

Shielded from Oversight

***The Disastrous US Approach
to Strategic Missile Defense***

<http://www.ucsusa.org/shieldedfromoversight>

Appendix 10: Sensors

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This appendix discusses the main ground-based radar sensors of the Ground-based Midcourse Defense (GMD) system, the Upgraded Early Warning Radars, the AN/TPY-2 X-band forward-based radars, and the US Navy's Aegis SPY-1 radars. The Sea Based X-band radar is discussed in Appendix 2, the planned Long Range Discrimination Radar is discussed in Appendix 3 and the infrared sensor of the GMD system's kill vehicles is discussed in Appendix 6.

The Aegis SPY-1 Radar and the SPY-6 (AMDR)

INTRODUCTION

The Aegis SPY-1 phased-array radar is part of the Aegis combat system deployed on US Navy cruisers and destroyers as well as on a number of foreign ships.¹ Originally designed for air defense, the Aegis system on many US Navy cruisers and destroyers has been upgraded to include a ballistic missile defense (BMD) capability. Although the interceptors of the Aegis BMD system are intended for regional rather than national defense, the Aegis SPY-1 radars on forward-deployed ships can potentially contribute to the Ground-based Midcourse Defense (GMD) national missile defense system by providing radar tracking data on early parts of a long-range missile's trajectory. In addition, while not intended for that purpose, the higher-speed SM-3 Block IIA interceptors scheduled to begin deployment in 2018 would likely have significant capabilities against adversaries' intercontinental-range ballistic missiles, depending on where the ships are deployed.

The US Navy currently has 62 Aegis destroyers, the most recent of which was commissioned in 2012. As

¹ The term "phased array" refers to radars in which the position of radar beam is moved electronically rather than mechanically. This technology allows the radar beam to be moved essentially instantaneously, allowing the radar to track many targets or perform multiple tasks simultaneously. All the radars discussed in this report are phased arrays.

discussed below, the first 28 of these destroyers, the Flight I and Flight II ships, have received an upgrade to a "basic" or "intermediate" BMD capability. Several of these ships have already (about three) or soon will be upgraded to an "advanced" BMD capability. None of the subsequent 34 destroyers, the Flight IIA ships, have yet received a BMD upgrade, but most or all will be upgraded to an advanced BMD capability in the future. Beginning in the fall of 2016, the Navy will begin commissioning 10 new Flight IIA destroyers, at a pace of about two per year. These ships will have the advanced BMD capability built in.

Beginning in about 2023, the Navy will begin commissioning new Flight III destroyers, again at a pace of about two per year. The ships will also come with BMD capabilities built-in, and will also incorporate the new and much more powerful Air and Missile Defense Radar (AMDR)— also known as the SPY-6—in place of the current Aegis SPY-1 radar.

The US Navy also has 22 Aegis cruisers, five of which have been upgraded to either the basic or intermediate BMD capability. However, the Navy plans to put the 11 youngest cruisers (including four of the five upgraded for BMD) through a life-extension program that, to save money, will remove their BMD capability. Although Congress is currently prohibiting the Navy from implementing this plan, if it proceeds it would leave the Navy with only a single BMD-equipped cruiser scheduled for retirement in the mid-2020s.

AEGIS BMD VERSIONS

Aegis ships have been given BMD capabilities through the installation of a series of increasingly capable Aegis BMD system versions. The US Navy refers to ships with a 3.6.x BMD system as having a "basic" capability, ships with a 4.x BMD system as having an "intermediate" capability, and ships with a 5.x BMD version as having an "advanced" capability. Only ships with the advanced capability are capable of performing air defense and ballistic missile defense simultaneously; ships with the

basic or intermediate capability must be configured for one or the other.

AEGIS BMD 3.0E AND AEGIS BMD 3.0

The first deployed Aegis BMD capability was the Aegis Long Range Surveillance and Tracking (LRS&T) capability using the Aegis BMD 3.0E system. This LRS&T capability gave forward-based Aegis ships the capability to track long-range ballistic missiles and relay such tracking information back for possible use by the US GMD system, and all subsequent BMD ships have this LRS&T capability. Several Aegis BMD 3.0E destroyers were forward-deployed in the Pacific as part of the initial GMD Limited Deployment Option in September 2004. Aegis BMD 3.0E ships did not have a ballistic missile engagement capability. The next version, Aegis BMD 3.0, added an engagement capability against short- and medium-range missiles using SM-3 Block I interceptors (essentially SM-3 Block IA prototypes).

AEGIS BMD 3.6.x

All 33 current US BMD capable ships have now been upgraded to at least the Aegis BMD 3.6.1 capability. Aegis BMD 3.6.1 is intended to provide engagement capabilities against short-, medium- and some intermediate-range ballistic missiles using the SM-3 Block IA interceptor. Aegis BMD 3.6.1 ships are capable of being configured for either ballistic missile defense or air defense, but not both simultaneously. Aegis BMD 3.6.1 also added a launch-on-remote capability using data from another Aegis ship or data from non-Aegis sensors such as TYPY-2 X-band radars as well as a terminal, within-the-atmosphere, ballistic missile defense capability using the SM-2 Block IV interceptor.

Aegis BMD 3.6.3 added the capability to operate SM-3 Block IB interceptors.²

Current plans call for 21 of the 28 Aegis Flight I and Flight II destroyers to be upgraded to an Aegis BMD 4.0.x capability, and the other seven to be upgraded to an Aegis BMD 5.x capability.

AEGIS BMD 4.0x

Aegis BMD 4.0.1/4.0.2 is often described as the “second generation” or “intermediate” Aegis BMD

system. As of 2015, about nine of the 28 Flight I and Flight II Aegis destroyers had been upgraded to an Aegis BMD 4.0.x capability. Aegis BMD 4.0.1 adds both a new Aegis BMD Signal Processor (BSP) and the new SM-3 Block IB interceptor. The Aegis BSP is intended to improve the discrimination capabilities of the Aegis system’s SPY-1 radar. According to the Missile Defense Agency (MDA): “The Aegis BMD Signal Processor (BSP) provides a real-time identification capability through signal processing. Such processing enables tracking of individual objects and identification through the use of advanced algorithms.”³ Aegis BMD 4.0.1 also includes an improved launch-on-remote capability.

Aegis BMD 4.0.2 is an upgrade to 4.0.1 system to correct for a problem discovered in the FTM-16 E2 intercept test failure, which was due to a problem with the third stage rocket motor thrust pulse timing that caused the motor to explode. According to the Government Accountability Office (GAO), “a new version of the second generation Aegis weapons system” was developed “to control the amount of time between the pulses,” and that this change “will have minimal consequences on missile performance and ship operations.”⁴ Aegis BMD 4.0.2 was successfully tested in the FTM-20 intercept test of February 12, 2013.⁵

AEGIS BMD 5.x

Aegis BMD 5.x introduces the new Baseline 9 computer system. Baseline 9 uses a commercial-off-the-shelf computer infrastructure to enable faster system upgrades and increased commonality, and to facilitate the addition of BMD capabilities to additional ships. It also enables Aegis ships to perform air defense and ballistic missile defense simultaneously, and is referred to by the Navy as the “advanced” Aegis BMD capability.

² O’Rourke, R. 2016. *Navy Aegis ballistic missile defense (BMD) program: Background and issues for Congress*. Congressional Research Service Report RL33745. Washington, DC. May 26. Figure 1. Online at www.fas.org/sgp/crs/weapons/RL33745.pdf. Note: All URLs in footnotes to this appendix were accessed June 12, 2016.

³ Missile Defense Agency (MDA). 2011. Aegis ballistic missile defense FTM-16 factsheet. August 22. Online at <http://www.stratcom.mil/files/FTM-16%20Fact%20sheet%20-%20v13.pdf>.

⁴ Government Accountability Office (GAO). 2013. *Missile defense: Opportunity to refocus on strengthening acquisition management*. GAO-13-432. April. 53. Online at www.gao.gov/assets/660/654233.pdf.

⁵ Syring, J. 2013. Ballistic missile defense update. Presented to the American Society of Naval Engineers. February 22. Slide 15. Online at <https://mostlymissiledefense.files.wordpress.com/2013/06/bmd-update-syring-february2013.pdf>.

A few ships were initially equipped with Aegis BMD 5.0, which did not have a within-the-atmosphere terminal-phase BMD capability such as that provided by Aegis BMD 3.6.x or 4.0.x. These ships (about three as of 2015) have since been upgraded to the Aegis BMD 5.0 CU (Capability Upgrade), which restores a terminal within-the-atmosphere BMD capability using SM-2 Block IV and SM-6 Increment 1 interceptors. The new construction Flight IIA destroyers scheduled to begin commissioning in fall 2016 and the Aegis Ashore system now operational in Romania in 2016 will initially be deployed with Aegis BMD 5.0 CU.

