AN INTRODUCTION TO ELECTRONICALLY SCANNED ARRAYS FOR AIRBORNE PLATFORMS

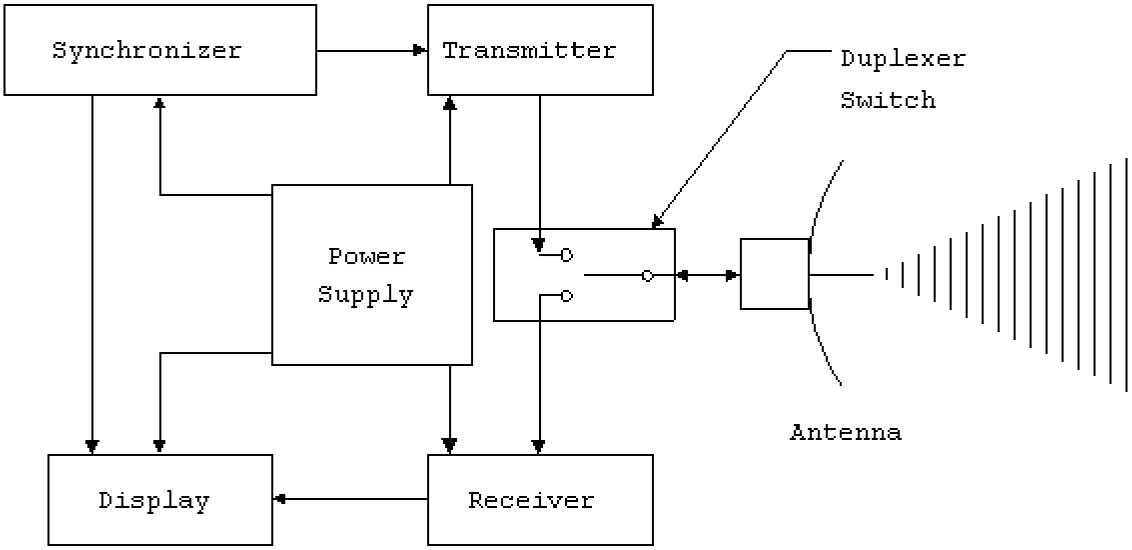
A Technical Paper by Aditya Mandrekar

Index

Topic **Page No.**

1. Introduction

Radar is an acronym for Radio Detection and Ranging. The term "radio" refers to the use of electromagnetic waves with wavelengths in the so-called radio wave portion of the spectrum. Radar systems typically use wavelengths on the order of 10 cm, corresponding to frequencies of about 3 GHz. The detection and ranging part of the acronym is accomplished by timing the delay between transmission of a pulse of radio energy and its subsequent return. If the time delay is δt, then the range may be determined by the simple formula: $\mathbf{R = c*\delta t/2}$ where $c = 3 \times 10^8$ m/s, the speed of light at which all electromagnetic waves propagate. The time delay is halved in the formula, as the radar pulse must travel to the target and back before detection, or twice the range. A simple flow diagram of a radar system is depicted below[1].



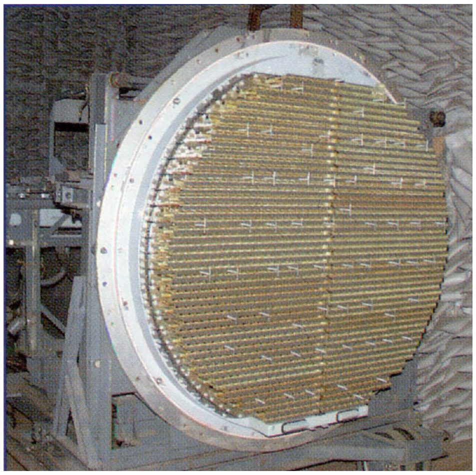
Now, the antenna emits a beam in the general direction it points to. For a radar to scan a particular sector, the antenna needs to be moved from one extreme to another in both planes horizontal (azimuth) or vertical (elevation). Such an antenna is called a mechanically steered antenna and the radar is called a “slotted array”.

In the late seventies with an increased research in the properties of ferrite materials, it was found that radio waves could change phase while passing through ferrites depending on their electromagnetic state. This led to the development of a new type of radar in which the radio beam was not steered by an antenna that physically moved, but was steered *electronically* by shifting the phase between the radio wave transmitted by multiple antennae. Such radars are called **electronically scanned arrays** or **phased arrays**[2].

