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## SHIPBOARD PHASED-ARRAY RADARS

### Requirements, technology and operational systems

By Dimitris V. Dranidis

The sight of huge planar arrays aboard warships has been with us for a good two decades now, beginning with the fleet introduction of the Aegis system and more recently expanding with the current European naval construction programs. At this point, most defence analysts agree that such radar systems are going to become the standard norm not only in naval construction programs, but also throughout the various military branches. In the naval section, this



An SPY-1 radar antenna

obviously begs the common-sense question by the observer & taxpayer: Ships have done quite satisfactory with plain-old rotating mechanical radar sets for over half a century by now, so what's the deal with these funky new, slick and ultra-expensive gizmos? Given that naval forces worldwide have to answer that awkward question in times of constantly reduced budget appropriations, it is worth taking a closer look at the subject of phased-array radars: the principles behind the technology, the problems it is meant to overcome and some of the operational systems of the past, the present and the near future.

### The problem

For modern shipboard AAW systems, the most critical performance requirement is the ability to successfully counter saturation attacks: such attacks may include numerous aircraft and particularly anti-ship missiles converging from multiple directions in close coordination, with the clear intention of overwhelming the defences.

The successful engagement of each of these targets by the AAW system(s) requires their precise tracking so that useful fire-control grade can be supplied to the ship's overall combat system. Conventional mechanically-scanned 2D or 3D radars achieve this tracking by correlating successive radar echoes for each target. This function is often referred to as "Track-While-Scan" (TWS) and is usually performed for multiple targets at the same time, the system's computational power permitting. Obviously, the higher the sweep rate of the radar, the finer-grained the tracking information is going to be for each air target. In mechanically-scanned radars, the rotation speed of the radar antenna and the update rate of target information (often referred to as "data rate") are obviously identical.

However, the data quality required for the successful control of anti-aircraft weapons dictates very high data rates, much higher than the rotation speed of typical mechanical-scan radars. If the data rate is not increased, targets of high speed or high agility are virtually impossible to engage. The obvious solution, spinning the radar antenna faster, entails a significant drawback: In pulse and pulse-doppler radars (ie. The vast majority of mechanically-scanned radar systems), the ability to detect targets at long range is directly relevant to the total electromagnetic energy reflected back to the receiver from the target (in more detail, it is proportional to the transmitter's PRF and the time duration of the target's presence within the main lobe [radar beam] of the transmitter). As the radar antenna spins faster, it has less time to gather the reflected energy – thus, the target detection range shrinks dramatically, particularly for targets with reduced radar signature or under the cover of surface clutter. This places the AAW system designer between a rock and a hard place: he has to accept either short-range penalty or poor fire-control solution.

The answer to this problem, and the accepted practice for most current warships, is to provide separate radars dedicated to the target-tracking function. This creates a clear separation of duties: the surveillance radar performs the initial target detection and low-quality tracking, and then passes this data to the tracking radar, which performs the high-quality tracking and fire-control operation (frequently providing illumination for radar-guided weapons). But this solution, while perfectly adequate for the "single incoming target" scenario, is severely handicapped in a saturation attack scenario: as the maximum multi-target ability is equal

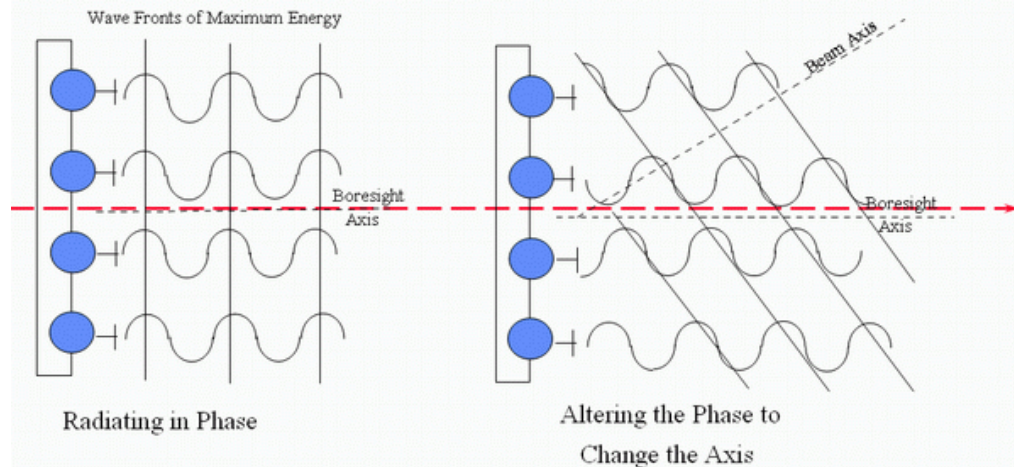


Strategic phased-array radars such as this PAVE PAWS unit have been in service for decades, but their great expense has until recently prevented them from being mass-employed in tactical military branches

to the number of dedicated tracking & illumination radars, and with a very finite number of these systems being installed on the ship (typically 2 for frigates & destroyers, 2-4 on cruisers etc.), it is quite easy to overwhelm the ship's defences with multiple simultaneous attacks. Clearly, what is needed is a way to provide target-tracking data of very high quality (sufficient for weapons guidance) while at the same time being able to do this for a very large number of targets, and without sacrificing long-range performance.

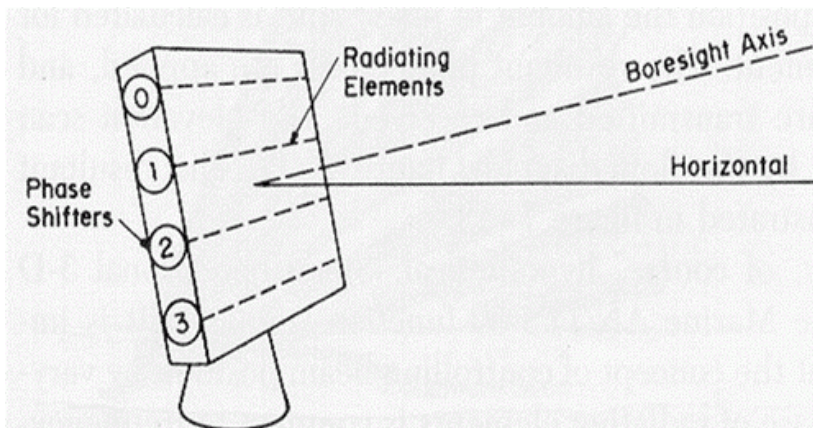
## The technology

The requirement for the concurrent high-quality tracking of a large number of targets essentially dictates breaking off from the shackles of mechanical scan: the need for high data-rate means that the radar beam has to jump between widely-separated targets near-instantaneously in order to quickly provide updates on their status, something impossible for a mechanical antenna. On the contrary, this is perfectly possible if the management of the radar beam is instead handled electronically, by antennas formed by multiple independent transmitters, spaced at predefined regular intervals. Understanding how this works calls for a small diversion into EM physics (fear not, the principle is simple).



