

From Vision to Reality

50+ Years of Phased Array Development

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Abstract—Phased array radar systems, which emerged over 55 years ago, have continually evolved from the early 60s to present day. Over 55 years ago, U.S. phased array radar systems brought a new dimension or capability that is fully realized in today's all-solid-state arrays, such as those on the F-22 and F-35 military aircraft. This process of expanding phased array capability involved an evolutionary series of steps each decade. This paper cites the most prominent U.S.-deployed phased array radars as viewed by one phased-array radar advocate.

Key words: radar, antenna array, phased array, phased array radar, radar antennas, array

I. INTRODUCTION

I welcome the opportunity to talk with today's phased array engineers and scientists. I have always felt comfortable interacting with the phased array community, probably because I see myself as an early worker and advocate of the phased array art. I do not consider myself a "pioneer" or "founder" although I met a fair number of them along the way.

I will offer you a commentary on our phased array situation in the 1960s era, some 55 years ago. Did we have a vision then and did we make it? Yes, we had a vision way back then and "yes", we made it, but it took over 40 years – much longer than we thought.

I will illustrate some prominent deployed phased array radars that evolved over the ensuing 50-plus years. I picked U.S. systems which I see as "stepping" stones – systems that brought some new dimension or capability to the art. I believe our 1960s "vision" is realized in today's all-solid-state arrays such as those on the F-22 and F-35 military aircraft. In the 60s, we wondered how we would cram all that X-band hardware into the one-half-inch spacing allowed, but it has been accomplished and is impressive to see! Not surprisingly, the "vision rolls on" and amazing phased arrays are now being developed and deployed.

I close with a return to the "vision" process and its important role in the careers of engineers and scientists. Persisting with a vision for a long duration is not easy but it is what we engineers/scientists do for the public at large. In our phased array case, this "vision" process has a happy ending.

II. THE 1960s

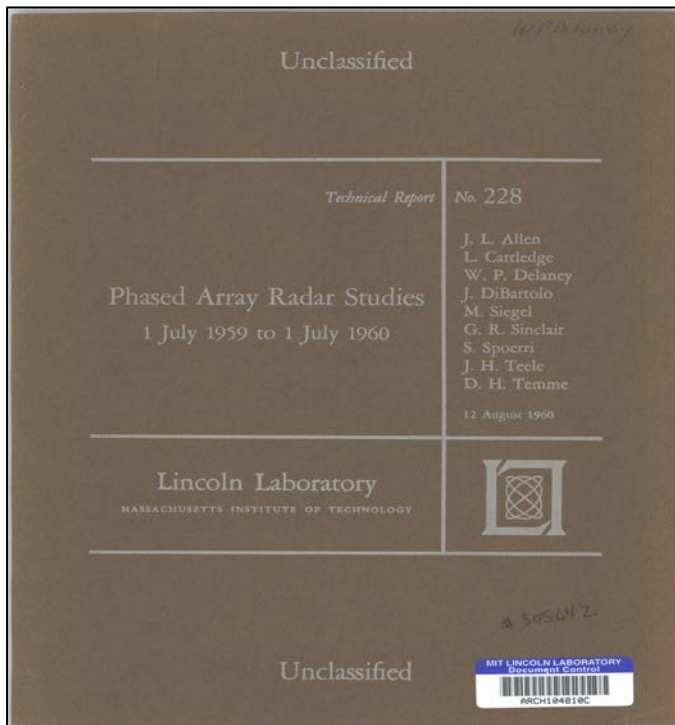
I joined Lincoln Laboratory in May of 1957 with a joint appointment to the Laboratory staff and the MIT Graduate School. 1957 became an exciting year on 4 October when the engineers and scientists of the Soviet Union launched the first artificial earth satellite. The "Space Age" had begun and it was

obvious that our radar technology was inadequate to the task of space surveillance. A long-range aircraft surveillance radar of that era could detect a large jet aircraft at 200 miles, but the satellite detection job would require at least 2,000 miles! Early satellite radar returns would be smaller than jet aircraft so we were some 50 dB shy in radar power-aperture product. This huge deficiency in radar plus the need for very wide angle scanning turned our thoughts to phased arrays – big phased arrays! Also, the ability to put a satellite in orbit also conveyed the ability to send warheads to intercontinental distances so ballistic missile defense became a national concern. Missile defense would demand radars of great power-aperture and very agile beam scanning for surveillance, tracking and fire-control.