Aegis BMD 5.1, scheduled to begin deployment in FY 2018 on several ships and the Poland Aegis Ashore site, will add the new high-speed SM-3 Block IIA interceptor as well as the SM-6 Increment 2 terminal interceptor.

NUMBERS OF AEGIS BMD SHIPS

By April 2016, 33 U.S. Navy ships have been upgraded to have a BMD capability; this number is expected to rise to 49 by 2021.⁶ The US Navy has stated that its current requirement is for 40 ships with the advanced BMD capability (four for the European Phased Adaptive Approach (EPAA), nine based in Japan, and 27 for aircraft carrier battle groups) and that it will first be able to meet this requirement in 2026.⁷ Including the 21 Flight I and Flight II destroyers not planned to be upgraded to the advanced capability gives a total of 61 BMD-capable ships in 2026. The total number of Aegis BMD ships requested by regional Combatant Commanders—77 ships in 2015—is significantly greater than the current US Navy requirements.⁸ Under current plans, the number of BMD capable ships will level off at roughly 80 ships in about 2040 as new deployments are almost balanced by retirements of older destroyers.⁹

AEGIS RADAR VERSIONS

⁶ O'Rourke 2016, 7.

⁷ O'Rourke 2016, 14-15; Seligman, L. 2015. Surface warfare chief: Navy won't meet BMD ship requirement until 2026. *Inside Missile Defense*, June 24.

⁸ O'Rourke 2016, 14-15.

⁹ See Lewis, G. 2015. How many Aegis BMD ships in 2040? *Mostly Missile Defense*. Blog. December 13. Online at <http://mostlymissiledefense.com/2015/12/13/how-many-aegis-bmd-ships-in-2040-december-13-2015/>.

Four or five different versions of the Aegis SPY-1 radar are currently deployed on US ships, although only two or three of these versions are on ships that have been upgraded for BMD. It is possible that the BMD and other upgrades may have erased some of distinctions between the different versions.

THE SPY-1

The SPY-1 was a test version of the radar that was never deployed.

THE SPY-1A

The SPY-1A is currently deployed on the seven oldest cruisers still in service, up through CG-58. (Five earlier cruisers with the SPY-1A but not the vertical launching system have already been retired.) None of the SPY-1A cruisers ever has or ever will be given a BMD capability.

The SPY-1B/SPY-1B(V)

The SPY-1B was deployed on the first six (CG-59 to CG-64, including CG-62 Monterey which subsequently received a BMD upgrade) of the final 15 cruisers. The 1B version has a new antenna, with much better sidelobe characteristics than the 1A antenna, which is important when operating in an environment with surface clutter as the Aegis radars must often do. The SPY-1B also has about twice the average power of the 1A version, plus other improvements. The power increase was achieved by increasing the radar's duty cycle (the percentage of the time the radar is emitting) without changing its peak power. The upgraded SPY-1B(V) was installed on the final nine cruisers, starting with CG-65, including four ships that subsequently received a BMD upgrade. Little information about the 1B(V) upgrade is available, but it may consist primarily of a new set of Aegis computers—the same computers as used on the initial Aegis destroyers. It is possible that the earlier 1B radars have been subsequently upgraded to the 1B(V) version.

THE SPY-1D

The SPY-1D was deployed on the first 40 destroyers (DDG-51 to DDG-90).¹⁰ It is similar to the 1B(V) version, except for using one transmitter for all four radar faces instead of two transmitters each powering two faces as in the cruisers. The first 28 of these ships (the 28 DDG-51

¹⁰ The designation SPY-1C was apparently reserved for a manufacturer's proposed but never built version for aircraft carriers.

Flight I and Flight II destroyers) have received a BMD upgrade. The four Aegis BMD ships based at Rota, Spain as part of the EPAA are all destroyers with the 1D radar.

THE SPY-1D(V)

The SPY-1D(V) is a “littoral warfare” (near-shore) version of the radar deployed on the subsequent Aegis destroyers (22 so far), starting with DDG-91 in 2005. This upgrade added a number of waveforms for improved clutter rejection and moving target detection to improve the capability of the Aegis radar in environments with ground and other near surface clutter. It also increased the transmitter average power (by at least 33 percent) and added a dual-beam capability which enabled it to put out two beams simultaneously (out of opposite faces).¹¹ None of the 1D(V) ships has yet received a BMD upgrade.

AEGIS RADAR CHARACTERISTICS

Each SPY-1 radar has four antenna faces, each covering slightly more than 90 degrees in azimuth. In the 1A, 1B, and 1B(V) versions on the cruisers, there are two transmitters each multiplexed between two antenna faces on each of the two deckhouses. The 1D and 1D(V) versions on the destroyers use a single transmitter to drive all four faces, which are located on a single deckhouse.

The focus of the description here is on the 1B/D versions, and on their physical characteristics relevant to BMD use.

FREQUENCY AND BANDWIDTH

The Aegis system operates in S-band, from about 3.1 to 3.5 gigahertz (GHz) (wavelengths λ of 8.6 to 9.7 centimeters (cm)). Early descriptions indicated that the system reportedly had a “sustained coherent bandwidth” of 10 megahertz (MHz) and an instantaneous bandwidth

¹¹ Several other countries have built or are planning to build ships similar to the US Aegis destroyers. Japan has built four Kongo class (SPY-1D) and two Atago class SPY-1D(V) destroyers and plans to buy two more. So far only the four Kongo’s have been given a BMD capability, but eventually all eight will be BMD capable. Spain has built five Aegis-equipped frigates (four SPY-1D, one SPY-1D(V)). South Korea and Australia both plan to build three SPY-1D(V) equipped destroyers. Norway has deployed five frigates equipped with the SPY-1F, a smaller version of the radar.

of 40 MHz.¹² The Aegis system’s bandwidth was apparently subsequently increased, perhaps up to its maximum frequency extent of 400 MHz. The 4.0.1 version of the Aegis Ballistic Missile Defense system, which is now entering service, added an adjunct BSP signal processor that, among other things, allows the formation of two-dimensional inverse synthetic aperture images with better resolution than had previously been possible, which indicates a wideband capability.¹³

A 1999 Lincoln Laboratory briefing slide shows a “Wideband Waveform Concept for AN/SPY-1 Radar” using a 400 MHz wideband waveform constructed from ten 40 MHz bandwidth pulses frequency jumping from 3.1 to 3.5 GHz.¹⁴ A 2002 paper cites a bandwidth of 300 MHz for Aegis.¹⁵ Such bandwidths would likely permit a range resolution of about 0.5 to 1.0 meters.

ANTENNAS AND BEAM WIDTHS

Each Aegis radar system has four radar antenna faces. Starting with the SPY-1B, a new antenna was introduced, that although outwardly similar in appearance to the antenna of the SPY-1A, incorporated significant improvements. In particular, the 1B has improved peak and average sidelobes relative to the 1A version and eliminates grating lobes within the antenna scan angles. These improvements were accomplished by subdividing the antenna into many more subarrays (2,175, each with two elements, for a total of 4,350 elements) than the 1A antenna (68 subarrays of 64 elements each, for a total of 4,352 elements) and by

¹² Friedman, N. 2006. *The Naval Institute guide to world naval weapon systems*, fifth edition. Annapolis, MD: Naval Institute Press, 316. However all the information from Friedman cited in this appendix also appears in earlier book editions going back to at least the 1991/92 edition.

¹³ Ulfers, B. and G. LeFurjah. 2010. AN/SPY-1B/D radar design changes supporting Aegis ballistic missile defense. *Leading Edge* 7(2):100–105. Online at www.navsea.navy.mil/Portals/103/Documents/NSWC_Dahlgren/LeadingEdge/Sensors/Sensors03.pdf.

¹⁴ Evans, E. 1999. Missile Defense Technology (Can BMD Systems Work?) Mini DTS Course, MIT Lincoln Laboratory, December 10.

¹⁵ Ingwersen, P.A., W. W. Camp and A. J. Fenn. 2002. Radar Technology for Ballistic Missile Defense. *Lincoln Laboratory Journal*, 13 (1): 109-148.

improved machining tolerances and alignment techniques.¹⁶

The antenna face physical structure is octagonal, with a height of 4.06 m and a width of 3.94 m.¹⁷ In the 1A version, the antenna elements themselves are contained within a similar hexagonal shape with dimensions of roughly 3.84 m in height and 3.67 m in width.¹⁸ The area populated by the antenna elements (the aperture) appears to be about 12 m².¹⁹ In the 1B/1D versions, the antenna face itself (the area occupied by the elements) is more nearly circular than in the 1A antenna, but since the number of elements is essentially the same, it is likely that its aperture area is also about the same.