Over the last two decades electronically steered arrays have become a **must** for any modern fighter or early warning aircraft because in air combat, split seconds are crucial and the advantage offered by phased arrays could mean the difference between life and death for a pilot.

2. Electronically Steered Arrays

Existing mechanical scanning methods are inherently slow and require large amounts of power in order to respond rapidly enough to deal with large numbers of high speed maneuvering targets. With mechanically scanned systems, antenna inertia and inflexibility prevent employment of optimum radar beam positioning patterns that can reduce reaction times and increase target capacity.



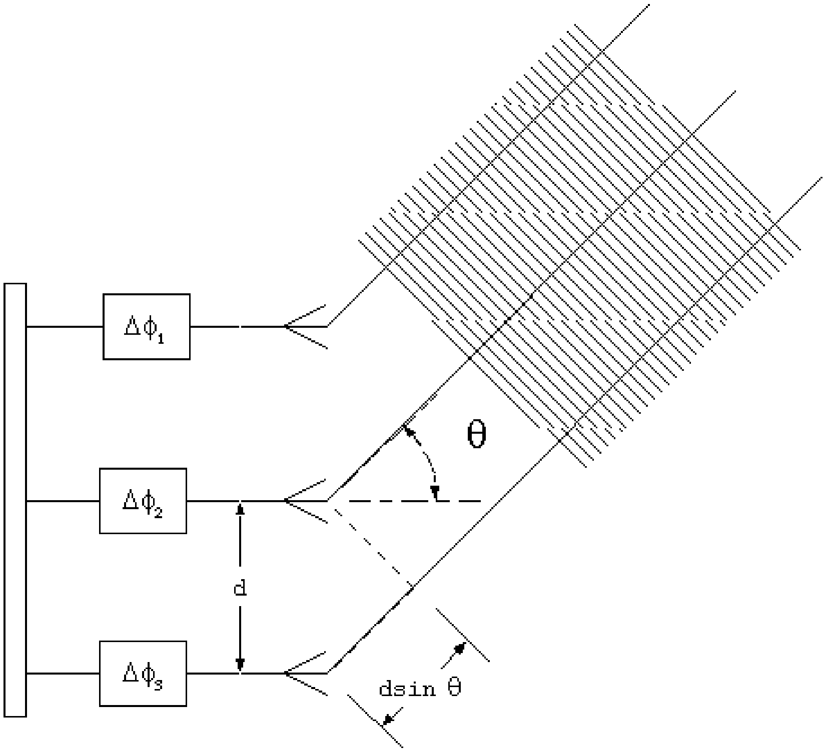
The solution to this was to create an array of radio transmitters that would use the phase difference between adjacent waves to steer a beam. This array is created more often than not, by having multiple lenses fed with radio waves from a single transmitter antenna instead of many independent wave tubes, which can be expensive, and power hungry. Hence multiple independent transmitters for phased array radars are generally used on large ground and ship based stations.

The following analogy[2] provides an illustration of an electronically scanned array's principle:

Three stones are dropped a few centimeters apart in a pool of water. The stones are dropped simultaneously and when the ripples on the water meet each other, a composite wave front forms and expands in parallel with an imaginary line between each stone' s points of impact.

If the same stones are now dropped at the same distance from each other, but with a time difference of a few seconds between each stone' s impact on the pool of water, the composite wave front will expand at an angle to the imaginary line between each stone' s point of impact. The greater the time difference, the greater is the angle. By changing time differentials between points of impact, accordingly, it' s possible to change the angle of the composite "pulse" created by the stones.

A simple three-antenna array is shown below[3]. Here we have a three element linear array, all fed from a common source, with a variable phase shift at each element.