Let us assume that we have a flat radar antenna composed of regularly-spaced transmitters. All transmitters emit the same signal. For each transmitter, the signal follows the typical sinusoidal pattern, with a maximum and a minimum amplitude value. Naturally, as the multiple transmitter elements are tightly stacked, there is strong interference between them. In our case, this is intentional and welcome: according to the principle of constructive interference, the electromagnetic energy received at a point in space from two or more closely-spaced radiating elements is at a maximum when the energy from each radiating element arrives at a point in phase (concurrently). These “pulse-intersection” points, if joined together, form an apparent (virtual) dimensional plane. The vector axis of the main lobe of the transmitted pulse (i.e. the main radar beam) is always perpendicular to that apparent plane (wave front) of the electromagnetic field generated by the transmitters.

Now, when all elements transmit in the same phase (as happens with mechanical-scan antennas), the plane of the EM field is parallel to that of the antenna, and the main lobe will be staring right forward (boresight). By shifting the



order of transmission however (essentially altering the relative phase of the EM pulse on each transmitter, i.e. making some of the transmitters shoot their pulse slightly ahead or after others), the apparent EM plane rotates, and the main lobe can be steered around, right out to the maximum scan limits of the antenna. Because this is an electronic, not mechanical operation, the steering of the main beam is near-instantaneous, thus fulfilling the need for rapid updates between targets.

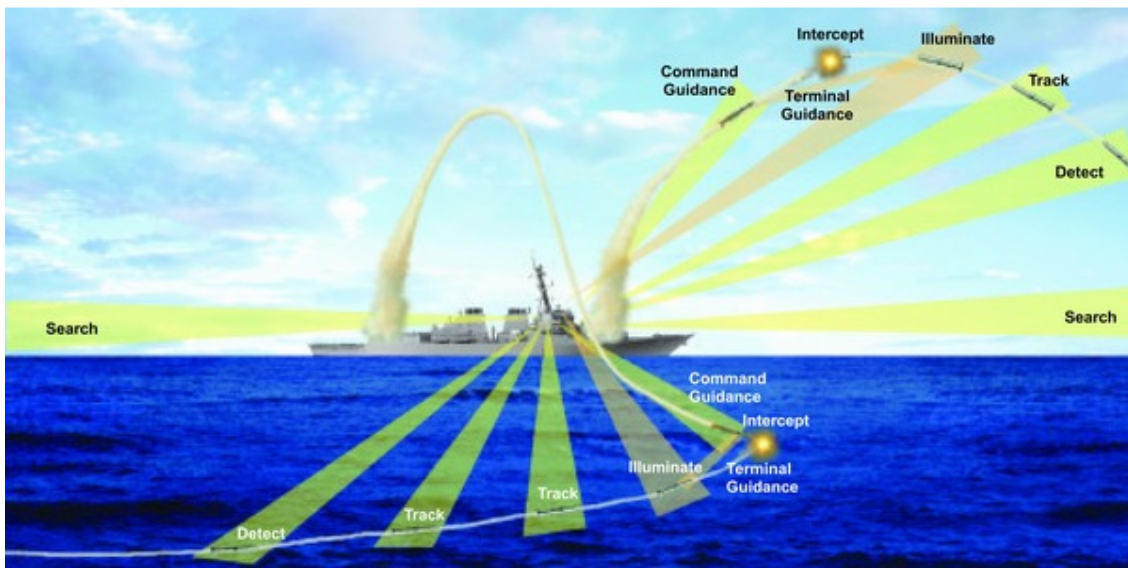
Phased-array technology finds its simplest form of implementation in single-dimension scanning systems. This graph demonstrates how 3D radars like the SPS-48 series use the vertical steering of the beam to stabilize against ship movement by forming a “virtual” horizontal axis independent of the true boresight axis. A similar technique is used by E-3 Sentry AWACS aircraft to stabilize the beam when banking to turn.

Initially, this principle was applied to 3D mechanical-scan radars. These use an antenna formed by multiple horizontal slotted waveguides, each of them being an independent transmitting element. By altering the phase of the RF pulse

transmitted by each waveguide, the beam can be steered on the vertical axis in order to provide altitude data on multiple targets – but horizontal scanning still depends on the antenna spin. Radars that employed this technique include the APY-1/3 of the E-3 Sentry AWACS aircraft, as well as most 3D air-search radars installed on USN ships in the 70s and 80s (most notable being the SPS-48 family) as well as most modern air-surveillance radar sets. This single-dimension scanning was adopted as an interim step because of the high cost of independent transmitters and the general immaturity of the technology at the time. With the rapid cost decrease of such transmitters however, it became practically feasible to populate an antenna with multiple elements both horizontally and vertically. This in turns means that the radar beam can be steered on both axes, thus eliminating the need for mechanical scan altogether.

The ability to provide a high data-rate on a large number of targets at sufficient range is not the only advantage of electronic-scan arrays. Other benefits include:

- Because of the near-instant redirection of the main beam, a single radar unit can perform multiple functions concurrently: For example long-range air surveillance, low-rate tracking of neutrals or suspected contacts, high-rate tracking of confirmed hostiles and radar illumination of hostiles within weapon parameters. These duties typically require the flawless cooperation of several different mechanical-scan radar sets to be successfully performed, as previously described. While obviously beneficial to a ship of any size, this consolidation of capabilities is particularly important where hard upper limits on size & displacement are present, thus limiting the number of sensors that can be installed (as is normally the case with most naval forces).