I wanted to do a substantial experimental thesis at the MIT Graduate School and the topic that came my way was "Phase Stabilization of UHF Power Amplifiers", a project funded by U.S. Air Force interest in phased array technology. So I joined the phased array business early in 1958.

I finished my graduate study in 1959 and joined a small Lincoln Laboratory group which was exploring phased array technology. This group had formed around a most talented individual, John Allen, who had great analytical skills and a creative, dynamic leadership style. He was a frequent writer of technical papers and his name is prominent in the phased array literature of the 1960s.

Lincoln Laboratory's role as a Federally Funded Research Center prompted John to set a goal for our work that was "national" in scope. The goal was to make electronically steered arrays a practical option for the defense/military user. To achieve this goal, our program would have to foster tight coupling to the wide variety of industrial teams, laboratories, and academia around the nation who were investigating this technology. I can recall at least a dozen major electronic firms plus some six laboratories and a few universities, all with small teams, interested in phased array technology. We set out to collaborate with these some 20 teams around the nation. We invited them to our laboratory and briefed them on our work, visited their facilities, shared data with them and occasionally undertook joint investigations or hardware ventures with them. One important step we took was to publish a comprehensive technical report on our work each year and distribute that report widely to the community. Fig. 1 is a copy of the cover of our first such report, Lincoln Laboratory Technical Report, TR-228 with some 230 pages. Over the ensuing 5 years, we published TR-236, 299, and 381 plus a variety of other reports and papers. This publications process served our goal very well and I recall lots of feedback from the community on our work described in these publications.



(MIT Lincoln Laboratory)

Figure 1. Reprinted from “Phased Array Radar Studies: 1 July 1959 to 1 July 1960”, by J. L. Allen, L. Cartledge, W.P Delaney, J. Dibartolo, M. Siegel, G. R. Sinclair, S. Spoerri, J. H. Teele and D. H. Temme, 1960, Lincoln Laboratory Technical Report, cover. 1960

The electronic technology situation in 1960 was such that many knowledgeable technical people considered the vision of an affordable, high-powered 5,000-element array with all elements acting reliably and in complete amplitude and phase coherence an “impossible dream.” The cost, complexity, and reliability of such arrays were substantial concerns to those knowledgeable engineers. Our early experimental arrays certainly were a complex assembly of disparate hardware pieces. One 16-element test array I assembled must have had 100 pounds of cables to connect the elements to the receivers, beam formers, etc.

Clearly, an all-solid-state configuration would be the solution, but there were no appropriate high-frequency or high-powered solid-state devices available in the early 1960s! Thus, a high-frequency, high-power solid-state array became our “vision.” In the mid-1960s, the nation undertook focused solid-state array device work at L band, and that work by a variety of industry teams and national laboratories carried us some 50 years later to today’s fine X-band, all-solid-state transceiver modules and the realization of the “vision.” In response to an urgent need for high frequency solid-state devices at low cost and high reliability, the Defense Advanced Research Projects Agency (DARPA) initiated the MIMIC program in 1988 and continued it with sustained investments through 1995. The program established robust, controllable manufacturing processes for gallium arsenide (GaAs) integrated-circuit chips, multichip ceramic packages, accurate computer-aided device and circuit modeling tools, automated on-wafer testing techniques, and advanced fabrication methods.

The technologies developed in the MIMIC program established a mature manufacturing base for the production of active phased arrays at lower cost, improved reliability, and higher performance.

We told our sponsors it might take 10 to 15 years to “realize the vision,” but we were very optimistic. It has taken closer to 50 years, and today we have all-solid-state radars, such as the active electronically scanned arrays in the F-22 and F-35 fighters, and the realization of even more advanced arrays which will be discussed in the next section.