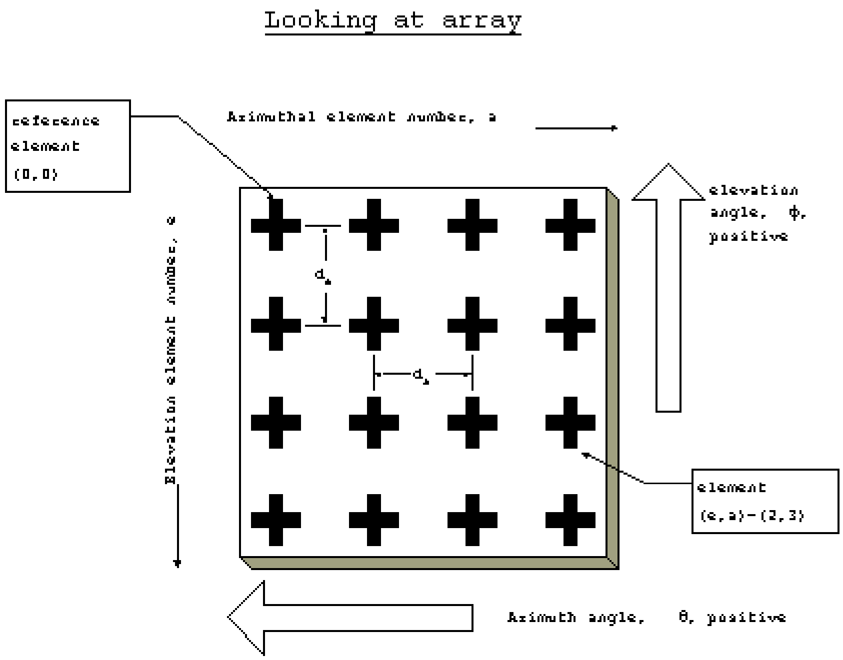


In order to change the direction of maximum constructive interference by the angle, θ, the phase shifts must be chosen to exactly compensate for the phase shift created by the extra distance traveled, d sin(θ). The condition for the phase shift between adjacent elements can be found from

$\boldsymbol{\delta\phi_{adj} = (2\pi/\lambda)\, d \sin(\theta)}$, where the symbols indicate the same parameters as before.

This same principle may be applied to a planar array. In this case, the phase shift will steer the beam both in azimuth and elevation. The phase shifts required may be computed independently and combined algebraically to give the net phase shift required.

Consider a planar array as shown below[1].



First we must establish the coordinate system. When facing the array, the upper leftmost element will be the reference with coordinates (0,0). The elements will be assigned coordinates with the first number representing the elevation and the second the azimuth element number. The general element coordinates will be (e,a) where: e = elevation element number & a = azimuth element number.

The phase shift required to steer the beam to an elevation angle ϕ (defined so that upwards is positive) and azimuth angle θ (positive when to the left as seen looking into the array), will be

$$\boldsymbol{\Delta\phi_{e,a} = (2\pi/\lambda)[\, e\, d_e \sin\phi + a\, d_a \sin\theta \,]}$$

where d_e and d_a refer to the element spacing in the vertical and horizontal directions respectively.

The Phased Array principle is also used in Active Electronically Steered Arrays (AESAs) that use semiconductor technology instead of wave tubes for generating radio waves.

With electronic scanning, the radar beams are positioned almost instantaneously and completely without the inertia, time lags, and vibration of mechanical systems. In an era in which the numerical superiority of adversaries is expected to remain large, electronic scanning can offset that advantage.

The specific benefits of electronic scanning include:

1) Increased data rates (reduction of system reaction time),
2) Virtually instantaneous positioning of the radar beam anywhere within a set sector (beam position can be changed in a matter of microseconds).
3) Creation of '*null spots*' in a particular scan field so as to skip areas of either known enemy warning receiver positions or sources of jammers.
4) Elimination of mechanical errors and failures associated with mechanically scanned antennas
5) Vastly increased flexibility of the radar facilitating multi-mode operation, automatic multi-target tracking, highly directional transmission of missile guidance and control orders, interceptor and general air traffic control from one radar at virtually the same time

But in spite of this there remain certain disadvantages of phased arrays:

- Phased Array radars are bulky and are better suited to middle and heavy weight fighters as compared to small lightweight fighters.
- The initial cost of phased array antennae is expensive, though a lot of it is recovered in the long run where less maintenance is required
- In case of battle damage phased arrays take longer to replace or repair than slotted arrays, which can seriously hamper the functioning of the aircraft.

3. Active Electronically Steered Arrays (AESAs)

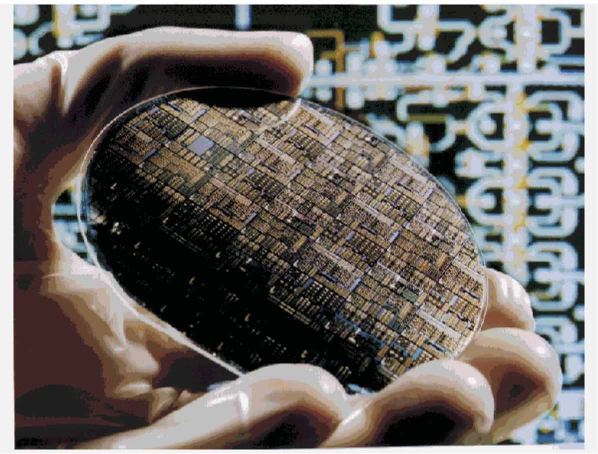
AESA radars represent the cutting edge of radar technology. There are at present at least eight aircraft and unmanned aerial vehicles all over the world[5] that will be fitted with them in the coming decade. So what makes them so special?