**This advertising graph from Lockheed Martin emphasizes the multifunction capability of the SPY-1 radar; similar advantages are offered by most phased-array systems**

- Upon detecting a potential target, a mechanical-scan radar system typically waits for a second sweep return so that it can correlate the two echoes, extract course & speed information and start a new tracking process. Depending on the sweep rate (typically not very fast for long-range surveillance sets), this wastes valuable time against an incoming enemy aircraft or weapon. Furthermore, if for any reason the target denies one or a few sweeps during tracking (if, for example, the targeted aircraft temporarily drops under the horizon or masks even for a few seconds behind an island or mountain range) the radar will typically drop the track<sup>1</sup> and will have to start all over again, with the same inherent delays. This means that, by periodically somehow breaking the track (denying LOS, jamming, beaming etc.) an enemy aircraft or weapon has a good chance of approaching dangerously close without being successfully tracked and engaged. Phased-array radars can start a track immediately upon detecting a target, since they can instantly reposition the beam upon it instead of waiting for the next sweep. Furthermore, while they too can be disrupted by much the same track-breaking techniques, they can counter them much more effectively: for example, the main beam can be instructed to increase its dwell time on the direction that the threat was last detected (at the expense of reduced scanning on other, non-threatening sectors), so that when eventually it does (unavoidably) reappear, it will be immediately re-detected and the track will recommence instantly.
- All mechanical-scan radars typically create secondary beams (sidelobes) in addition to the main beam produced. These sidelobes are highly undesirable as they represent both a significant prize for enemy ELINT

<sup>1</sup> Many radars have a “track memory” feature to counter such problems, and for some time after loosing track they will keep searching in the expected direction of the threat, trying to re-acquire. This however is only effective if the target does reappear soon.

assets and also a source of vulnerability to jamming. Electronic-scan arrays produce sidelobes of relative lower signal strength; they are therefore less vulnerable to such exploits.

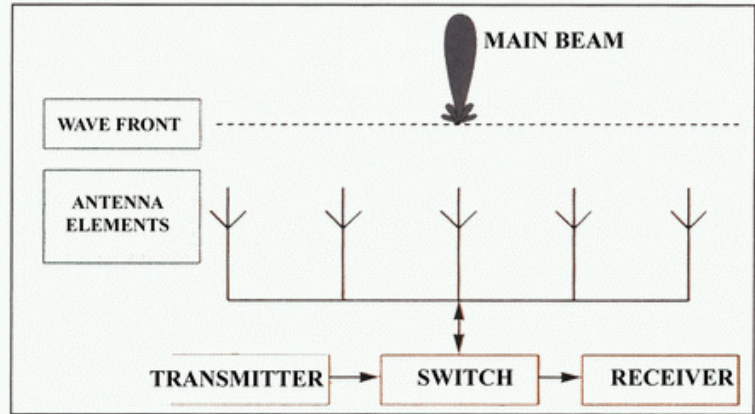
- Like most electromechanical devices, mechanical arrays are vulnerable to own vibration and have strict maintenance requirements for the effective operation of their moving parts. Electronic arrays have no moving parts and suffer from no vibration of their own. They are also inherently better stabilized against the ship's motion: mechanical antennas have complex multi-axis stabilization systems to compensate (themselves a source of maintenance & reliability headaches), whereas electronic arrays simply steer the main beam counter to the detected motion.

- Mechanical-scan radar systems typically have several single points of failure inherent in their design: if the servo motors for the antenna spin fail, the radar is out. If the stabilizing servos fail, the tracking data quality gets so bad that the radar is good as out. If the antenna itself gets bend out of shape even partially, the radar is out. The list goes on.

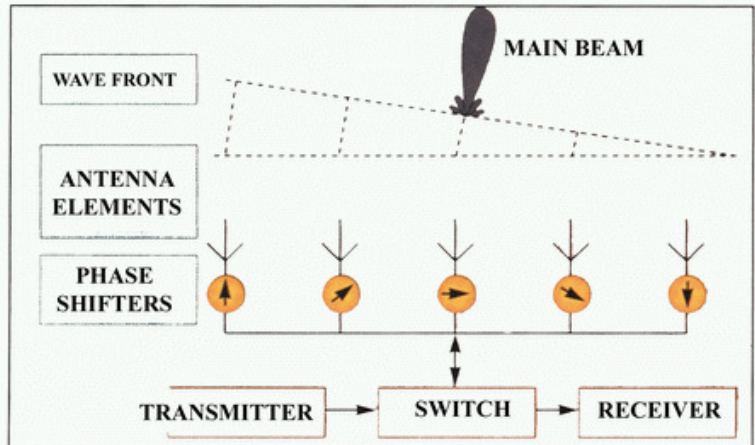
- Electronic-scan sets, while not impervious to sub-system failures or damage (particularly with regards to the RF pulse-generator tubes), are typically more resistant to them. This is partly a result of the modular structure of the antenna itself, and of the disposable nature of the independent transmitter elements: if any of the transmitters fails, the others will take over. This means that the antenna can have a significant portion of its elements destroyed (e.g. from the fragments of an ARM detonation) and still be able to function, albeit at a reduced capability.

- Mechanical-scan antennas are designed under a certain set of operational assumptions, which in turn drive the technical specifications: the radar will transmit a pulse of such and such energy and frequency, with a given PRF, forming a beam of a given width (the physical size & shape of the radar antenna is precisely formed over these requirements), rotating at some set speed (thus having a fixed data rate) etc. etc. Now, what if the adversary uses a new jamming technique or employs different technical characteristics than those predicted? What if the land- or sea-clutter is greater than expected? What if the tactical circumstances call for a higher data-rate than the "standard"? What if years of actual operational employment show that the desired technical specs are different than those of the hardware in hand? In any of these cases, the hardware has to be redesigned and physically rebuilt.