A. “STEPPING STONES”

I can describe the migration from vacuum-tube arrays to today’s all-solid-state configuration by pointing to a time-ordered sequence of deployed phased arrays. Each one of the more than dozen cited arrays in this quick review is in my view considered a “stepping stone”, with each bringing something important or new to the phased array art. The phased array systems cited offer my perspective on the more important developments; a different author might pick different systems. I limited my selection to phased array radar systems (vs. communications systems) and to radars that were actually deployed. All are U.S. systems which are the only arrays I am familiar with in detail. I order my list in time sequence of their Initial Operational Capability (IOC) dates, starting with the earliest.

B. 1962: AN/SPS 32/33 RADARS

I select these two radars because I believe they were the first substantial phased arrays deployed. They were sponsored by the U.S. Navy for ship defense and were built by the Hughes Company of Fullerton, CA. They are shown in Fig. 2, deployed on the forward superstructure of the cruiser “Long Beach” (they were also deployed on the aircraft carrier “Enterprise”). The SPS-32 was a UHF radar with long-range surveillance and tracking capability. The SPS-33 was an S-band array with fine resolution tracking capability. The SPS-32 was a phase-scan aperture and the SPS-33 utilized a phase-frequency scan. Both were large arrays. I visited their test site in Fullerton, CA in the mid-1960s and was impressed by the size of the antennas. Eight apertures were deployed on each ship to provide 360-degree azimuth coverage.



Figure 2. AN/SPS-32/33 Radars

C. 1969: THE FPS-85

This large UHF phased array, shown in Fig. 3, was built for Air Force satellite surveillance purposes by the Bendix Corporation of Maryland. It is located at Eglin Air Force Base in Florida and is still operating today. It represented to me a classical realization of the early phased array art. The square aperture is the 5,000-element transmitter radiating some 175 kilowatts of average power. The larger aperture is the 4,700 element receiver with many dummy elements to form an effective amplitude taper across the array.

This phased array provides an example of the reliability concerns about these early arrays. Each transmitter element was originally driven by three high-power vacuum tubes: a tetrode final amplifier of 10 kW peak power and two triode amplifiers as drivers; thus, the transmitter features some 15,000 high-power tubes (plus a multitude of low-power tubes). These high-power amplifiers operated 24 hours a day and if one operated them conservatively, a 10,000-hour service life was achievable. A simple calculation of 10,000 hours life for 15,000 tubes has 12,000 tubes replaced each year which calculates to 33 replacements per day. I visited this radar in 1974 and the Air Force sergeant who monitored the transmitter told me that on a “good day” he replaced 10 tubes, on a “bad day” 35 tubes, and on the day of my visit 17 tubes. So there was a substantial burden in maintenance with arrays with high-power vacuum tubes (the receivers of the FPS-85 featured transistor circuits).

D. 1975: MSR, PAR

These two radars are noteworthy since they were the main sensing elements of the United States first national missile defense system. They were located at Grand Forks, ND near the ICBM Minuteman missile deployment at Grant Forks Air Force Base.

The massive concrete structures that house the arrays are testimony to the nuclear environment in which they were designed to operate.

The Missile Site Radar (MSR), shown in Fig. 4, was designed for medium-range surveillance, tracking, fire control and missile guidance. It was built for the Army’s missile



(USAF)

Figure 3. FPS-85



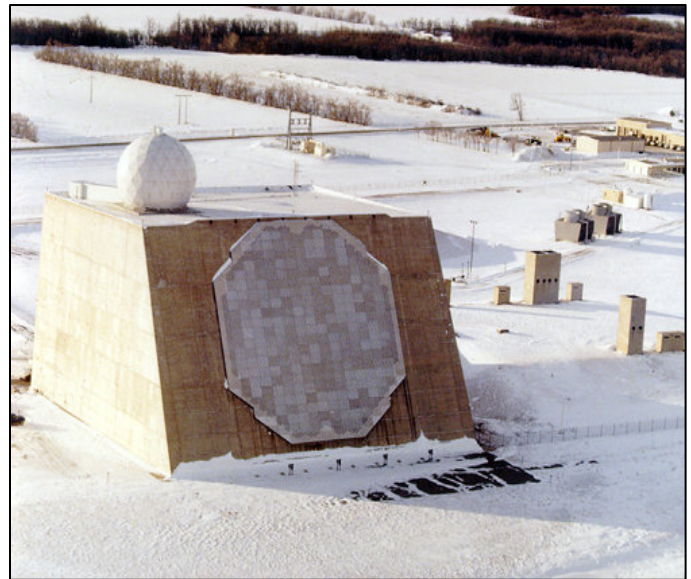
(Craftsman2001)