In all radars electrical energy is converted to electromagnetic waves. Passive Phased Array radars use wave tubes (just like slotted or mechanically scanned arrays), but they employ a multiple number of lenses attached to a single antenna to achieve simulated higher numbers of transmitters with ferrite phase shifters behind each lens. A sample wave tube is shown on the left. It is approximately a foot long and three inches wide. It is a gas-filled tube with multiple electrodes operating at high power.

The wave tube itself has its inherent losses both in the transmit and receive paths, which means that the power output of the radar is significantly lower than that supplied by the power supply

In the case of the transmit path, RF power is lost in the power distribution network ("plumbing"), phase shifters, circulators, and T/R switches. On the return path these losses reduce the signal strength prior to the low noise amplifier, thereby reducing the received S/N ratio. Combined, these losses can reduce the overall sensitivity on the order of 10 to 15 dB (a factor of 10 to 30). On reception, the signal travels the reverse path, through the phase shifter, possibly multiple corporate feeds (for multiple phase centers/antenna beams), to receivers with low noise amplifier (LNA) front ends, and then to A/D converters whose outputs are fed to the signal processor. Additional components in this signal chain are required to switch the elements between transmit and receive (T/R switches) and to provide isolation and protect against element mismatches (circulators).

AESA radars on the other hand use **MMIC**s (*monolithic microwave integrated circuits*) that are inside the **transmit/receive** (T/R) module to convert electrical energy to electromagnetic waves. The main advantages of the MMICs themselves are that they do the conversion much more efficiently. By putting the final stage of transmit power generation, as well as the receive amplifier, at the radiating element, these losses can be greatly reduced. To accomplish this reduction, the T/R modules containing the phase shifter, transmit power amplifier, T/R switch (possibly including a circulator) and the LNA/receiver are located as close to the radiating element as possible. In some cases the radiating element is made an integral part of the module itself as seen in an MMIC. This way the losses occurring due to the plumbing networks are not only low but do not affect the received power.



Although some passive phased array radars are very efficient because they use non-equidistant radar field distribution which improves their efficiency, but it still does not match that of an AESA. This extra efficiency means that if two radars are identical in terms of power input, but one is an AESA antenna, it will have greater search and track capability

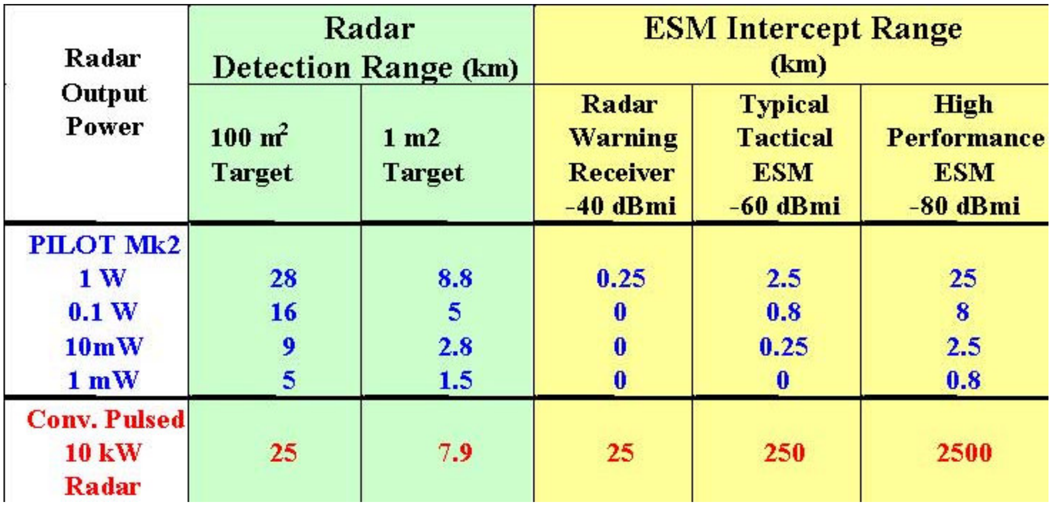
The other advantage is the reaction time of MMICs, being semiconductors, will be much less than that of travelling wave tube and they will have a far greater bandwidth. This means they can ‘hop’ frequencies very fast and this itself has enormous advantages:

1) The target will not pick up the transmitted signal because there is no clear signal, but rather just background noise
2) The target can' t jam the transmitted radar because the frequency constantly changes so even if it does catch a frequency it will be of little use.