The Aegis radar reportedly has a gain $G = 42$ decibels (dB) = 15,800 and a beamwidth of 1.7 degrees by 1.7 degrees.²⁰ However, the stated beamwidth of 1.7 degrees is larger than a gain of 42 dB and the antenna diameter would imply, both of which suggest an actual beamwidth of about 1.3 degrees.²¹

EMITTED POWER

As noted above, the 1B and 1D versions are nearly identical except that the 1B version uses two transmitters each powering two antenna faces, whereas the 1D version has one transmitter for all four faces. However, since a transmitter can apparently be used with only one face at a time (two faces for the 1D(V)), the maximum power that can be put out of any antenna face should be same for both versions.

The original SPY-1A version reportedly has a peak power of up to 5 megawatts (MW) and an average power of 32 kilowatts (kW).²² The SPY-1A's transmitter output

is provided by 32 crossed field amplifiers (CFAs), each with peak power of 132 kW, which would give a combined peak power of 4.2 MW.²³ The SPY-1B reportedly has an average power of 58 kW with a peak power of 4–6 MW.²⁴ These powers are consistent with reports that the 1B version had the same peak power but twice the average power (that is, its duty cycle was doubled) of the 1A, and that, more specifically, the SPY-1B/1D used a new CFA with a doubled duty cycle.²⁵ According to a 2004 Defense Science Board Report, “the average radiated power aperture for the Aegis radar system is 485 kwm².”²⁶ Assuming that statement applies to the SPY-1D (since the SPY-1D(V) version was not yet operational) and an antenna area of 12 m², this would give an average emitted power of about 40 kW. This lower average power may in part indicate that reported peak and average powers for the radar are the transmitter power, not the power actually emitted (which will be less due to losses between the transmitter and antenna) and that the effective antenna aperture is less than 12 square meters (m²) (as the reported 1.7° x 1.7° beamwidth may indicate).

PULSE LENGTHS

The Aegis radar (SPY-1B version) can produce pulses with lengths of 6.4, 12.7, 25 and 51 microseconds (μs), with a pulse compression ratio of 128.²⁷ This 51 μs maximum pulse length is consistent with a 1997 study that stated that the electromagnetic interference produced by an Aegis radar pulse would last for at most 52 μs.²⁸ However, given the many upgrades to the Aegis

peak power of 4 to 6 MW (Elliot, F. 1986. An inside look at Aegis, shield for the fleet. *Navy Times*, August 25, 35–36.)

²³ Friedman 2006, 316.

²⁴ Friedman 2006, 316. This book (along with numerous other similar titles by Friedman) appears to be the only public source for the 58 kW average power figure.

²⁵ As of 1982, both the Varian SFD-262 CFA and the Litton L4707 CFA had met the duty cycle requirements but still required additional testing. Britton et al. 1982.

²⁶ Defense Science Board Task Force (DSB). 2004.

Contributions of space based radar to missile defense.

Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. June. 2. Online at www.acq.osd.mil/dsb/reports/ADA42877L.pdf

²⁷ Friedman 2006, 316.

²⁸ Sanders, F.H., B.J. Ramsey, and R.L. Hinkle. 1997. Summary of results of tests and measurements related to RF interference at Bath, Maine. Institute for Telecommunication Sciences and Office of Spectrum Management. National Telecommunications

¹⁶ Britton, R., T. Kimbrell, C. Caldwell, and G. Rose. 1982.

AN/SPY-1planned improvements. In *Radar Applications*, edited by M.I. Skolnik. New York: IEEE Press, 192–199.

¹⁷ Britton 1982.

¹⁸ Patton, W. 1991. Compact, constrained feed phased array for AN/SPY-1. In *Practical Phased-Array Antenna Systems*, edited by E. Brookner. Norwood, MA: Artech House, 8-1–8-35 (Figure 8.1). Figure 8.1 is actually for the SPY-1, which has the same 64x68 element arrangement as the 1A.

¹⁹ Estimated from Figure 8.1 of Patton 1991.

²⁰ Friedman 2006, 316.

²¹ According to Skolnik (Skolnik, M. 2001. *Introduction to radar systems*, third edition. New York, NY: McGraw-Hill, 541) a good approximation when other information is lacking is $G = 26,000/\theta_B\phi_B$, where θ_B and ϕ_B are the half power beamwidths in degrees. This gives $G = 9,000$ for a beamwidth of 1.7 degrees.

²² Adam, J. 1988. Pinning defense hopes on Aegis. *IEEE Spectrum*, June, 27. Another description of the system gives a

system, including the BMD upgrades, these pulse lengths may have changed significantly.

NOISE FIGURE

A 1978 paper states that the noise figure for the Aegis SPY-1A receiver was about 4.25 dB = 2.66.²⁹ Again, this noise figure could have changed significantly as the system was improved and upgraded.

THE SPY-1D(V)

The version of the Aegis radar currently being built, the SPY-1D(V), was first deployed on US Navy destroyers in 2005, beginning with DDG-91.³⁰ This upgrade to the radar does not appear to involve significant changes to the antenna. A 33-percent increase in duty cycle was apparently set as a requirement for the SPY-1D(V) upgrade.³¹ An increase of “over 33%” in amplifier duty cycle over that of SFD-262 CFA was achieved in the SFD-268 CFA, intended for use in the SPY-1D(V) radar, in part by using improved cooling techniques.³² This increased duty cycle would give an average transmitter power of at least 77 kW, based on a 58 kW average transmitter power for the 1B/1D versions.

DETECTION RANGE AND BMD CAPABILITIES

A public numerical figure on Aegis detection range against a specific target is that the SPY-1D “can track golf ball-sized targets at ranges in excess of 165 kilometers.”³³

and Information Administration. US Department of Commerce. September 17. Online at

<https://www.ntia.doc.gov/report/1997/summary-results-measurements-and-tests-related-rf-interference-bath-maine>

²⁹ Socci, R.J. 1978. The AEGIS radar receiver. *Microwave Journal* 21:38–45, 47. October. This noise figure applies to all receiver output channels except for the sidelobe blanking channel, which was somewhat lower (3.75 dB).

³⁰ Mazumdar, M. 2005. USS Pinckney sails with latest Aegis suite. *Jane's Defence Weekly*, October 12, 31.

³¹ Wheeland, C.L., M.S. Worthington, K.F. Ramacher, and E.M. Doyle. 1996. Ultra low-noise CFA design and development for the AN/SPY-1B/D radar. Presented at IEEE International Conference on Plasma Science, Boston, MA. (Abstract). 235.

³² Einarson, S. 2000. Development and production of the SFD-268 CFA for the Aegis AN/SPY-1D(V) radar. Presented at International Vacuum Electronics Conference (Abstract), Monterey, CA, May 2-4. Input power was increased by 45 percent, which also produced improvements in noise and jitter.

³³ Robinson, J.A. 2004. Force protection from the sea: Employing the SPY-1D radar. *Field Artillery*, March–June, 24–

A golf ball-sized (1.68 inches diameter) sphere corresponds to radar cross section of about $\sigma = 0.0025 \text{ m}^2$ at 3.3 GHz.³⁴ This statement was made in the context of the then soon-to-be deployed SPY-1D(V) radar to detect mortar and artillery shell and small-caliber rockets against a clutter background, so presumably it applies to the 1D(V) version. Scaling to a radar cross section more typical of a ballistic missile final booster stage (1.0 m^2) or warhead (0.03 m^2) gives ranges of at least 740 km and 310 km, respectively.³⁵

Such range may be sufficient for tracking a missile booster if the ship is deployed close to the launch site, but it will likely only be able to track a warhead itself for a very short period, if at all. Two recent government-sponsored reports make it clear that the current Aegis radar has severe limitations against anything but short-range ballistic missiles.

The first of the reports, *Science and Technology Issues of Early Intercept Ballistic Missile Defense Feasibility*, was published by the US Defense Science Board in September 2011.³⁶ The DSB report stated: “The current Aegis shipboard radar is inadequate to support the objective needs of the EPAA mission,” and that “Radars of much more substantial operating range than

25. Online at http://sill-www.army.mil/firesbulletin/archives/2004/MAR_JUN_2004/MAR_JUN_2004_FULL_EDITION.pdf.

³⁴ RCS calculated using NASA's Size Estimation Model. For a discussion of this, see, for example, Stokely, C.L., J.L. Foster, Jr., E.G. Stansbery, J.R. Benbrook, and Q. Juarez. 2006. *Haystack and HAX radar measurements of the orbital debris environment*; 2003. 20–22. JSC-62815. NASA Lyndon B. Johnson Space Center. November. Online at www.orbitaldebris.jsc.nasa.gov/library/Haystack_HAX_radar2003.pdf.

³⁵ Stage RCS from Barton, D.K., R. Falcone, D. Kleppner, F.K. Lamb, M.K. Lau, H.L. Lynch, D. Moncton, D. Montague, D.E. Mosher, W. Priedhorsky, M. Tigner, and D.R. Vaughan. 2004. Report of the American Physical Society study group on boost-phase intercept systems for National Missile Defense: Scientific and technical Issues, *Reviews of Modern Physics* 76 special supplement. Figure 10.8. S174. Online at <http://journals.aps.org/rmp/abstract/10.1103/RevModPhys.76.S1>.