Figure 4. Missile Site Radar (MSR)

defense program by the Raytheon Company of Massachusetts. The Bell Telephone Laboratory was heavily involved in its design and testing. It contained four S-band array faces, each with 5,000 elements (the array is the smaller circular aperture in the figure, the larger ring was for future expansion).

The array features a lens feed with diode phase shifters and the transmitter was a very high-power klystron pair. The average radiated power was some 225 kW (the futuristic appearance of this radar building has resulted in the building being used in television science fiction programs representing various kinds of alien structures).

The Perimeter Acquisition Radar (PAR), shown in Fig. 5, was built for the Army missile defense program by the General Electric Company of Syracuse, NY. The radar, which still operates today for satellite surveillance, has been renamed PARCS and sometimes is referred to as the “Cardinal” radar. It is located several miles from the MSR site.



(USGov-Military-Air Force)

Figure 5. Perimeter Acquisition Radar (PAR)

The PAR's role in missile defense was long-range surveillance and tracking. It operates at UHF and contains some 6,000 elements in its 100-foot aperture. It features a corporate feed with traveling wave tubes providing the 700-plus kW of average radiated power.

E. 1977: COBRA DANE RADAR

The COBRA DANE radar, shown in Fig. 6, was built for the U.S. Air Force by the Raytheon Company of Massachusetts and it still operates today. The radar is located on the Shemya Island in the Aleutian Islands archipelago southwest of Alaska. Its site and its long-range capability allow it to track satellites and to monitor ballistic missile flights in the Pacific Ocean area.

The COBRA DANE development featured a strong emphasis on reducing the cost of large phased arrays. The array operates at L-band and has some 15,000 active elements in its 95-foot diameter aperture. The array is corporate-fed with travelling wave tube transmitters providing some 900 kW of average radiated power.

I recall that the goal of lowering the cost of arrays was achieved and COBRA DANE became the prominent example of a high-performance, lower-cost array.

F. 1980: PAVE PAWS

The PAVE PAWS array radar (Fig. 7) development is noteworthy since it was the world's first high-powered all-solid-state array. PAVE PAWS' mission was warning of ballistic missile attack. It was built for the U.S. Air Force by the Raytheon Company of Massachusetts. The first two PAVE PAWS radars were located at Cape Cod in Massachusetts and Beale Air Force Base in California. These UHF radars had two 100-foot diameter array faces with some 1800 active elements per face. Each antenna element was driven by a 325 watt peak-power solid-state module.

One can argue that PAVE PAWS realizes our vision of an all-solid-state array. It did certainly validate the solid-state array potential but at the time of its development the military interest was focused on arrays at higher frequency than UHF. That interest extended to L, S, C and X-band so I argue PAVE PAWS was a significant step in answering the vision but was not the final step.



(U.S. Air Forces)

Figure 6. COBRA DANE Radar



(U.S. Army Corps of Engineers)

Figure 7. PAVE PAWS

The architecture of a large all-solid-state UHF surveillance radar became a popular construct and the PAVE PAWS approach was used in a major upgrade of the Ballistic Missile Early Warning System (BMEWS), with improved versions of the PAVE PAWS UHF array faces installed at Clear, Alaska; Thule, Greenland; and Fylingdales, UK.

G. 1981: PATRIOT

The PATRIOT array radar, shown in Fig. 8, was built for the U.S. Army by the Raytheon Company of Massachusetts. The PATRIOT system role/mission was a surface-to-air missile system (SAM) for defense of Army assets against aircraft and missile attack. The PATRIOT SAM was an early tactical user of a phased array for surveillance, tracking, and missile guidance.

