*). The elevation beam broadening has been neglected in these preliminary evaluations for the sake of simplicity. The transmit beam is obtained by proper defocusing of the transmission wavefront, generated by all radiating elements operating ad the same peak power. An example of transmission beam shape is shown in Fig. 3: its design pattern is of the *"flat top"* type, obtained with defocusing of the array in transmission.

Finally S-band (2.7 to 3.0 GHz) has been considered because of its low attenuation effects in rain, and of its standard use in ATC.

Other interesting architectural choices, not analysed here, concern: (i) the transmitted and received polarization, whose requirements for targets detection are contrasting with those for weather analysis; (ii) the frequency-division operation for the various functions of Table II, subject to the limitation of the number of allowed operating frequencies for each installation (generally ranging from two to four, the latter when the weather function is considered).

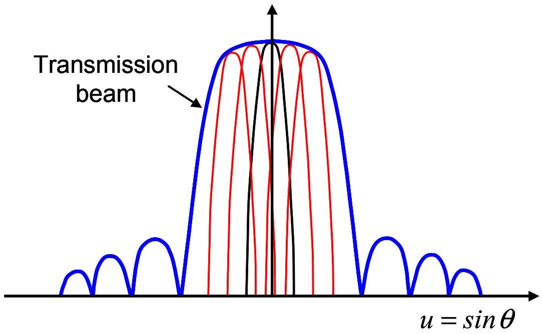

Fig. 3 Example of transmission beam shape.

IV. Design Methods and Related Tools

For the generic function F the revisit time t_F (or execution time) is the time necessary to scan the entire coverage volume associated to the function. It depends on: (a) the antenna dimension (i.e. the beamwidth in azimuth and in elevation): we suppose a Gaussian pattern and three beam intersection values: at -1, -2 and -3 dB; (b) the pulse repetition time (PRT): we considered the minimum non ambiguous PRT; (c) the number of samples: we start from 16 samples for low elevation angles and decrease this value when increasing the elevation in according to the coverage (see Table III).

TABLE III
ATC Function Medium Range with Antenna 5m x 6m

Beams Number	Elevation (°)	Rmax (km)	PRT (ms)	Pulses	Azim. beams	Elev. beams	Time (s)
1	0,35	110	0,73	16	4	1	0,219000
2	1,45	110,1	0,73	16	4	1	0,219000
3	2,55	110,2	0,73	16	4	1	0,219000
4	3,65	110,3	0,74	16	4	1	0,222000
5	4,75	110,5	0,74	16	4	1	0,222000
6	5,85	110,7	0,74	16	4	1	0,222000
7	6,95	94,9	0,63	10	4	1	0,118125
8	8,05	82,9	0,55	6	4	1	0,061875
9	9,15	73,5	0,49	4	4	1	0,036750
10	10,25	66	0,44	4	6	1	0,022000
11	11,35	59,9	0,40	2	8	1	0,007500
12	12,45	54,9	0,37	2	8	1	0,006938
13	13,55	50,6	0,34	2	12	1	0,004250
14	14,65	47	0,31	2	12	1	0,003875
15	15,75	43,8	0,29	2	20	1	0,002175
16	16,85	41,1	0,27	2	20	1	0,002025
17	17,95	38,7	0,27	2	32	1	0,001266
18	19,05	36,6	0,26	2	32	1	0,001219
19	20,15	34,7	0,23	2	32	1	0,001078
20	21,25	33	0,23	2	32	1	0,001078
21	22,35	31,4	0,21	2	32	1	0,000984
22-23	23,45-24,55	30	0,20	2	32	2	0,000938
24-25	25,65-26,75	27,6	0,20	2	32	2	0,000938
26-29	27,85-31,15	25,6	0,17	2	32	4	0,000797
30-37	32,25-39,95	22,4	0,15	2	32	8	0,000703
							1,5975

Obviously, for each function, the revisit time t_F must be less than the update time T_F reported in Table II. Instead the cycle time T_{cycle} defines the period in which all functions are executed al least once so the cycle can be repeated.

The following steps describe the scheduling of two or more functions: (1) Verification that the functions (Table II) can be performed in a time lower than their own update time. (2) Evaluation of the T_{cycle} (that is the least common multiple of the update times) and computation, for each function, of the number of executions per cycle. (3) Fill the time cycle starting from the function with smaller update time and setting how much time is available for other functions. (4) Fill the time available in step 3 with the function that has smaller update time among those remaining. (5) Repeat step 4 until all functions are interlaced.

The scheduling is simplified if the T_{cycle} coincides with the greatest update time T_F and the others T_F are submultiple of T_{cycle}.

With respect to the power dimension, for ATC functions to evaluate the peak power per active module we have considered the radar equation supposing a SNR derived from a fixed values of $p_{fa} = 10^{-6}$ and $p_D = 0.9$, target Swerling 1, and pulsewidth of 1 microsecond, no pulse compression has been supposed in this preliminary analysis in order to maintain the execution time at low value.

For Weather functions the peak power for module has been evaluated using the Probert-Jones equation [8], [9] supposing a SNR = 10 dB with a minimum value of reflectivity of -7 dBz, and a pulsewidth of 1 microsecond.