³⁶ Defense Science Board Task Force (DSB). 2011. *Science and technology issues of early intercept ballistic missile defense feasibility*. Washington, DC: Office of the Secretary of Defense. September. Online at www.acq.osd.mil/dsb/reports/ADA552472.pdf.

the current radar on the Aegis ships will be necessary for the full realization of a robust regional defense.”³⁷

The second report, published by the US National Academy of Sciences (NAS) one year later, in September 2012, did not discuss the limitations of the Aegis radar, at least in the unclassified part of the report.³⁸ However, the report envisioned only a very limited role for the Aegis radar in defense of Europe. In response to a question about the 2011 DSB report’s conclusion that the Aegis radar was inadequate to support the EPAA, David Montague, co-chair of the NAS panel, at a telephone press conference announcing the NAS Report’s release stated that: “What the DSB said was the SPY-1 radar is not capable enough to do—support missile intercepts in— in European deployment, which we agree with.”³⁹ He went on to say that X-band radars would have to provide the data for tracking targets and launching interceptors, and that all the Aegis SPY-1 radar would do was “communicate back and forth with the interceptor.”⁴⁰

THE AIR AND MISSILE DEFENSE RADAR (AMDR)

Given the limitations of the current SPY-1 radar in a missile defense role, starting in FY 2016 (with destroyer number 123) US Navy destroyer production will switch over to the new Aegis Flight III ships, in which the current SPY-1 radar is replaced by the new Air and Missile Defense Radar (AMDR), also known as the SPY-6 radar. The AMDR will replace the current S-band Aegis SPY-1 radar with two radars—the S-band AMDR-S and the X-band AMDR-X—along with a common control system. The AMDR-S will be a large four-faced S-band phased array (similar to the existing Aegis radar) and will be used for volume search and for air and missile

defense. The much smaller AMDR-X radar will be used for roles such surface and horizon search.⁴¹

Like the X-band TPY-2 radars, the AMDR-S will be use active-array antennas with a large number of transmit/receive (T/R) modules, rather than central transmitter tubes. Under the current plan, the AMDR T/R modules will use new gallium nitride (GaN) technology, capable of giving higher peak and average powers that the current gallium arsenide (GaAs) technology modules can.

In January 2012, the US Navy announced that it had decided on a SPY+15 design for the AMDR-S.⁴² The “+15” indicates that the new radar would have a 15-dB = 31.6 signal-to-noise advantage over the current Aegis SPY-1 radar. Thus the SPY+15 radar would obtain a signal-to-noise ratio against a given target that was about a factor of 32 greater than that obtained by the current Aegis radar (presumably a SPY-1D(V)). Each of the AMDR-S’s four antenna faces would have an aperture with a width of 14 feet (compared to about 12 feet for the current SPY-1 antenna). The AMDR-S is designed to be scalable in size, and the Navy determined that the 14-foot antenna was the largest that could be accommodated on the Flight III destroyers.

While this factor of 32 improvement in radar sensitivity relative to the current SPY-1 radar would represent a very significant increase in the missile defense capability of individual Aegis ships, and in particular would reduce their reliance on other, external sensors, it still appears to fall short of radar capabilities desired by the Navy.

A January 2012 GAO report stated: “Flight III with a 14-foot AMDR will not be powerful enough to meet the Navy’s objective, or desired IAMD capabilities.”⁴³ [IAMD = integrated air and missile defense] The GAO cited two

³⁷ DSB 2011, 26 and 8.

³⁸ National Research Council. 2012a. *Making sense of ballistic missile defense*. Committee on an Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison to Other Alternatives. Division on Engineering and Physical Sciences. Washington, D.C.: National Academies Press. Online at www.nap.edu/catalog.php?record_id=13189.

³⁹ National Research Council. 2012b. The National Research Council Holds a Teleconference on Missile Defense Report, CQ Transcriptions, September 11.

⁴⁰ National Research Council. 2012b. Specifically, Montague stated that: “That means all the tracking data and information that is used to launch an interceptor is—comes from the X-band radar. All the SPY-1 in—in Aegis Ashore does is communicate back and forth with the interceptor.”

⁴¹ Current Aegis ships use a rotating SPS-67 radar for the surface and horizon search roles. Early Flight III destroyers will use a single rotating SPQ-9b radar as the AMDR-X. Later Flight III ships (possibly starting with FY 2024 purchases) could use a three-faced SPY-3 X-band phased-array radar as the AMDR-X.

⁴² Eckstein, M. 2013. Flight III DDGs to cost about \$2 billion, have margins for future growth. *Inside Missile Defense*. January 23.

⁴³ Government Accountability Office (GAO). 2012. Arleigh Burke destroyers: Additional analysis and oversight required to support the Navy’s future surface combatant plans. GAO-12-113. Washington, DC. January. 41. Online at www.gao.gov/assets/590/587883.pdf.

recent Navy studies as support for this finding.⁴⁴ A 2009 “Radar/Hull Study red team” said that a SPY+15 capability would give a “marginally adequate” capability against the threats considered in that study. (However, these threats are probably not limited to just ballistic missiles.) An earlier Maritime Air and Missile Defense of Joint Forces study rejected the SPY+15 as inadequate and concluded that a radar close to a SPY+30 capability (30 dB = 1,000) would be needed for the most stressing threats. Such capability would require an array diameter greater than 20 feet. However, according to the GAO, the Navy has concluded that 14-foot radar now planned is the largest that can be built into the existing DDG-51 hull.

TPY-2 Forward-Based X-Band Radars

INTRODUCTION

The AN/TPY-2 is an X-band phased-array radar that can be configured as either a fire control radar for a Terminal High-Altitude Area Defense (THAAD) ballistic missile defense battery or as a forward-based X-band radar (FBX) in the overall US Ballistic Missile Defense System (BMDS).⁴⁵ In the forward-based mode, a TPY-2 radar can be incorporated into the GMD national missile defense system. The radar is air-transportable and can be operational within four hours of reaching its deployment site.⁴⁶

The TPY-2 is part of Raytheon Company’s “family” of X-band radars that also includes the GBR-P and the Sea-Based X-band (SBX) radars, and which all use very similar X-band transmit/receive (T/R) modules. Compared to the SBX and GBR-P, the TPY-2 has a much

smaller antenna that is much more densely populated with T/R modules, giving it a shorter range but a much larger electronic field of view (EFOV) than the larger radars. Unlike the SBX, which is optimized for precision tracking and discrimination rather than search, the TPY-2 is more of a general-purpose missile defense radar.

RADAR CHARACTERISTICS

The rectangular TPY-2 antenna has an aperture of about 9.2 m² and is about 4.6 m wide and 2.0 meters high. It is populated by 25,344 transmit/receive (T/R) modules arranged in an equilateral triangular array. One estimate is that the modules are third generation modules (with those on the SBX being second generation) with a peak power of 16 W and an average power of 3.2 W.⁴⁷ Thus the entire radar has an average power of about 25,344 x 3.2 W = 81,000 W.

The radar operates in X-band (8-12 GHz) and has a bandwidth of about 1 GHz, giving a range resolution of 25 cm or less.⁴⁸ Assuming a 9.5-GHz center frequency, corresponding to a wavelength of $\lambda = 3.16$ cm, the radar would have beam widths of approximately $0.0316/4.6 = 0.0069$ rad = 0.39 degree in azimuth and $0.0316/2.0 = 0.0158$ rad = 0.92 degree in elevation.

The TPY-2 is usually described as having a full EFOV of ± 60 degrees in azimuth and 90 degrees in elevation.⁴⁹ However, a detailed technical paper on the TPY-2 antenna states that its EFOV is $\pm 53^\circ$ in both azimuth and elevation.⁵⁰ The antenna’s area per element is about $9.2 \text{ m}^2/25,344 = 3.6 \text{ cm}^2 = 3.6\lambda^2$. This area is somewhat larger than the $0.332\lambda^2$ maximum area that is usually described as being necessary to get a full ± 60 degrees EFOV with an equilateral triangular array,

⁴⁴ GAO 2012, 42.

⁴⁵ T = ground, transportable, P = radar, and Y = surveillance and control. AN/TPY-1 is a Marine Corps air traffic control radar.