The radar featured a C-band lens-fed array of 5,000 elements with diode phase shifter. Traveling wave tubes provided the RF power.



Figure 8. PATRIOT Surface-to-Missile (SAM) System

The lens feed of PATRIOT was a favorable choice for a field mobile system like PATRIOT since the radiating aperture could be folded flat onto the top of the vehicle for transport. This type of lens feed has become popular and Russia and now China are producing tactical SAMs with this style of array. Over 200 PATRIOT SAMs have been produced and used by a number of nations. The PATRIOT system has been used in combat a number of times.

H. 1983: AEGIS SPY-1 RADAR

The AEGIS SPY-1 radar, shown in Fig. 9, was built for the Navy by the Lockheed Martin Corporation of Moorestown, NJ. The array face can be seen on the forward superstructure of the ship. The AEGIS system’s role is air and missile defense of the surface fleet. The system has seen combat a number of times.

The SPY-1 radar is an S-band, 4,000-element array that uses cross-field amplifiers for transmitters in a corporate feed arrangement. Average radiated power is some 60 kW.

Four array faces are used on each AEGIS cruiser or destroyer to provide 360 azimuth coverage. Some 77 major ships carry the AEGIS system, which adds up to some 300 array faces deployed – probably a record number of arrays in the U.S. inventory. An advanced version of AEGIS is in development.

I. 1983: COBRA JUDY RADAR

The COBRA JUDY radar system, shown in Fig. 10, was built for the U.S. Air Force by the Raytheon Company of Massachusetts. Its mission was data collection on ballistic missile flights. COBRA JUDY is my favorite array radar system since I had a lot to do with its specification and development during my tour in the Department of Defense (DoD) in the 1973-76 time frame. The COBRA JUDY system served for 31 years and was recently retired. The COBRA JUDY ship, the “Observation Island”, is one of a long line of range instrumentation ships that collect data on a wide variety of missile testing. The “Observation Island” was preceded by the “Arnold” and “Vandenberg” ships and is succeeded by the “Howard O. Lorenzen”, which will be described shortly.

The COBRA JUDY radar is a 12,000-element S-band array with a 20-foot diameter. Its transmitters are travelling wave tubes in a corporate feed structure. The array is mounted on an azimuth pedestal.



Figure 9. AEGIS SPY-1 Radar



Figure 10. COBRA JUDY Radar

J. 1987: JSTARS

JSTARS, shown in Fig. 11, is the first airborne array on my list of prominent phased arrays. It was built for a joint Air Force-Army program by the Northrop Grumman Corporation of Florida. The JSTARS mission is wide area surveillance of ground targets, both moving targets and fixed targets. The 24-foot X-band array is mounted on the forward fuselage of a 707 aircraft. The array is scanned in azimuth and has a limited mechanical scan in elevation. Sixteen JSTARS aircraft are operational and the system has been used in combat. A current program is investigating a JSTARS-like capability on a smaller air frame, such as a business jet.

K. 2005, 2012: APG-77, APG-81 (ALSO APG-79)

In 2005, the APG-77 radar, shown in Fig. 12, fully answered our 1960’s vision of an all-solid-state radar operating at the higher microwave frequencies. This X-band radar was built for the Air Force for installation in the F-22 fighter (187 F-22s have been produced), by the Northrop Grumman Corporation of Baltimore, MD.

Northrop Grumman also built the APG-81 X-band all-solid-state array, shown in Fig. 13, for the Air Force for use in the F-35 fighter. Raytheon Company of Massachusetts also produced a similar array for the F/A-18 fighter called the APG-79.



(U.S. Air Force ID 100311-F-0672C-402)

Figure 11. JSTARS



Figure 12. APG-77 Radar

These three programs alone will produce more than 1,000 of these modern airborne arrays. They all feature more than 1,000 array elements and many of the “bells and whistles” enabled by modern solid-state microwave components and modern digital engineering.

In 1960, we had a hard job considering how one might cram all the hardware into the one-half inch space allowed for an X-band array. The nation’s steady and long-lasting MIMIC program produced this amazing capability.