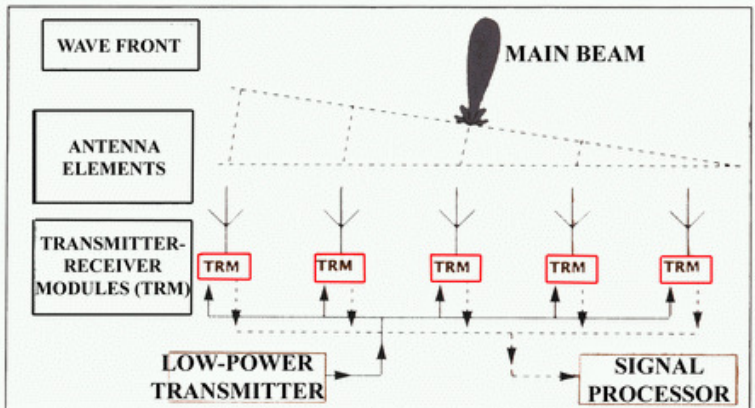
- Electronic-scan systems, while having their own physical limitations with regards to transmitted power, scan coverage etc, are considerably more flexible on their operation within these limits. Their technical characteristics are largely driven by the controlling software rather than the underlying hardware. This means that by altering the software code, the same piece of hardware can be modified/enhanced to adjust to new threat environments. The system's software-driven nature also increases the tactical flexibility of its



**Forming the main beam in a conventional mechanical-scan radar**



**Steering the main beam in a passive electronic-scan array**



**Steering the main beam in an AESA**

operational employment: The precise characteristics of the transmitted beam can be altered on-the-fly to suit the tactical situation at hand, rather than arbitrary pre-assumptions based on imperfect intelligence.

## The next step: AESA

The technology described so far assumes a system comprised of a number of transmitter modules, but only one receiver module, forming a single main beam. Such antennas are often described as passive electronic-scan arrays. The next evolutionary step in this technique is to make each of the transmitters a receiver in its own right, essentially constructing an antenna formed by thousands of independent (but coordinated) transmitter-receiver (T/R) modules. Such systems are referred to as active electronic-scan arrays (AESA). This technique obviously requires a much higher level of electronics integration and is more expensive to develop than the previous solution, which is why systems embodying this principle have only very recently begun reaching operational status.

The benefits, however, fully justify the extra costs & complexity: instead of forming a single main beam and electronically steering it around, the presence of multiple T/Rs allows the forming of multiple independent main beams, each assigned to its own task. So, instead of having the single beam being time-shared between the various duties (surveillance, tracking, fire-control etc.) and hop from one target to another, we can assign each of the beams to a specific function or permanently “stick it” to follow a specific target, while other duties & targets are handled to the other beams. This “true” multi-function capability opens up other potential uses: for example, since it is possible to transmit two or more signals with completely different characteristics concurrently, it is perfectly feasible to have the radar antenna double-up as a powerful jammer. AESAs are also inherently less power-hungry, as each of the T/R modules transmits a low-power EM pulse, the beams being formed by the intersections of the pulses (This contrasts to the very powerful EM pulse being transmitted by passive electronic-scan systems). This is a significant consideration when thinking about the applicability of such a technology on platforms with a limited power budget.

## Past, present and future platforms: Failures and successes

### SPG-59/Typhon

The first attempt for an operational phased-array system commenced in 1958 as a US Navy venture. The aim was to develop an extremely advanced SAM system called Typhon, which would offer significantly enhanced multi-target abilities than the existing family of Terrier, Tartar and Talos systems. These systems, while technological marvels in their own right, were never designed to handle the then-emerging threat of huge numbers of bombers and anti-ship missiles entering service with the Soviet Naval Aviation (AV-MF). The intended solution to this problem was track-via-missile guidance (adopted much later successfully in the land-based Patriot SAM), in which radar signals were received by the missile, but forwarded and processed on the surface ship with its much greater available computing power. The system structure called for a radar component able to perform all the different duties (including fire-control & terminal target illumination on multiple contacts) concurrently. It was therefore sensible that the first venture for an operational phased-array radar (PAR) began with this project: The heart of the new system would be the massive SPG-59 electronically scanned tracking radar, which could track multiple targets and intercept missiles. This would be matched to an extremely advanced missile, able to intercept both fast aircraft and missiles out to 110nm.

As soon as the technological R&D commenced in earnest, the hurdles began materialising: the state of the art was not up to par. While it was practical to construct multiple parallel waveguides for height-scanning on conventional 3D radars, making small individual transmitter elements was simply too expensive – the yield rates were too low to satisfy mass-production requirements, and the modules themselves suffered from reliability problems. The costs of fully constructing even a single complete PAR antenna was going to be prohibitively high.



The Typhon missile during trials

Even worse, from a naval architect's point of view, were the enormous projected power consumption requirements of the system. At the time of development, the only power source that could even begin to satisfy the power feed of the radar would be a nuclear power plant. The question on the employment of nuclear power on surface vessels was a hot issue at the time; although the carrier Enterprise and a single large cruiser (Long Beach) had already been authorised for construction, their extravagant costs were causing a turmoil of controversy. The combination of these reasons, together with the

increasing development difficulties, led to the cancellation of the project in December 1963.

## SPG-32/SPG-33 SCANFAR

The SPG-32 and SPG-33 systems were the USN's next attempt at PARs, and commenced in concurrence with the cancellation of Typhoon. To avoid some of the pitfalls and dead-ends of the SPG-59/Typhon endeavour, some of the operational requirements were relaxed: target illumination for SARH weapons, for example, was not required from the radars as it would be tasked to dedicated director sets, and some redundancy in the surveillance role was to be provided by the presence of other conventional mechanical-scan systems (SPG-59 was envisioned as the sole radar system aboard a warship). The requirements for the precise tracking of multiple targets concurrently fully remained, however, and were further perplexed by the need for effective ECCM against the then-emerging dedicated jamming & chaff-laying escorts of the AV-MF. While the cost of electronics had significantly reduced during the turn of the decade, it was still going to be a massively expensive undertaking. The relevant technology was only beginning to mature; transistors were not yet available in mass numbers to be employed, so the system had to rely instead on vacuum-tube elements. Despite these headaches, the program proceeded on the operational deployment level, being installed on the carrier CVN-65 Enterprise and the cruiser CGN-9 Long Beach.

That the system was installed on the sole two nuclear-powered surface vessels of the USN, and on two of the largest ones in displacement, was by no means accidental. Like the SPG-59 before it, the SCANFAR system was insanely power hungry. A high power demand is one of the inherent design weaknesses of passive electronic-scan systems, and in this case it was compiled by the power requirements of the vacuum tube arrays. Furthermore, despite the advances in electronics miniaturisation since the late-50s, the antennas still ended up being very heavy and bulky. Fitting them into a ship of lesser displacement would create severe stability problems, unless they were placed very close to the waterline (thus drastically limiting their effective range). Even on the Enterprise, they were positioned just high enough to avoid the vertical fins of aircraft parked on the flight deck.