⁴⁶ “THAAD provides the only air transportable, fast reaction capability for the warfighter to provide area coverage against Short and Medium Range Ballistic Missiles within four hours of arrival.” Missile Defense Agency (MDA). 2015. **Research, development, test & evaluation, defense wide**. Defense wide justification book volume 2a of 2 of **Fiscal Year (FY) 2016 president’s budget submission**. Washington, DC: Department of Defense. February. 2a-73. Online at http://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2016/budget_justification/pdfs/03_RDT_and_E/MDA_RDTE_MasterJustificationBook_Missile_Defense_Agency_PB_2016_1.pdf

⁴⁷ Lewis, G. 2012. Ballistic missile defense: Power of X-band radars. **Mostly Missile Defense**. Blog, June 4. Online at <http://mostlymissiledefense.com/2012/06/04/ballistic-missile-defense-power-of-x-band-radars-june-4-2012/>.

⁴⁸ Ingwersen, 2002, 109-148, 141.

⁴⁹ For example, NRC 2012a, 115. Specifically, the report states that their proposed “stacked” X-band radar, which would have the same electronic FOV as the TPY-2, has a ± 60 degrees by 90 degrees electronic FOV.

⁵⁰ Sarcione, M., J. Mulcahey, D. Schmidt, K. Chang, M. Russell, R. Enzmann, P. Rawlinson, W. Guzak, R. Howard, and M. Mitchell. 1996. The design and testing of the THAAD (Theater High Altitude Area Defense) solid state phased array (formerly ground based radar). IEEE International Symposium on Phased Array Systems and technology, Boston, October 15–18, 260–265.

suggesting that its EFOV is somewhat less ± 60 degrees in at least one direction.⁵¹

The TPY-2 antenna can be tilted in elevation from 10 to 60 degrees.⁵² However, once set up, the antenna is fixed in azimuth. While there has been some discussion of retrofitting TPY-2s with a rotating turntable, there do not appear to be any current plans to do so.⁵³

FORWARD-BASED MODE VS. TERMINAL MODE

A TPY-2 can be configured either as a terminal mode or forward-based mode radar. The two radar configurations differ primarily or exclusively in their software, and a TPY-2 can be converted from one configuration to the other in eight hours or less.⁵⁴ According to a US Army manual, “The hardware used by the two modes is identical, but their controlling software, operating logic, and communications package are different.”⁵⁵ In the terminal mode, the TPY-2 radar is integrated into a THAAD missile defense battery. According to the radar’s manufacturer, Raytheon,

When the AN/TPY-2 radar is deployed in terminal mode, the radar’s job is to detect, acquire, track and discriminate ballistic missiles in the terminal (descent) phase of flight. The terminal-mode AN/TPY-2 also leads the Terminal High Altitude Area Defense ballistic

⁵¹ Frank J. and Richards J. 2008 . Phased array radar antennas. In ***Radar Handbook***, third edition, edited by M. Skolnik. New York, NY: McGraw-Hill. Online at http://airspot.ru/book/file/961/radar_handbook.pdf.

⁵² Sarcione et al. 1996, 261.

⁵³ Judson, J. 2013a. DOD: Rotational platform for AN-TPY-2 radar would require major redesign. ***Inside Missile Defense***, September 4.

⁵⁴ Missile Defense Agency (MDA). 2011. ***Fiscal year (FY) 2012 budget estimates. Procurement, defense-wide***. February. Online at http://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2012/budget_justification/pdfs/02_Procurement/Procurement-MDAw%20P-1P.pdf.

⁵⁵ Manual quoted by Hyun, P. 2015. Pentagon document confirms THAAD’s eight-hour conversion time. ***The Hankyoreh***. June 3. Online at http://english.hani.co.kr/arti/english_edition/e_international/694082.html.

missile defense system by guiding the THAAD missile to intercept a threat.⁵⁶

In the forward-based mode, the TPY-2 operates as a sensor in the overall US BMDS and can be tied directly into the GMD system.

In forward-based mode, the radar is positioned near hostile territory, and acquires ballistic missiles in the boost (ascent) phase of flight, shortly after they are launched. It then tracks and discriminates the threat, and passes critical information required by decision makers to the Command and Control Battle Management network.⁵⁷

These tracking and discrimination data can then be forwarded to the GMD fire control system or to other defense systems such as THAAD batteries or Aegis BMD ships. According to the MDA, such early tracking and discrimination data “identifies the lethal object, significantly reduces the target uncertainty, and provides additional reaction time to increase the probability of successful BMDS engagements.”⁵⁸

TPY-2 radars have participated (as of June 2016) in two GMD intercept tests. In FTG-05 (December 2008), the TPY-2 radar was deployed at Juneau, Alaska, and in FTG-06a (December 2010) it was deployed on Wake Island.

In June 2015, it was announced that the US government had authorized Raytheon to sell forward-based mode TPY-2s to several foreign countries, although no such sales have yet been announced.⁵⁹ The only foreign sales to date are two terminal-mode radars to the United Arab Emirates as part of two THAAD batteries.

RADAR RANGES

The range of a TPY-2 radar in the terminal mode is much less than that in the forward-based mode. This range

⁵⁶ Raytheon Company. No date, Army Navy/transportable radar surveillance (AN/TPY-2). Waltham, MA. Online at www.raytheon.com/capabilities/products/antpy2/.

⁵⁷ Raytheon n.d.

⁵⁸ MDA 2015, 2a-172.

⁵⁹ Raytheon Company. 2015a. Allies may acquire advanced ballistic missile defense radar. News Release, June 15. Online at <http://www.prnewswire.com/news-releases/allies-may-acquire-advanced-ballistic-missile-defense-radar-300097923.html>

difference has become an issue in the South Korean debate over whether or not to allow the United States to deploy a THAAD battery in South Korea. China is strongly opposed to such a deployment. South Korean press reports indicate that in the terminal mode the range of a TPY-2 is about 600 km, while in the forward-based mode its range is about 1,800–2,000 km.⁶⁰ The much greater range in the forward-based mode results from operating the radar in a way that is able to devote a much greater fraction of the radar's resources (dwell time) to each target, and possibly also because of the larger radar cross section of a missile during its boost phase relative to a separated warhead. Supporters of THAAD deployment argue that since the radar would be a terminal-mode version, it could not look deeply into China, and thus China should not be concerned about it. Critics counter that it could be quickly converted to the forward-based mode.

Published figures for the detection or tracking range of a TPY-2 radar vary greatly, likely reflecting its wide range of possible operating parameters. The published ranges are difficult to compare because they do not always provide the full set of assumptions on which they are based. According to its manufacturer, a TPY-2 radar could track a baseball from several hundred miles away.⁶¹ Such a range is consistent with the terminal-mode range in South Korean press reports, although it is for a relatively low radar cross section of about 0.004 square meters.⁶² Simply scaling the MDA's stated detection range of 4,800 km for the SBX gives a TPY-2 detection range of about 900 km.⁶³ A 2012 estimate obtained a

detection range of about 870 km (with target RCS = 0.01 m², S/N = 20, and a dwell time of 0.1 seconds).⁶⁴

Longer dwell times can give longer ranges, although fewer targets can be tracked simultaneously. Figures in the 2012 NAS Report show a range of about 1,500 km for the TPY-2.⁶⁵ In 2008, Major General Patrick O'Reilly (then deputy director of the MDA) stated that the TPY-2 had a range "greater than 1,800 miles" (2,900 km).⁶⁶

NUMBERS AND DEPLOYMENTS

A TPY-2 radar, including supporting equipment, costs about \$180–190 million and typically takes about 30 months to build. The first production version of the TPY-2 radar (AN/TPY-2 #1) was completed in 2004. The United States currently plans to procure 12 TPY-2s for its own use.⁶⁷ As of early 2016, 11 TPY-2s had been delivered, with one more under construction.

Five TPY-2s are deployed as forward-based radars, in northern Japan, central Japan, Turkey, Israel, and Qatar. Of these five radars, at least the two in Japan have been incorporated into the GMD system. The remaining seven radars will be deployed with THAAD batteries. As of early 2016, four THAAD batteries have been delivered and their crews trained, one of which has been deployed on Guam since April 2013. The fifth battery is undergoing training, and both the six and seventh batteries will be delivered by 2017. Unless additional TPY-2s are bought, it may at some point become necessary to "borrow"

⁶⁰ Hyun 2015; The Chosun Ilbo. 2015. U.S. seeks compromise over missile defense system. Chosun Media, February 24. Online at http://english.chosun.com/site/data/html_dir/2015/02/24/2015022400979.html; China.org.cn. 2015. News analysis: U.S. defense chief's visit to Seoul adds controversy to THAAD deployment. China.org.cn, April 9. Online at www.china.org.cn/world/Off_the_Wire/2015-04/09/content_35278924.htm.

⁶¹ Raytheon Company. 2015b. Sharp eyes for missile defense: Bus-size radar rolls like a truck, sees like a hawk. Waltham, MA. August 26. Online at www.raytheon.com/news/feature/an_tpy2_radar_behind_headlines.html.

⁶² A reflective sphere the size of a baseball (diameter = 2.9 inches) has a radar cross section of 0.004 m².