A suitable tool has been designed to define the transmission schedule for the various functions (four in this cases, see Table II) compatible with the requirements; the first tentative results are shown in next section. One of the input is the selected antenna dimension, variable from 3 x 6 to 6 x 6 metres (six cases).

V. Preliminary Results

Figures 4 and 5 show that without DBF the revisit time (Execution Time) always exceeds the requirements of Table II.

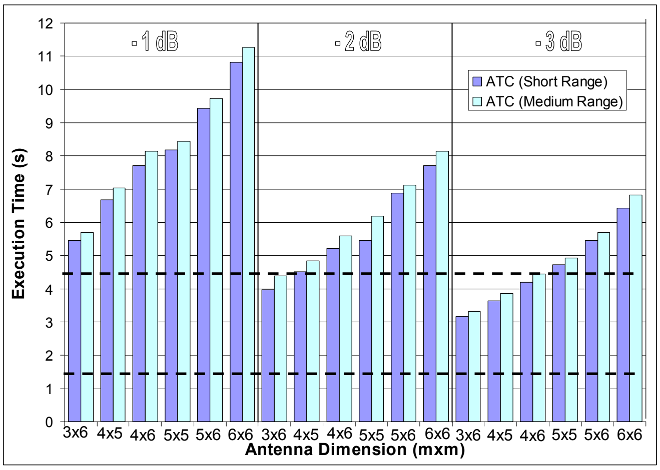

Fig. 4 Execution time without DBF for the two ATC functions versus the antenna dimension, at S band with T/R modules spacing at λ/2. Dashed line represent the requirement for the revisit time.

Dashed line represent the requirement for the revisit time, while –1 dB, –2 dB and –3 dB are referred to the antenna beams intersections in elevation, Fig. 6.

With respect to the peak power per module, Fig. 7 reports the values of evaluated power versus both the dimension of the antenna. The most critical function results the ATC Medium Range, and -2 dB beams intersection in elevation appear to be a good trade off between the revisit time and the peak power. To permit a quick revisit time, DBF has been introduced.

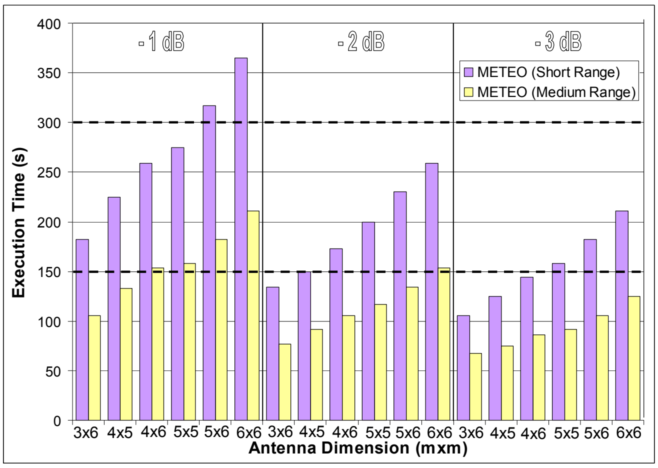

Fig. 5 Execution time without DBF for the two Weather functions versus the antenna dimension, at S band with T/R modules spacing at λ/2. Dashed line represent the requirement of the revisit time.

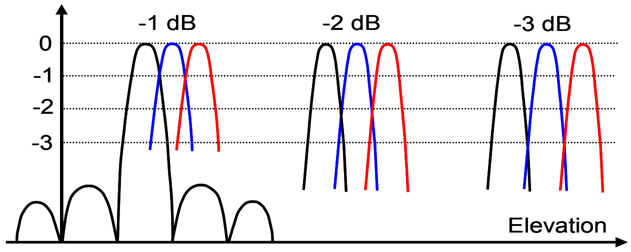

Fig. 6 Intersection of elevation beams.

The peak power per module has been computed for the most critical function (ATC Medium Range) imposing 4 beams in azimuth at zero elevation, increasing this values as reported in Table III. Fig. 8 shows the radar coverage in elevation for the ATC Medium Range function using *5m x 6m* antenna ($\theta_{el\text{-}2dB}$ = 1.1°) with DBF, and a peak power per module of 8.5 W obtained supposing $p_{fa} = 10^{-6}$, $p_D = 0.9$, SNR = 21.1 dB, target SW1. The revisit time is reduced from 7.1 s (Fig. 4) to about 1.6 s (Table III), well within the requirements.