This gives an AESA unprecedented Low Probability of Intercept (LPI) and Anti-Jam capabilities, making it perfect for stealth purposes, so the aircraft is not detected by the targets or early warning radar receiver stations. It also means that more information can be gained about the target without compromising the location of the radar.

Also, unlike high power wave tubes that require tens of kilovolts of power, MMICs require approximately only ten volts of power for their working. This means that high power generating equipment is either not required on the aircraft or can be used for other equipment. Another added advantage is that with low power and current values, the cooling systems required for AESA radars is much lesser in quantity as compared to conventional or passive phased arrays. This is one of the biggest considerations for radars as space inside the aircraft is always at a premium. However, the network for cooling is far more complex as each wafer dissipates power and the working of semiconductors is easily affected by temperature changes..

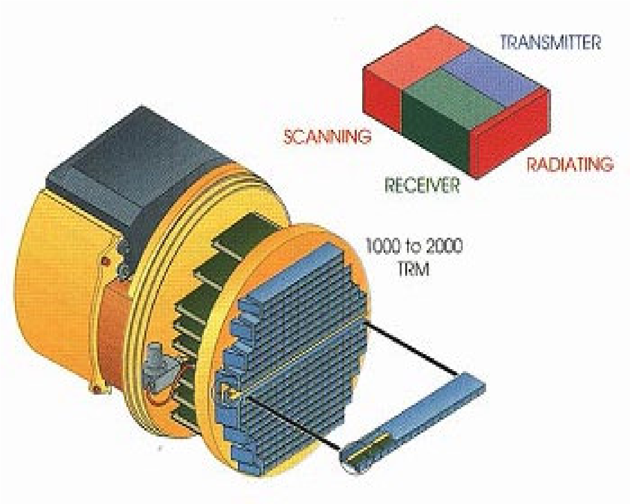
The chart[4] shown below gives a clear idea on the effectiveness of the Pilot Mk.1 AESA radar. The Pilot is a radar developed by Swedish car, aircraft and avionics manufactured SAAB for ground-based systems. It can be clearly seen from the chart that AESA based radar uses much less power than its wave-tube counterpart and is much tougher to detect by current radar warning receivers (RWRs) than conventional wave tube based radars.



Radar Output Power	Radar Detection Range (km)		ESM Intercept Range (km)		
	100 m^2 Target	1 m2 Target	Radar Warning Receiver -40 dBmi	Typical Tactical ESM -60 dBmi	High Performance ESM -80 dBmi
PILOT Mk2					
1 W	**28**	**8.8**	**0.25**	**2.5**	**25**
0.1 W	**16**	**5**	**0**	**0.8**	**8**
10mW	**9**	**2.8**	**0**	**0.25**	**2.5**
1 mW	**5**	**1.5**	**0**	**0**	**0.8**
Conv. Pulsed 10 kW Radar	**25**	**7.9**	**25**	**250**	**2500**

In addition to the advantages of the MMICs themselves, there is the advantage of the size, weight and layout of AESA radar. These MMICs are inside the T/R module and most fighter plane AESAs have up to 2,000 of these T/R modules in their radar arranged in stacked rows and yet their weight remains less than that of conventional radar. The diagram of a small technology demonstrator for the AMSAR (future AESA for Rafale and Eurofighter) is shown below.

The rectangular prisms on the radar antenna are T/R modules. Each T/R module can convert electric energy to electromagnetic waves on its own using MMICs inside them. For each row of T/R modules, there is an electric power supply separate from the other rows. This means that the emissions of each row can be controlled **independently** from the rest of the radar.



This too gives several advantages:

1) You can dedicate each row, or a group of rows against a specific target and you can use a waveform or frequency that best suits against that target. A target specific waveform means that you need to use less power against a target since what you put against it will be very efficient against that particular target. This of course means you can track more targets and detect different kinds of targets faster.
2) You can dedicate certain rows or multiple groups of rows for jamming, radar warning receivers, or even communications.
3) The third advantage of T/R modules is that if one or a few modules fail, the radar will still work with an automatic correction via software. But on conventional wave tube radar, a failure will mean the radar will not work.