⁶³ Scaling by the fourth root of (P_{AVG}) gives a range for the TPY-2 of [(81/90.5)(9.2/249)²]^{0.25} = 0.187 that of the SBX. This figure seems low, given that the SBX certainly operates more

like a forward-based TPY-2 rather than like a terminal-mode radar, and may reflect different radar cross section assumptions.

⁶⁴ Lewis, G., and T. Postol. 2012. Ballistic missile defense: Radar range calculations for the AN/TPY-2 X-band and proposed GBX radars. *Mostly Missile Defense*. Blog. September 21. Online at <http://mostlymissiledefense.com/2012/09/21/ballistic-missile-defense-radar-range-calculations-for-the-antpy-2-x-band-and-nas-proposed-gbx-radars-september-21-2012/#more-420>.

⁶⁵ NRC 2012a, 124, Figure 5.8.

⁶⁶ Suderman, A. 2008. Radar array placed in Juneau. Juneau, AK: *Juneau Empire.com*, June 1. Online at http://juneauempire.com/stories/060108/loc_285173550.shtml#V2FrWOO-JyF.

⁶⁷ Before 2012, MDA planned for a total of 14 TPY-2s. However, in 2012 the planned number of THAAD batteries was reduced from nine to six, and the planned number of TPY-2s was correspondingly decreased to 11. In 2013, in part due to concerns about maintaining the production line, Congress increased the planned number of US TPY-2s to 12.

radars from THAAD batteries for ballistic missile testing against ballistic missiles.⁶⁸

However, it appears plausible that more TPY-2s will be needed than the 12 currently planned. The Army's original plans had envisioned a total of 18 TPY-2s—nine for use as forward-based radars and nine for THAAD batteries—and this remains the official requirement for THAAD batteries.⁶⁹ In 2013, Missile Defense Agency (MDA) Director Admiral James Syring stated that he was working to find funding for a possible eighth THAAD battery.⁷⁰ In May 2015, MDA announced that it had extended Raytheon's TPY-2 contract from 2015 to 2021, although at present this contract only calls for production of TPY-2 radar components, not complete radars.⁷¹

At least several possible additional locations for future forward-based radars have been proposed. In September 2012, the *Wall Street Journal* reported that in addition to the second forward-based radar to be deployed to central Japan, the United States was evaluating potential sites, such as the Philippines, for a third deployment in eastern Asia.⁷² Given the limitations of the Aegis Ashore radars in Romania and planned for Poland (by 2018), additional TPY-2s may also be sought for deployment in Europe. The September 2012 National Academy of Science (NAS) report stated that the MDA has proposed deploying a TPY-2 at both Aegis Ashore sites (although possibly this could be accomplished by deploying a THAAD battery to either or both sites).⁷³

The Upgraded Early Warning Radars (UEWRs) and Cobra Dane

INTRODUCTION

The core radar infrastructure of the current GMD system is composed of four large, phased-array radars. These are the upgraded PAVE PAWS at Beale Air Force base in northern California, the upgraded Ballistic Missile Early Warning System (BMEWS) radar at Thule, Greenland, the upgraded BMEWS radar at Fylingdales, Britain, and the Cobra Dane radar on Shemya Island. Two additional PAVE PAWS radars, at Clear, Alaska, and on Cape Cod, Massachusetts, are scheduled to be upgraded and incorporated into the GMD system by 2017 and 2018 respectively, which will bring the total to six.

Each of these large, powerful phased-array radars is capable of tracking missiles and warheads at ranges of thousands of kilometers. Each was originally built for purposes other than ballistic missile defense (primarily ballistic missile early warning) and had to be upgraded in order to be incorporated into the GMD system, although they also retain their original missions. The five PAVE PAWS and BMEWS radars use essentially the same technology (for example, transmit/receive modules) and the two types of radars are nearly identical except that the BMEWS radars is somewhat larger and more powerful. After being upgraded and incorporated into the GMD system, these radars are referred to as Upgraded Early Warning Radars (UEWRs), and designated as AN/FPS-132s.

The single Cobra Dane radar uses considerably different technology and was originally built primarily as an intelligence gathering radar (although it did have an early warning mission up until 1994). In the context of the GMD system, Cobra Dane is frequently referred to as a UEWR, because its capabilities and roles in the GMD system are similar to that of the PAVE PAWS and BMEWS UEWRs.⁷⁴ Cobra Dane is discussed in more detail below.

⁶⁸ Judson, J. 2013b. Army could borrow THAAD AN/TPY-2 radar for future missile tests. *Inside Missile Defense*, July 24.

⁶⁹ Judson 2013b.

⁷⁰ Syring, J. 2013. Testimony before the Defense Subcommittee of the Senate Committee on Appropriations. July 17. Online at <https://www.gpo.gov/fdsys/pkg/CHRG-113shrg39104550/pdf/CHRG-113shrg39104550.pdf>.

⁷¹ Doubleday, J. 2015. Pentagon plans contract extension for Raytheon AN/TPY-2 Production. *Inside the Army*, May 4.

⁷² Entous, A., and J.E. Barnes. 2012. U.S. plans new Asia missile defense. *The Wall Street Journal*, August 23, A1.

⁷³ NRC 2012, 273, Table E-42, note c.

⁷⁴ For example, Cobra Dane is described as an UEWR in Department of Defense. 2010. *Ballistic missile defense review report*. Washington, DC. February. Online at www.defense.gov/Portals/1/features/defenseReviews/BMDR/BMDR_as_of_26JAN10_0630_for_web.pdf Also in Missile Defense Agency (MDA). 2011 *Missile Defense Agency program update 2011*. ncr-113599A/081011. Washington, DC. August. Online at

The characteristics of these radars are summarized in Table 1.

THE PAVE PAWS AND BMEWS RADARS

ORIGINAL CONFIGURATIONS

The PAVE PAWS and BMEWS radars are large, fixed, ground-based radars. The diameters of the circular PAVE PAWS and BMEWS antenna faces are 22.1 m and 25.6 m, respectively. Most of these radars have two antenna faces, each covering 120 degrees in azimuth, for a total of 240 degrees azimuthal coverage. However, the Fylingdales radar has three antenna faces, providing full 360-degree azimuth coverage. Each radar face is tilted 20 degrees back from vertical and can cover elevation angles between 3 and 85 degrees.

Both the PAVE PAWS and BMEWS radars operate at frequencies between 420 and 450 MHz in the UHF band of the radar frequency spectrum. These frequencies correspond to wavelengths of 0.71 to 0.68 m. The PAVE PAWS radars have beamwidths of about 2.2 degrees and a transmit gains of 37.92 dB = 6,194.⁷⁵ The somewhat larger BMEWS radars have beamwidths of about 2.0 degrees.

Each face of a PAVE PAWS is populated with 1,792 active transmit-receive (T/R) elements, each powered by a single T/R module, and 885 passive elements. Each active T/R element has a peak power of 330–340 W, giving a peak power per face of about 582 kW and a maximum average power per face of about 145 kW,

TABLE 1. GMD Upgraded Early Warning Radars (UEWRs)

| | Upgraded PAVE PAWS | Upgraded BMEWS | Upgraded Cobra Dane |
|--|---|--|--|
| Location(s), Year Incorporated Into GMD | Beale AFB, CA (2004) Clear, AK (2016) Cape Cod, MA (2017) | Fylingdales, UK (2007) Thule, Greenland (2011) | Shemya, AK (2004) |
| Frequency | 420–450 MHz | 420–450 MHz | 1.175–1.375 GHz |
| Wavelength | 67–71 cm | 67–71 m | 22–25 cm |
| Antenna Diameter | 22.1 m | 25.6 m | 29 m |
| Angular Beamwidth | 2.2° (0.038 radians) | 2.0° (0.035 radians) | 0.6° (0.01 radians) |
| Antenna Aperture | 384 m ² | 515 m ² | 660 m ² |
| # of Active/Dummy Elements | 1792/885 | 2560/1024 | 15,360/19,408 |
| Average Power (per face) | 145 kW | 255 kW | 920 kW |
| Bandwidth | ≤ 30 MHz | ≤ 30 MHz | 5 MHz/200 MHz ^a |
| Range Resolution | ≥ 5 m | ≥ 5 m | 30 m/ 1.1 m |
| Published Single-Pulse Detection Range (pre-upgrade, on boresight, S/N = 20) | 2,700 km ($\sigma = 0.2 \text{ m}^2$, 16 ms pulse length) | 3,400 km ($\sigma = 0.2 \text{ m}^2$, 16 ms pulse length) ^b | 4,200 km ($\sigma = 0.1 \text{ m}^2$, 1.5 ms pulse length) |

a. The 200 MHz bandwidth is only within ±22° of the radar’s boresight.

b. Scaled from PAVE PAWS detection range.

www.mda.mil/global/documents/pdf/The_Missile_Defense_Program.pdf

⁷⁵National Missile Defense (NMD). 2000. Appendix H: Upgraded Early Warning Radar analysis. In *NMD deployment final environmental impact statement (EIS)*. Washington, DC: Ballistic Missile Defense Organization. H-es-2. Online at www.mda.mil/global/documents/pdf/env_gmd_eis_append_h.pdf



Fylingdales Upgraded Early Warning Radar (UEWR) at Royal Air Force Station Fylingdales, England. UEWRs form the core of the BMD sensor infrastructure, and are used to track missiles but do not have sufficient resolution to provide discrimination capability. Photo: Missile Defense Agency.

corresponding to a duty cycle of 25 percent.⁷⁶ As originally built, the PAVE PAWS radars had a bandwidth of 100 kHz in search mode and 1.0 MHz in track mode, which are far too low to provide any meaningful discrimination capability. The maximum pulse length was 16 milliseconds (ms).