**The characteristic antennas of the SPG-32/33 radars are evident in this 1970's shot of the cruiser Long Beach. Note the four separate missile illuminators**

The role of the system as fitted on the Enterprise was to provide a clear air picture, updated instantaneously. Both wide-area surveillance and specific target-tracking were on the requirements list, but it was discovered during development that each profile called for the use of slightly different beam characteristics. This eventually necessitated the parallel operation of two antennas of different shape: the SPG-32 used a wide rectangular antenna for air surveillance, while the SPG-33 used a vertical-positioned square set for target tracking. The same set was installed on Long Beach, but there the system also had the additional role of handing-off precise tracking data to the missile illuminators. In both installations there were four antenna pairs covering 90 degrees each.

The system proved unsatisfactory throughout its operational career. Even when it worked (which was not often the case), the system was unable to provide the practical benefits expected. This was mostly the result of the imperfections of the analog or analog/digital subsystems used rather than fundamental design flaws in the system itself. The additional maintenance load imposed on these two ships (which had a severe effect on their overall availability as fleet units) was deemed excessive compared to the benefits. As a result, both Long Beach and the Enterprise had their antennas and internal system electronics removed during their late-70s/early-80s overhaul, and had them replaced with other more conventional sets.

## SPY-1/Aegis

RCA electronics received the initial contract for the development of Aegis and its most important component, the SPY-1 radar system, by the USN on 1969. The radar was to cooperate with a new modified version of the RIM-66 Standard

SAM, which was then beginning to enter service en masse. The lessons from both Typhon and in particular SCANFAR were fresh in the minds of the system designers, and therefore a great deal of effort was directed on ensuring that the resulting system would be a “real”, practically useful system rather than a paper tiger. For example, from the onset of the design stage emphasis was placed on the integration of wholly digital elements both for the control & manipulation of the main beam (and the sidelobes) as well as the subsequent processing of the received signal. This ensured that the system would work “as advertised” much more frequently than its predecessors. It also had the equally important side effects of making the antenna considerably lighter and also of reducing the power requirements (this latter benefit proved to be crucial on the operational deployment). A clear separation between the hardware layer and the controlling software was made, in order to facilitate long-term system upgrades. Significant emphasis was given on system maintainability and reliability, in many cases even sacrificing outright performance for the sake of total system uptime (a trend that has since been growing in importance in both the military and civilian sector).

In 1974 a prototype antenna was ready for installation on the trials ship AVM-1 Norton Sound. Along with the fitting of a single antenna on the superstructure, the ship also received the prototype modules of the entire system, including an entire CIC “box”, the processing computers, the display consoles, the fire-control modules and missile illuminators etc. Between 1974 and 1979-80 extensive tests and trials were carried out in order to both test and improve the basic concept. The results were impressive. The adoption of much more modern computing elements (of a much larger scale of integration than anything hitherto employed) not only realised the projected performance figures but also drastically improved reliability. The system’s operational readiness never fell under 96%, which is even more impressive considering that the crew was formed mostly by members of the regular crew of Norton Sound, people far from ideally suitable to handle the system.

The multiple target engagement capability was first demonstrated in 1977: the ship launched two Standard-2 (RIM-66C) missiles against two BQM-34 target drones. The missiles were not SARH-illuminated all the way as typical with all previous naval SAMs; instead they were initially launched at a preset point in the sky and guided there by their onboard INS units, then received mid-flight updates on the target positions from the SPY-1 radar. Terminal SARH illumination for the endgame was provided by a single SPG-62 illuminator time-shared between the two missiles. Both targets were destroyed.



Attribute	SPY-1B/D	SPY-1D(V)	SPY-1F	SPY-1F(V)	SPY-1K
<b>Primary Ship Classes</b>	Destroyers Cruisers Frigates	Destroyers Cruisers Frigates	Frigates Destroyers Amphibs Carriers	Frigates Destroyers Amphibs Carriers	Corvettes Patrol Vessels Frigates
<b>Antenna Diameter</b>	12 ft. (3.7 m)	12 ft. (3.7 m)	8 ft. (2.4 m)	8 ft. (2.4 m)	5.5 ft. (1.7 m)
<b>No. of Elements</b>	4,350	4,350	1,856	1,856	912
<b>SM-2 and ESSM Capable</b>	Yes	Yes	Yes	Yes	Yes
<b>All-Weather Performance</b>	Yes	Yes	Yes	Yes	Yes
<b>Key Features</b>	Strong Multi-Mission Performance, Widely Deployed in the Fleet, TBMD Capability	Strong Multi-Mission Performance, Enhanced Littoral Operations and TBMD Capability	Low-Cost Multi-Mission Performance	Strong Multi-Mission Performance, Enhanced Littoral Operations and ASCM Missile Defense	Lowest Cost Multi-Mission Performance

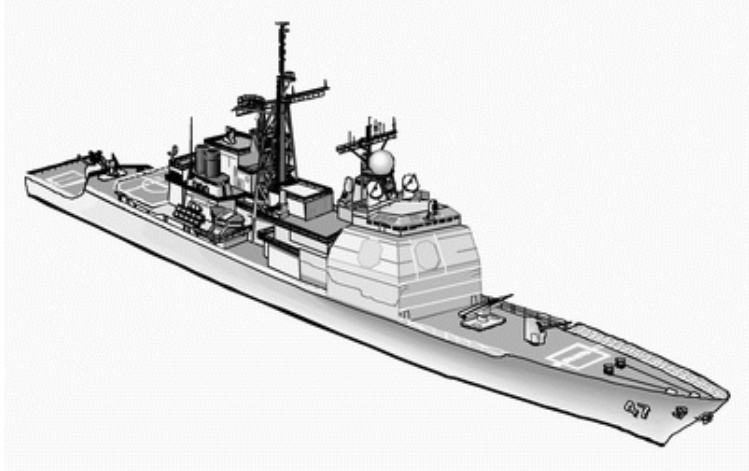
Lockheed Martin’s presentation of the SPY-1 line, apart from the typical marketing blurb (*all weather performance...*), contains some useful information on the technical characteristics and capability improvements of each successive version. Notice the antenna size difference in the most recent versions.