L. 2008: TPY-2 RADAR

As we celebrated the realization of our all-solid-state vision by the APG-77 radar, we received a reminder that “the vision marches on” when the TPY-2 radar, shown in Fig. 14, appeared in the scene somewhere around 2005 (prior to its declared operational date of 2008). I was shocked to see the 25,000-element X-band array in development at the Raytheon Company. This development was testimony that the solid-state array technology had taken hold.



Figure 13. APG-81 Radar



Figure 14. TPY-2 Radar

The TPY-2 radar was developed for the Missile Defense Agency by Raytheon Company of Massachusetts. Its mission was to be the principal sensor in a medium-range missile defense system. It also has found use as a surveillance-tracking sensor around the world. My recollection is that some 12 of the radars are operating around the world.

M. 2005: SBX RADAR

Whatever surprise I had at 25,000-element TPY-2 was exceeded when I witnessed the SBX seaborne X-band array, located under the radome in Fig. 15, built for the Missile Defense Agency by Raytheon Company of Massachusetts. This huge radar in a unique sea-going platform features a world-record 45,000 elements on an azimuth-elevation pedestal. It is part of our current missile defense capability, operating from various locations in the Pacific.

N. 2014: COBRA KING RADARS

The Cobra King radars on the new ship, the “Howard O. Lorenzen”, are the range instrumentation ship radar replacement for the COBRA JUDY system. The ship, shown in Fig. 16, was developed for the Air Force with radars by Northrop Grumman Corporation of Maryland and Raytheon Company of Massachusetts. The upper radar is an S-band all-solid-state array by Northrop Grumman and the lower radar is an X-band system by Raytheon. Both of these modern all-solid-state arrays feature thousands of elements and substantial average radiated power.



(United States Missile Defense Agency)

Figure 15. SBX Radar



Figure 16. COBRA KING Radars

O. 2018 IOC: SPACE FENCE RADAR

Further testimony that the “vision marches on” is offered by the Space Fence Radar, shown in an artistic concept in Fig. 17, currently being installed on Kwajalein Atoll in the Marshall Islands in the Pacific. The radar is being built for the Air Force by the Lockheed Martin Corporation of Moorestown, NJ. A second site for this type of radar is planned for Australia.

The S-band Kwajalein array features a transmitter array of some 36,000 elements and average radiated power of some 810 kW. The separate receiver array has some 86,000 receiver elements. The role of this radar is space surveillance with an ability to see even very small objects in orbit (a following paper in this plenary session by Joseph Haimel gives details on this fantastic evolution in array technology).

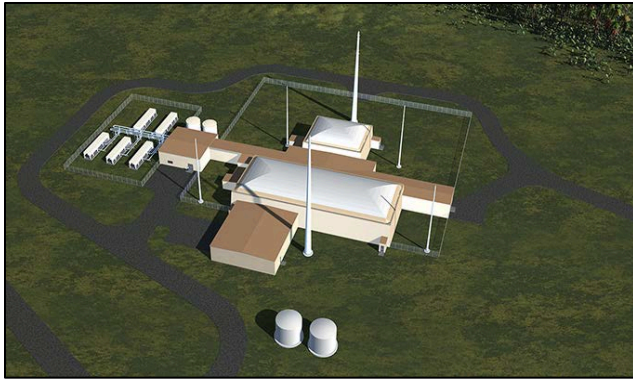


Figure 17. Space Fence Radar

III. ENGINEERS AND VISIONS

Our development of truly amazing array technology over the past 50-plus years is testimony to the vision of engineers and scientists. We are the “keepers of visions” and the public at large has grown accustomed to this march of visions which provides an ever increasing supply of devices and systems that benefit mankind.

As young engineers, most of us found ourselves working to implement somebody else’s idea or vision. Most of us took a good while to realize we are entitled or, rather, we are somewhat obligated to be visionaries.

The visionary role is not easy. A really great vision will create a lot of upset and even hostility in the community of folks doing things the “old way”. If one has a great idea that does not upset a lot of folks, maybe it is not so great an idea! Many years ago, the Navy folks who added steam engine drive to a Navy sailing ship were not welcome in Navy circles. It seems that coal for the steam

boilers got the white uniforms of the crew sooty and the test ship for steam drive was allowed to rot at its dock! So be prepared for rough road as you pursue your vision.