⁷⁶ NMD 2000, H-1-7. As originally built, each of the two faces of a PAVE PAWS radar typically operated at an 18-percent duty cycle. The duty cycle either of the two faces of the radar could be raised to as high as 25 percent, but only by decreasing the duty factor of the other face by a corresponding amount. Thus if one face was operated at a duty cycle of 25 percent, the other face's duty cycle must be decreased to 11 percent.

Each face of the two BMEWS UEWRs is populated with 2,560 active T/R elements and 1024 passive ones and produces a peak power of 850 kW and an average power of 255 kW, corresponding to a duty cycle of 30 percent. As originally built, these radars had search bandwidths of 300 kHz (Fylingdales) to 600 kHz (Thule) and track bandwidths of 5.0 and 10.0 MHz, respectively, which are still far too low to be useful for discrimination. Like PAVE PAWS, the maximum pulse length of a BMEWS radar was 16 ms.

The original specifications for PAVE PAWS indicated that the radar could obtain a detection range of 5,550 km with a signal-to-noise ratio of $S/N = 17.7 \text{ dB} = 58.9$ on boresight against a 10 m^2 radar cross section (RCS) target (such as a final rocket booster stage) with a

single 16 ms pulse.⁷⁷ However, detection or tracking ranges much greater 4,000–4,500 km are rarely encountered with ballistic missile targets due to the curvature of the Earth. Against a warhead sized target (~0.2 m²) and with a S/N = 20, PAVE PAWS's maximum range would then be about 2,700 km. The range of the larger BMEWS radars would be roughly 27 percent greater, or about 3,400 km.

UPGRADED EARLY WARNING RADARS (UEWRs)

As noted above, the PAVE PAWS and BMEWS early warning radars required upgrades in order to be incorporated into the GMD System. These upgrades reportedly reused approximately 80 percent of the equipment at the existing radar sites.⁷⁸ In addition to their new missile defense role, the UEWRs continue their original ballistic missile early warning mission and also remain part of the US outer space surveillance system.

According to the Pentagon, these radar upgrades were needed because in their original configuration,

...these radars can detect and develop approximate impact-location data for objects associated with a missile launch, such as the last missile stage. This information is insufficient for use by a ballistic missile defense system, for two reasons: it does not track each missile long enough before returning to the search mode, and it does not permit the derivation of sufficiently accurately trajectory parameters to support intercepts.⁷⁹

The upgrades were intended to enable the radars to detect warhead sized objects at greater ranges and to increase the precision of the radars' tracking data so that interceptors could be launched earlier.⁸⁰ The upgrades

were also intended to improve the radars' capability to distinguish between threatening and non-threatening objects and to provide real time communications with the national missile defense command system.⁸¹ A draft environmental impact statement for PAVE PAWS spells out which equipment would be replaced.

The hardware modifications would consist of replacing existing computers, graphic displays, communication equipment, and the radar receiver/exciter to perform the NMD mission (i.e., identification and precise tracking of a ballistic missile launched against the United States). The EWR [early warning radar] software would be rewritten to incorporate the NMD function and allow the acquisition, tracking and classification of small objects near the horizon. The UEWRs would be able to search for different types of missiles, distinguish hostile objects such as warheads from other objects, and provide this data to other NMD elements using improved communications systems.⁸²

Despite these changes, “The radiated peak and average power, radar antenna patterns, and operating bands of the UEWRs would remain unchanged from current operations.”⁸³ Specifically, the increased instantaneous bandwidth remained within the radar's allocated UHF bandwidth (420–450 MHz) so that no additional frequency allocation was needed.⁸⁴

The increased radar sensitivity signal and processing capabilities achieved via these upgrades were expected to lead to increased detection ranges and improved tracking capabilities that would allow the UEWRs to be used to guide interceptors to targets. The changes are reflected in the acquisition and tracking requirements for the UEWRs compared to those of the original Early Warning Radars (EWRs).

The acquisition requirement for the original EWRs was to “acquire tank-sized objects at long range using autonomous surveillance with moderate probability,” while for the UEWRs the requirement is to “acquire RV-sized objects at long range using BMC3-provided search

⁷⁷ National Research Council (NRC). 1979. ***Radiation intensity of the PAVE PAWS radar system.*** Washington, DC: National Academy of Sciences. Table 1. Online at www.dtic.mil/dtic/tr/fulltext/u2/a088323.pdf.

⁷⁸ Chasteen, L. 2000. ***National Missile Defense and Early Warning Radars: Background and issues.*** RL30654. Washington, DC: Congressional Research Service. August 25. Online at <https://file.wikileaks.org/file/crs/RL30654.pdf>

⁷⁹ National Missile Defense deployment readiness program – “3+3.” Enclosure in a letter from Deputy Secretary of Defense John White to Representative John Spratt, June 5, 1996. Online at <http://fas.org/spp/starwars/offdocs/w960605e.htm>.

⁸⁰ Chasteen 2000, 6.

⁸¹ Chasteen 2000, 6.

⁸² NMD 2000, H-es-2.

⁸³ NMD 2000, H-es-2.

⁸⁴ Chasteen 2000, 6.

cues with high probability.”⁸⁵ (BMC3 is an acronym for Battle Management Command Control and Communications.)

The tracking requirement for the original EWR mission was that it “Provides sufficient accuracy to support ITW/AA warning and assessment requirements.” (ITW/AA is Integrated Threat Warning and Attack Assessment.) The requirement for the UEWR mission was increased; it must “Provide tracks with substantially improved accuracy and probability of reporting to support interceptor commit and fly-out.”⁸⁶

THE UEWRs AND DISCRIMINATION

The original early warning radars had tracking bandwidths of 1 MHz (the three PAVE PAWS), 5 MHz (Fylingdales) and 10 MHz (Thule), corresponding to best possible range resolutions of 150 m, 30 m and 15 m, respectively. The new receiver/exciter in the UEWRs reportedly increased their instantaneous bandwidth while still remaining within their allocated range of frequencies.⁸⁷ Thus the instantaneous bandwidth of the UEWRs is likely to be between 10 MHz and 30 MHz, corresponding to best possible range resolutions of 15 m and 5 m, respectively.

These resolutions are larger than a warhead and far too large to be able to permit discrimination much beyond the original early warning radars’ capability to classify objects as either potentially threatening or not threatening. That the improved capability is still not capable of supporting discrimination is reflected in the classification (discrimination) requirements for the original and upgraded radars. The requirement for the original EWRs was to “identify RV-sized objects” while for the UEWRs it is to “identify RV-like objects with a very high probability of correct classification and a very low probability of incorrect classification in disturbed ionospheric environments.”⁸⁸ While this classification requirement for the UEWRs might give the impression that these radars are capable of performing meaningful discrimination, it actually only reflects a requirement to be able to reject small pieces of debris as non-threatening.

The limited discrimination capability of the UEWRs is evident in a 2004 description by Government

Accountability Office of the first two to be integrated into the GMD system:

Neither the Cobra Dane radar nor the upgraded early warning radar at Beale is capable of performing rigorous discrimination, a function achievable only by the X-band radar. Rather, both radars will utilize common “target classification” software that enables them to classify objects as threatening or non-threatening. For example, debris would be classified as non-threatening, but objects like deployment buses and decoy replicas would be classified as threatening.⁸⁹

According to the Tim McKaig, the MDA’s program director for sensors, these radars can only “label an object as a reentry vehicle or a tank or debris.” He went on to say, “They can only classify target objects into those two bins.”⁹⁰

Cobra Dane

INTRODUCTION

Cobra Dane (AN/FPS-108) is a large and powerful single-faced phased-array radar located on Shemya Island at the western end of the Aleutian Island chain (52.7° N, 174.1° E), overlooking the northern part of the Kamchatka Peninsula. It became operational in 1977, replacing a number of older mechanically-steered radars on Shemya, and underwent a major modernization in the early 1990s, as well as a number of other subsequent enhancements.

Cobra Dane’s original primary mission was to gather technical intelligence data on Soviet ballistic missile flight tests. It also had secondary missions of missile early warning and outer space surveillance. Both of these secondary missions were dropped in 1994, although the space surveillance mission was restored in 1999.