From the beginning of the testing period, there was an intense debate within USN circles as to how to deploy Aegis. There were many basing proposals: one (“DG/Aegis”) called for the mass-employment of the system on top of low-cost, limited capability vessels. It was argued however that this would create a mismatch between the awesome capabilities of the combat system and the very limited firepower of the parent vessel. Another proposal was the so-called “Strike cruiser”, under which sixteen large, nuclear-powered cruisers (which might aptly be described as pocket-Kirovs) would be constructed and allocated at two per group, to form the then-projected eight wholly-nuclear CVBGs. This however meant that Aegis would be deployed on a relatively small number of ships and thus the



technology would not get the widespread service it deserved. Eventually what was adopted was an intermediate solution: using an enlarged version of the successful Spruance-class hull and matching Aegis with the “standard” cruiser weapons outfit of the era, including two dual Mk-26 launchers (to be later succeeded by vertical-launching systems). This design emerged as the Ticonderoga-class missile cruiser, with the lead ship becoming operational in 1983.

A description of the SPY-1 radar is unbalanced if taken out of the context of the Aegis combat system it supports. The radar itself operates in the S-Band (typically in 3.1-3.5GHz), and uses four passive electronic-scan array antennas of 3.65x3.65m each. The beam width is typically 1.7deg. In the initial operational version SPY-1A (installed in CG-47 Ticonderoga, and all subsequent class ships until CG-58 Philippine Sea), each antenna uses 4096 elements grouped into 32 transmitting batches. The transmitter elements are powered by 32 Cross-Filed Amplifier (CFA) units connected in parallel, each of which has a 132KW peak output. For each of the four antennas, the produced beam is controlled exclusively by the Aegis system: The core of the system (Mk7 Mod3 Baseline 1 & 2 configuration) is comprised of 16 UYK-7 mainframes, 1 UYK-19 server and 11 UYK-20 minicomputers (all provided by Unisys). The computing modules are grouped together physically to form a unified main processing unit, interfacing through 4 Hughes AN/UYA-4 color displays and 4 additional PT-525 smaller displays with a capacity of displaying up to 128 target tracks (this is an artificial limit to avoid system saturation; it can be raised in combat). In automatic mode, the computers receive full control authority not only of the ship's own sensor and weapon systems, but also of any other nearby ship whose systems have been subordinated to Aegis control (provided that the other ship hosts a suitable NTDS or compatible system). The system structure is compatible with previously existing NTDS protocols and can exchange data with NTDS-equipped ships through Link-11 and Link-16 (JTIDS) datalink networks. The SPY-1 radar itself is credited with a 175nm range for air search and 45nm for horizon search.



**A graph of the CG-47 class. The antennas of the SPY-1 system are visible on the front-end of the superstructure, just under the bridge. The rear-facing antenna is located on the after end of the superstructure, abaft the main mast.**

The main difference of the next version (SPY-1B) was the addition of a high-elevation mode so that the beam can be steered up to the zenith of the scan limits, in order to successfully track anti-ship missiles that cruise at high altitude before diving on their targets near vertically (missiles such as the Russian AS-4 and AS-6 regularly use this profile). Furthermore, the use of lighter and more compact phase shifters reduced the volume and weight of the radar system (down from 5.440kg to 3.580kg). This also had the effect of enabling the reduction of the number of the array element subgroups, the result being the forming of a more narrow beam. Improvements extended on the Aegis system as well: more advanced UYK-43/44 mainframes were fitted, offering significantly greater processing output. Even with the reductions in power requirements made possible by the more efficient digital systems though, the power consumption is such that the Ticonderoga class loses almost 2000miles of endurance when the SPY-1 is continuously transmitting.

The new A. Burke Aegis destroyers, having a significantly reduced displacement than the Ticos, received the SPY-1D, a significantly modified version. (This was also installed on the last 9 Ticonderoga cruisers). The installation of all four antennas on a single mast enabled drastic reductions in cabling, volume and weight (down to 1.910 kg for each antenna). It also enabled all four antennas to be powered by a common shared TWT<sup>2</sup>. Apart from the US warships, the SPY-1D is also being installed on the Japanese DDG-173 Kongo class of AAW destroyers (a heavily modified version of the A.Burke design) and the new Spanish F-100 (Alvaro de Bazan class) AAW-frigates currently under construction.

The more recent SPY-1F and SPY-1K versions are considerably lighter (including antennas of reduced area and thus fewer transmitter elements; see the accompanying table) and are mainly targeting the export market. The SPY-1F version has been selected for the Norwegian F-310 (Fridtjof Nansen) class and is also offered for other European naval construction plans currently in consideration. SPY-1K is an even more compact version targeting the emerging market for new patrol frigates and corvettes, which will be needed in the next 10-15 years to replace a large number of outdated corvettes and FACs in numerous coastal-patrol navies around the world.

<sup>2</sup> On the Ticos, three of the antennas are on the forward superstructure and the aft-facing antenna is on the back-end. This also means that the aft antenna has to be powered by an independent power tube.

It should be noted here that the size shrink in the most recent versions does carry its own penalties: By virtue of its size, SPY-1D is a more powerful radar and, consequently, has increased range, but both the SPY-1D and the SPY1-F/K have air defense and ship self-defense capabilities. The SPY-1F/K, on the other hand, has not been designed to provide TBMD capability (as an example) through software and hardware modifications.

## Mars-Passat (Sky Watch)

The presence of the Mars-Passat radar was first identified from satellite photographs of the fourth Kiev-class carrier (then called Baku), under construction in the early 80s in the Nikolayev 444 shipyard in the Ukraine. The ship was launched in 1982. The radar was assigned the NATO designation "Sky Watch" and was observed with considerable interest by western analysts.

Its timeframe of introduction for service with the Soviet Navy fitted well with the concurrent phase-in of PARs in the Soviet air defence forces (with both the Zaslon radar on the MiG-31 interceptor and the Flap Lid radar on the SA-10 SAM system proving considerable successes). The Soviets had previously introduced a number of 3D air-search radars with vertical electronic scan (rough equivalents of the SPS-48 series in technological principle, if not in capability) and had demonstrated, with the Zaslon, the ability to package the relevant electronics within reasonable volume and weight restrictions. The Kirov and Slava classes were also coming online, both with significant multi-target engagement capability thanks to the TVM guidance provided by the Top Dome radar. So overall, it was not unreasonable to expect the Soviets to pull off a technological feat of this magnitude successfully – particularly as

throughout the 70's and early 80's a successive series of publicised spy cases had demonstrated their ability to boost their R&D efforts by successfully adopting various western concepts.