Some great individuals offer encouragement to the visionary. Famous aerodynamicist, Professor Theodore von Kármán of Caltech explains the engineer’s role:

“The scientist seeks to understand what is. The engineer seeks to create what never was.”

Prolific author, Mark Twain points to the need for self-confidence:

“If you think you can or if you think you can’t, you’re probably right.”

And finally, some anonymous wise individual offers you encouragement if you consider your expertise to be inadequate:

“The Titanic was built by professionals: The Ark was built by amateurs.”

Good luck to you in pursuit of your visions and congratulations to the phased array community, past and present, for the realization of a 1960’s vision for phased arrays.

REFERENCES

Images in this paper were taken from the “public domain” web sites listed below:

Fig. 2. AN/SPS-32/33 Radars

<http://militaryhistory.x10.mx/shippictures/uss%20long%20beach/uss%20long%20beach%2002.jpg>

Fig. 3. FPS-85

https://en.wikipedia.org/wiki/Eglin_AFB_Site_C-6#/media/File:2008_Eglin_AFB_Site_C-6_phased_array_building.jpg

Fig. 4. Missile Site Radar (MSR)

https://en.wikipedia.org/wiki/Safeguard_Program#/media/File:Safeguard_Missile_Site_Radar.png

Fig. 5. Perimeter Acquisition Radar (PAR)

https://en.wikipedia.org/wiki/Safeguard_Program#/media/File:Cavalierairforcestationparcs.jpg

Fig. 6. COBRA DANE Radar

https://en.wikipedia.org/wiki/Cobra_Dane#/media/File:Cobradane.jpg

Fig. 7. PAVE PAWS

https://en.wikipedia.org/wiki/PAVE_PAWS#/media/File:PAVE_PAWS_Radar_Clear_AFS_Alaska.jpg

Fig. 8. PATRIOT Surface-to-Missile (SAM) System

http://data3.primeportal.net/artillery/ulrich_wrede/nl_patriot/images/nl_patriot_03_of_87.jpg

Fig. 9. AEGIS SPY-1 Radar

<http://www.seaforces.org/marint/Japan-Maritime-Self-Defense-Force/Destroyer/Atago-class-Dateien/image082.jpg>

Fig. 10. COBRA JUDY Radar

Figure 1. USNS Observation Island. The Cobra Judy S- band radar array.. https://www.researchgate.net/figure/4242838_fig1_Figure-1-USNS-Observation-Island-The-Cobra-Judy-S-band-radar-array-is-located-aft-of [accessed Aug 8, 2016]

Fig. 11. JSTARS

<http://www.airforce-technology.com/projects/jstars/jstars1.html>

https://en.wikipedia.org/wiki/Northrop_Grumman_E-8_Joint_STARS#/media/File:Usaf.e8.750pix.jpg

https://en.wikipedia.org/wiki/Northrop_Grumman_E-8_Joint_STARS#/media/File:T-3_with_JT8D-219_engines.JPG

Fig. 12. APG-77 Radar

<http://www.globalsecurity.org/military/systems/aircraft/systems/images/an-apg-77-image1.jpg>

Fig. 13. APG-81 Radar

http://www.northropgrumman.com/Photos/pgM_AN-10137_001.jpg

Fig. 14. TPY-2 Radar

<http://www.defenseindustrydaily.com/antpy-2-ground-radar-07533/>

Fig. 15. SBX Radar

https://en.wikipedia.org/wiki/Sea-based_X-band_Radar#/media/File:Sbx_050701_001.jpg

Fig. 16. COBRA KING Radars

http://www.raytheon.com/capabilities/rtnwcm/groups/ids/documents/image/rtn_241433.jpg

Fig. 17. Space Fence Radar

<http://www.lockheedmartin.com/us/news/press-releases/2015/september/150928-mst-space-fence-program-completes-critical-design-review.html>

RELEASE STATEMENT

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