⁸⁵ Raytheon Company. 2001. Upgraded Early Warning Radars (UEWR) for missile defense. Factsheet.

⁸⁶ Raytheon 2001.

⁸⁷ Chasteen 2000, 6.

⁸⁸ Raytheon 2001.

⁸⁹ General Accounting Office (GAO). 2004. **Missile defense: Actions being taken to address testing recommendations, but updated assessment needed.** GAO-04-254. Washington, DC. February 26. 17. Online at www.gpo.gov/fdsys/pkg/GAOREPORTS-GAO-04-254/pdf/GAOREPORTS-GAO-04-254.pdf.

⁹⁰ Butler, A. 2013. Sensory Input, *Aviation Week & Space Technology*. August 5, 66-67.

TECHNICAL CHARACTERISTICS

Cobra Dane operates in L-band, at frequencies between 1.175 and 1.375 GHz. As originally built, in narrowband operation (search and tracking), Cobra Dane operated between 1.215 to 1.250 GHz, corresponding to a wavelength of about 24.3 cm. In search, it uses one-MHz bandwidth pulses with lengths of 1.5 or 2.0 ms, and in track it uses six different five MHz bandwidth pulses with lengths between 0.15 and 1.5 ms. The radar also has two 1.0 ms, 25 MHz bandwidth pulses used for ionospheric compensation.⁹¹ It can track more than 100 objects simultaneously.⁹²

In wide-band mode (for example, for imaging) Cobra Dane uses a 1.0 ms pulse with a 200 MHz bandwidth (obtained using linear frequency modulation pulse compression) at frequencies between 1.175 and 1.375 GHz. Wideband operation is limited to angles within 22.5° of its boresight (due to the time dispersion across each of the 96 subarrays that make up the entire antenna array). In wideband operation, Cobra Dane has a range resolution of about 3.75 feet (1.14 m).

Cobra Dane's antenna is 29 m in diameter and has 15,360 active elements and 19,408 dummy elements, for a total of 34,768 elements. The active elements are space-tapered, decreasing to 20 percent density at the antenna edge. This space tapering allows a narrower beamwidth to be achieved with a given number of active elements

and it also reduces near-in sidelobes. Cobra Dane's beam width is 0.6 degree.⁹³

In order to obtain better range resolution off-boresight, the antenna elements are subdivided into 96 subarrays, each powered by a separate traveling wave tube. The radar's peak power is 15.4 MW with an average power of 920 kW, corresponding to its maximum 6-percent duty cycle.

Cobra Dane's specifications call for it to achieve a range accuracy of 15 feet (4.6 m) and an angular accuracy of 0.05 degree at 0.6 degree elevation. Typical accuracies are 3 m in range and 0.02 degree in angle.⁹⁴

Cobra Dane's antenna boresight is at an azimuth of 319 degrees (that is, pointed 41 degrees west from due north) at 20 degrees above the horizon. When it was originally deployed, Cobra Dane had an azimuthal field of view of ±60 degrees. However, in 1995, its field of view was extended by ±8 degrees to ±68 degrees at elevations up to 30 degrees. It can track up to about 80 degrees in elevation.

As of 2000, Cobra Dane could achieve a signal-to-noise (S/N) ratio of 13.2 dB against a 0.01 m² target at a range of 1,852 km with a single 1.0 ms pulse.⁹⁵ However, this result was obtained at an elevation of 1.0 degree on the azimuth boresight, which results in atmospheric absorption and scan losses of about 2.3 dB = 1.7 relative to a beam along the boresight.⁹⁶ Taking these losses into account, the corresponding boresight sensitivity would be S/N = 46 dB = 42,000 against a 1 m² target at 1,000 km with a 1.0 ms pulse. Assuming that S/N = 20 is needed for detection, this sensitivity gives a detection range along the boresight of 3,800 km with a single 1.0 ms pulse against a warhead-sized target (0.1 m²). Using Cobra

⁹¹ One pulse is centered 1187.5 MHz and the other at 1363.5 MHz. Using satellite targets of opportunity, the ionospheric correction is then made based on the time delay difference between the two frequencies.

⁹² Unless otherwise noted, the information in this section is from Chorman, P. 2000. COBRA DANE space surveillance capabilities, In *Proceedings of the 2000 space control conference*, project report STK-255, edited by S.E. Andrews. Lexington, MA: Lincoln Laboratory. 159–168; Stansbery, E.G. 2004. Growth in the number of SSN tracked orbital objects. In *55th International aeronautical congress of the International Aeronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law*, Vancouver, Canada, October 4-8 (IAC-04-IAA.5.12.1.03). Online at <http://arc.aiaa.org/doi/abs/10.2514/6.IAC-04-IAA.5.12.1.03>; Earl Filer and John Hartt, "Cobra Dane Wideband Pulse Compression System," IEEE Electronic and Aerospace Systems Convention (EASCON) 1976, Washington, D.C., September 26-29, 1976, Paper 61; and Klass, P.J. 1976. USAF tracking radar details disclosed. *Aviation Week & Space Technology*, October 25. 41, 43, 46.

⁹³ Stansbery, G. 2001. Preliminary results from the U.S. participation in the 2000 Beam Park Experiment. In *Proceedings of the Third European Conference on Space Debris*, Darmstadt, Germany, March 19–21. edited by H. Sawaya-Lacoste. ESA SP-473, Vol. 1, Noordwijk, Netherlands: ESA Publications Division. 49–52. Online at <http://adsabs.harvard.edu/full/2001ESASP.473...49S>.

⁹⁴ Englander, K. 2001. Ground based midcourse missile defense, briefing slides, U.S. Ballistic Missile Defense Agency, August.

⁹⁵ Chorman 2000, 160.

⁹⁶ Atmospheric absorption loss (2.0 dB) from Nathanson, F.E., J.P. Reilly, and M.N. Cohen. *Radar design principles: Signal processing and the environment*, second edition. Mendham, NJ: Scitech, 1999. 216, Figure 6.1. Online at <https://selasl.files.wordpress.com/2011/08/mcgraw-hill-radar-design-principles.pdf>. Scan loss (0.33 dB) from Figure 5 of Chorman 2000, 166.

Dane's longest pulse length of 1.5 ms, the warhead-sized object could be detected at a range of about 4,200 km.

COBRA DANE AND THE GMD SYSTEM

In order for Cobra Dane to be incorporated into the GMD system, it needed a number of upgrades. These upgrades primarily involved software changes. None of the radar's existing hardware was changed.⁹⁷ A new communications system was added to allow Cobra Dane to communicate in real time with the GMD fire control system.⁹⁸ The upgrades, which allowed Cobra Dane to retain its intelligence gathering and space surveillance missions, were completed by September 2004, in time for the announcement of the GMD system's Limited Deployment Option capability.

Because of its location and orientation, Cobra Dane is not optimally positioned to observe trajectories from North Korea to the United States.⁹⁹ In particular, many trajectories from North Korea to the West Coast of the

United States will never enter the ± 22.5 -degree cone in which Cobra Dane can make wideband measurements, thus negating one of its biggest advantages relative to the other upgraded early warning radars in the GMD system. In addition, a missile flown from North Korea to Hawaii on a standard trajectory (not lofted or depressed) would be visible to Cobra Dane only for a few tens of seconds.¹⁰⁰

Because of Cobra Dane's location and orientation, it has never been used in a GMD intercept test. In September 2005, MDA conducted a flight test in which a ballistic missile was launched from a C-17 cargo aircraft and flown across the face of the Cobra Dane.¹⁰¹ The Cobra Dane radar data was used to construct a fire solution that was fed into the GMD command and control system, although no interceptor was involved. Other than this test, Cobra Dane's missile defense capabilities have been tested only in ground tests and by observing ballistic missile targets of opportunity.

⁹⁷ Jeffries, J. 2014. COBRA DANE: A piece of history transitions to AFSPC. Space Observer. Peterson Air Force Base, March 13, 3, 12. Online at http://csmng.com/wp-files/space-observer-weekly-pdfs/spaceobserver_2014-03-13.pdf.

⁹⁸ Jeffries 2014.

⁹⁹ Gronlund, L, D. Wright, G. Lewis, and P Coyle. 2004.

Technical realities: An analysis of the 2004 deployment of a U.S. National Missile Defense system. Cambridge, MA: Union of Concerned Scientists. May. 37, Figure 3. Online at www.ucsusa.org/sites/default/files/legacy/assets/documents/nwgs/technicalrealities_fullreport.pdf.

¹⁰⁰ Gronlund et al. 2004, 36.

¹⁰¹ Missile Defense Agency (MDA). 2005. Missile defense radar exercise successfully completed. Press release, September 26. Online at www.mda.mil/global/documents/pdf/05news0009.pdf.