**Two of the four antennas of the Sky Watch system are evident in this shot of Admiral Gorshkov**

The Sky Watch was installed on Baku, as mentioned, and also on the lead vessel of the new class of full-deck aircraft carriers, which went through several name changes during construction before entering service as Admiral Kusnetsov. From what is known, it was planned as a highly-sophisticated integrated air-battle management system, in many respects resembling the SCANFAR principle rather than the contemporary Aegis. It was clearly not meant to provide weapons control in the manner that Aegis/SPY-1 controls SM-2 missiles in flight.

That the system ran into technical difficulties was evident by the fact that Baku commissioned a full five years after its launch (1987). The Kusnetsov took even longer than that, but this had more to do with the economic & social implosion of the USSR in the late-80s/early-90s rather than problems with the vessel itself. What was unexpected, however, was that closer inspection of the system in both ships showed that major sub-components had in fact not been installed. Extreme close-ups of the antenna arrays revealed that no actual antenna elements were in place; instead, cement slabs had been fixed in place in order to give the appearance of a planar array.

It has not yet been possible to determine exactly what went wrong with the development of the system. What is known is that severe problems were encountered with the system software rather than the actual hardware. This is in itself a bit surprising, since similar software challenges were met successfully (though unconventionally from a western POV) on the A-50 AWACS project. Whatever the exact difficulties were, they proved to be insurmountable and the system as a whole was abandoned: Varyag, the almost-completed sister ship to the Kusnetsov, had her superstructure design changed and conventional mechanical-scan sets replaced the planar arrays of Sky Watch.

## EMPAR

The European Multifunction Phased Array Radar (EMPAR) system was designed to be the primary air defence sensor for the Horizon common new-generation frigate, originally slated to be employed by the French, Italian and British naval forces (the RN eventually withdrew from the Horizon project and went their own way). Under the Horizon specs, EMPAR is just one sensor subuded to, and totally controlled by the overall Principal Anti-Air Missile System (PAAMS), essentially the ship's main combat system. Apart from EMPAR, PAAMS also includes in terms of hardware:

- The Aster 15 & 30 SAMs, launched from SYLVER A-50 vertical launchers.
- A supplementary S1850M long-range air surveillance radar

The operational concept is that the S1850M radar is to provide the initial long-range detection of targets, then handing them off to EMPAR when they approach and supposedly constitute a higher threat. EMPAR itself is a frequency-agile set operating in the C-band (4-8GHz) with a primary operating mode at 5.6GHz. Power is provided by a software-controlled travelling-wave tube (TWT) with a 120KW peak output, and uses digital pulse compression for the signal, as well as a 2-stage super heterodyne receiver coupled to multiple TI C40-series DSP processors.

A potentially significant limitation of the system is the form of the antenna: contrary to the SPY-1 and other comparable 360-deg-coverage systems, EMPAR employs a single, rotating water-cooled passive electronic-scan antenna, typically inclined at 30 degrees. While this was obviously a cost-based decision, it does mean that the



system has a reduced capability to deal with saturation attacks converging from radically different directions (similar to the limitations of the Top Dome on the Kirov/Slava classes), although in this case this is offset to some extent by the fact that the ASTER missile requires only intermittent mid-course updates and has a terminal active-radar seeker, thus not tying-down the radar for the entire duration of the engagement.

The antenna is formed by 2160 transmitting elements, and produces a beam of typical width of 2.6 degrees, steerable on a 45deg arc horizontally and 60deg vertically. The system can perform concurrent monopulse tracking on 69 high-priority targets and additionally 231 low-

priority ones, the desired data-rate being adjustable for each target. According to manufacturer's claims, 50 of the high-priority targets can be tracked with sufficient precision and data-rate to be immediately engaged (though not all of them concurrently). Some sources estimate the radar as capable of controlling up to 24 missiles in flight at the same time. Performance goals include a 180km detection range against targets with a 10m<sup>2</sup> RCS, 120km against 2m<sup>2</sup>, and 50km against a typical 0.1m<sup>2</sup> RCS anti-ship missile.

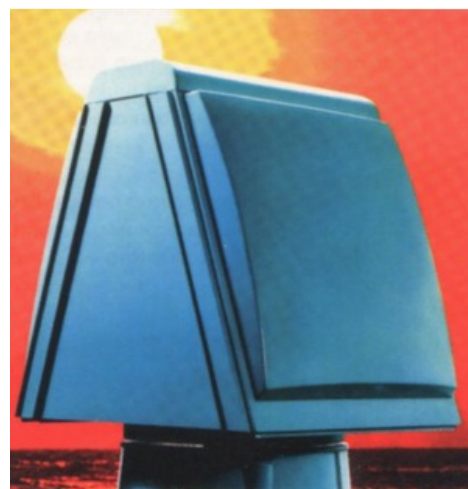


One of the control consoles for the EMPAR system

## SAMPSON

When the Royal Navy withdrew from the collaborative Horizon program, in order to freely customize its requirements and specifications for the new AAW destroyer class (Type 45), this did not mean abandoning all the benefits of the common R&D effort already undertaken under Horizon. The heart of the Daring-class destroyers is also going to be PAAMS, employing the same subcomponents as the original Horizon specs, but with an important difference: the EMPAR radar is replaced by the SAMPSON active phased-array system.

It can reasonably be argued that the RN's dissatisfaction with the performance goals for the EMPAR was one of the principal reasons for the eventual withdrawal from Horizon. It is understood that the RN has much higher performance requirements with regards to the system's ability to continuously provide a 360deg coverage. Thus it is not surprising that SAMPSON employs two back-to-back AESA antennas mounted on a common rotating stand. A typical 30-rpm rotation thus provides a much higher data rate than EMPAR, since the two-antenna design translates that to an effective 60-rpm equivalent. The adoption of AESA arrays rather than EMPAR's passive ones also allows the



An early artist's impression of the SAMPSON mount

employment of multiple independent beams, which further enhances the system's multi-tracking potential and also brings other benefits such as long-range detection against low-RCS targets, a lower false-alarm rate and an overall higher tracking accuracy. Official specs also mention the capability of the beam software-management to provide such abilities as precise raid-assessment mode, estimation of a target's actual physical size and non-cooperative target recognition (NCTR), but this has not been independently confirmed.