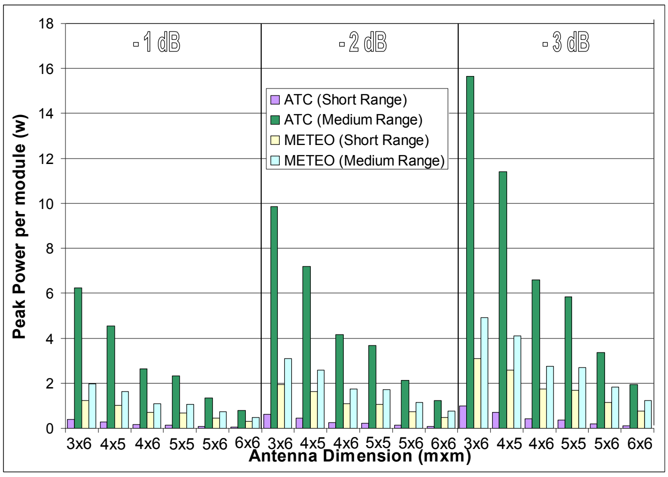

Fig. 7 Peak Power per module without DBF for the four functions versus the antenna dimension, at S band with T/R modules spacing at λ/2.

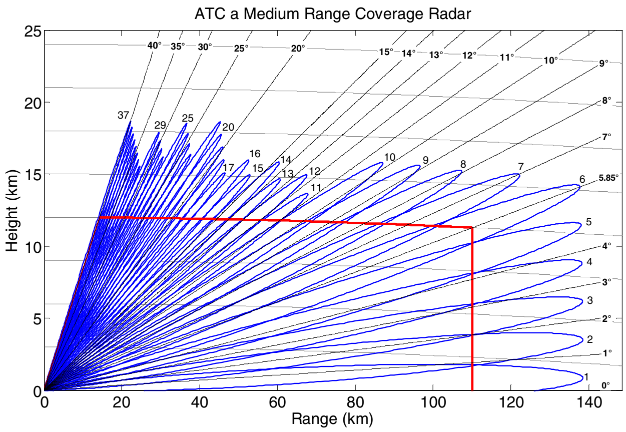

Fig. 8 Coverage radar volume for ATC Medium Range function using *5mx6m* antenna (θ_{-2dB} = 1.1°) with DBF in azimuth, and a peak power per module of 8.5 W obtained supposing a $p_{fa} = 10^{-6}$, $p_D = 0.9$, SNR = 21.1 dB, target SWR1.

Considering a peak power of 8.5 W per module (however this value has to be reduced by using frequency diversity and pulse compression), the revisit time for the ATC Short Range, using DBF, is 0.14 *s* while for Weather Medium Range it results equal to 115.2 *s*. These values are in according to the time requirements and permit to schedule the functions as shown in Fig. 9 for the first 8 seconds.

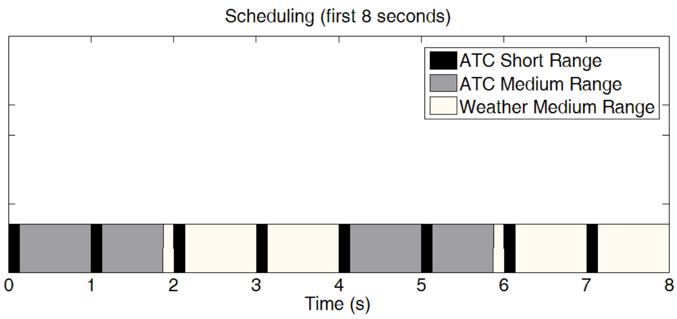

Fig. 9 First 8 seconds of the scheduling of the three functions: ATC (Short and Medium Range) and Weather Medium Range. The time of cycle is 300 s (it coincides with revisit time of the Weather Medium Range Function).

Fig. 10 reports the percentage of time for ATC and Weather functions referred to the time of overall cycle. (300 s).

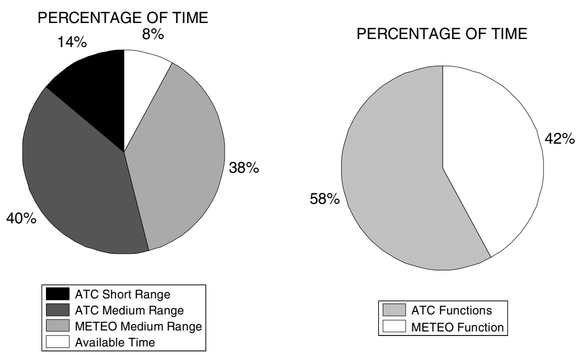

Fig. 10 Percentage of time for ATC and Weather functions referred to the time of cycle. (300 s).

VI. Conclusion and Perspectives

A preliminary study has been carried out to supply an example of overall system design for a Multifunction Phased Array Radar for civilian applications, whose main problems are of course the costs.

The main advantages of this solution are the reduction of the types of radar equipment and the enhanced performace due to fast scanning.

For the weather function, the decorrelation of the weather signal by fast scanning permits a reduction of dwell time up to 15–20 times (e.g. from 128 to 6-8 pulses) with the same measurements accuracy.

For the target function, the flexibility of coverage and the potential to create dedicated beams to track aircraft in special conditions of manoeuvre and/or when other localization and identification systems look erroneous.

The antenna architecture is with overlapped subarrays and digital beam forming in reception, adopted to the different elevation sectors.

The antenna element (in its preferred configuration) has a peak power of the order of a few watts, dual polarization.

In order to reduce the costs of the array, the instantaneous bandwidth is smaller than the overall operating band (i.e. from 2.7 GHz to 3.0 GHz).

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