Another major advantage of an AESA over a passive ESA or a mechanical array is the mean time between critical failures (MTBCF). Since the power supplies, final power amplification and input receive amplification, are distributed, MTBCF is significantly higher, 10-100 times, than that of a passive ESA or mechanical array. This results in higher system readiness and significant savings in terms of life cycle cost of a weapon system, especially a fighter. For fighter and unmanned aerial vehicles (*UAV*) applications, these large MTBCF means little or no radar array maintenance is required for the life of the platform.

In the near future T/R modules will be placed on the side of the aircraft so they can scan a much wider region. The Lockheed Martin F-22 Raptor was supposed to have this technology but it has not yet cleared the experimental stage. In the farther future, T/R module technology can be used for smart skin arrays. This means T/R modules can be placed right under the skin of an aircraft. This means given sufficient power supply, you can have a radar system all over the aircraft!

The major setback with these radars is cost of the antenna itself. For 2,000 T/R modules at around 1,000 US Dollars **each** (Japanese modules now cost around 600$) the cost **is Two million dollars** just for the antenna. This is why the AGP-77 radar on the F-22 Raptor costs close to 10 million dollars[6]... But with the requirement for microwave equipment increasing constantly in the civilian market and plans by the United States Department of Defense to fit various other aircraft such as the future Joint Strike Fighter (due 2008) and the Global Hawk unmanned surveillance aircraft the cost should go down.

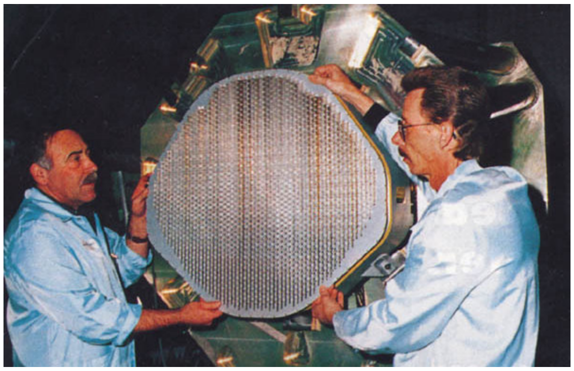
Another disadvantage is that hardware required for AESA radars is not easily available even in first world countries, and requires an established industry for manufacture of MMICs. This is one reason why European AESA projects have been significantly delayed. Another reason is the software programming is extensive but this is now no longer an impedance with the arrival of an IT boom.

4. Electronically Scanned Arrays on Fighter aircraft

Radar	Aircraft	In service with	Type	Status
Zaslon-M	MiG-31 ‘Foxhound’	Russia	Phased Array	In Service
N011M bars	Su-30MKI	India	Phased Array	In Service
Zhuk MS	Su-30MKK	China	Phased Array	In Service
RBE2	Dassault ‘Rafale’	France	Phased Array	In Service
APG-63(v1)	F-15C ‘Eagle’	USA	Phased Array	Fitted on 18 aircraft
APG-63(v2)	F-15E/K ‘Strike Eagle’	USA, South Korea*	AESA	Under trial
APG-77	F-22 ‘Raptor’	USA	AESA	Due 2004
APG-79	F/A-18E ‘Super Hornet’	USA, Malaysia*	AESA	Under trial
AMSAR**	Eurofighter	Britain, Italy, Germany, Spain, Greece	AESA	Under trial
AMSAR**	Dassault ‘Rafale’	France, Brazil*	AESA	Under trial
NORA	SAAB-BAe ‘Gripen’	Sweden, Czech Republic*	AESA	Projected 2006
(unknown)	Mitsubishi F-2	Japan	AESA	Partly in service

*Offered **being made by the same consortium but with minor structural differences

The Zaslon-M on the MiG-31 ‘Foxhound’



The APG-77 intended for the F-22 ‘Raptor’

5. India and Electronically Steered Arrays

The Sukhoi Su-30MKI parked for static display at Aero India 2003 at Yelankha Air Force Base near Bangalore in South India. This was the first time the Su-30MKI was showcased in Indian colours.

India will gain its first hands-on experience with airborne phased array radar with the arrival of the N011M 'Bars' radar fitted on the Russian Sukhoi Su-30MKI, ten of which were inducted on September 27th, 2002. This will be a major step as license manufacture of the aircraft and all components (from 2004 onwards), including the radar, will directly benefit the Indian domestic avionics establishment. India plans to buy 50 Su-30MKI from Russia, along with license manufacture of 140 more at Nashik under HAL along with technology from France and Israel. The indigenous Light Combat Aircraft (LCA) may later be fitted with a phased array, and any future project such as the Medium Combat aircraft is sure to incorporate an AESA radar.

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