**A refined artist's impression of the SAMPSON radar. The antenna shape has been compacted in order to fit in a spherical radome**



**A CGI illustration of a Type 45 destroyer. The SAMPSON figures prominently on the front mast. Notice also the supplementary air-surveillance radar on the third mast**

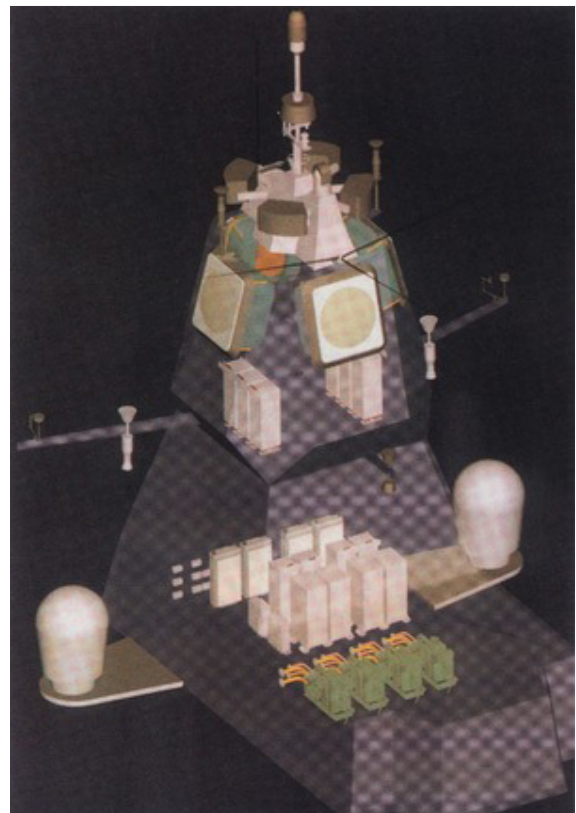
Each of the two antennas comprises 640 TRM modules, each linked to four antenna elements, thus forming an array of 2,560 elements and emitting at a peak power of only 25KW, operating at the S-band. The TRMs themselves are software-controlled and receive their input from fiber-optic cables through the main rotating antenna mount. The main beam can be steered to a 60deg arc in azimuth and has no practical elevation limit. The low power consumption allows for simple air-cooling of the two antennas, the heat exchangers being located separately from the antenna mount.

Official performance specifications have not been publicised. Unofficial sources claim that the system is effective to provide tracking out to 400km, track between 500 and 1000(!) targets and engage 12 of them concurrently with ASTER missiles<sup>3</sup>.

These performance figures have led the system integrator (BAe Systems) to claim that the supplementary S1850M radar is not really needed on ships fitted with SAMPSON, since the radar's long-range performance (mainly a result of the S-band being used) is sufficient for the early-warning role, thus making the supplementary radar redundant. BAe argues against the more "traditional" fixed 4-antenna solution employed by SPY-1 and APAR, claiming that such an installation is more expensive and top-heavy, forcing its fitting on a lower mast position and thus limiting its radar horizon.

## APAR

APAR is the main radar of choice for the AAW system of the Tripartite Frigate Cooperation (TFC-AAW). The system equipment, apart from APAR also comprises of the SMART-L long-range surveillance radar and Mk41 VLS for SM-2 area-defence SAMs and Evolved Sea-Sparrow (ESSM) point-defence missiles. The TFC-AAW package is fitted (or in the process of being installed) on the German F-124 Sachsen-class frigates and the Dutch LCF frigates, and is also slated for the modernisation of the Canadian Halifax-class frigates. The entire combat system has been developed by a wide-ranging industrial consortium comprised of Thales Nederland (ex-Signaál), Northern Telecom, EADS, Euroatlas, Comdev, Stork Canada and various subsidiaries of Lockheed Martin and Thales.



**A CAD overview of the APAR installation. Clearly visible are 4 main antennas, the missile uplinks and the SPUs, DPUs and TMUs on the lower decks**

The American influence may seem obvious at first sight of the system: the general configuration of four fixed phased-array antennas practically screams "Aegis". There are, however,

<sup>3</sup> The PAAMS architecture (EMPAR & SAMPSON) does not require terminal target illumination, since the ASTER missiles have their own active seeker. The SPY-1 system relies on separate SPG-62 illuminators for the endgame, while APAR handles the terminal illumination itself.

important differences under the hood. For once, APAR employs AESAs rather than passive arrays, with all the performance benefits (and cost penalties) this entails. Furthermore, whereas Aegis & SPY-1 still need separate SARH illuminators for terminal missile guidance, APAR guides the missiles completely on its own, from launch to impact. Naturally, this calls for a high operating frequency in order to provide the extremely precise target tracking on the endgame: APAR indeed operates on the X-band (8-12GHz). This reduces the system's nominal range but should provide increased tracking precision.

Each of the antennas is formed by 3.424 elements, controlled in quads by 856 TRM units. Each of the antennas provides a 60deg scan azimuth, so there is a certain degree of overlap at the extreme angles. Each of the 4 antennas is tied to its own signal-processing unit (SPU), its own data-processing unit (DPU) and two shared tracking & management units (TMUs). Presumably the SPUs & DPUs are not hardwired exclusively to their own assigned antennas, but can also be cross-linked to provide redundancy against battle damage. The TMUs are the radar system's main interface to the ship's overall combat system.

Publicised performance figures include a 75km range on horizon search (sea-skimming targets), a 150km range for the monopulse tracking of at least 250 targets and 32km for surface search. Up to 16 targets can be concurrently engaged with 32 SM-2MR Block IIIA/B, SM-2ER Block IVA or ESSM missiles in the air at any time. For the endgame illumination the radar employs intermittent continuous-wave illumination (ICWI) with which the mentioned weapons are compatible. As an indication of the benefits of active array employment, the system is reportedly able to form over 1.000 independent beams in order to perform multiple different functions at the same time.

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**One of the 4 main antennas of the APAR radar**

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