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## **Development of the Airborne Warning and Control System (AWACS) Radar**

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### **THE NEED FOR AWACS**

In the early 60's the United States Air Force (USAF) recognized the necessity for improving the detection of low-flying aircraft by an airborne platform at relatively long ranges [1]. At that time the GE APS-20 pulse radar in the EC-121 aircraft provided an airborne surveillance capability, but "was unable to see airborne targets at low altitudes over land." [2] In the previous decade a new technology had emerged - pulse Doppler radar. This radar used pulses, but also utilized the Doppler shift to distinguish moving targets from the fixed ground clutter. This technology was first used operationally in the Westinghouse DPN-53 Target Seeker of the Boeing BOMARC IM-99B Interceptor Missile. [3] Later the U.S. Navy used pulse Doppler in the Westinghouse AWG-10 Radar in the F-4J aircraft. Hughes provided the APG-63 pulse Doppler radar for the F-15 aircraft. All of these early radars were basically single target tracking radars. However, in the late 50's the Navy had started development of an airborne surveillance radar using pulse Doppler in a track-while-scan mode - the APQ-81 [4] (Figure 1). This radar showed promise in a feasibility flight demonstration. [3] The stage was set for AWACS.

In 1962 both the Tactical Air Command (TAC) and the Air Defense Command (ADC) defined new systems for airborne surveillance. These were similar in basic concept but considerably different in their specific target requirements. Because of the Continental U.S. (CONUS) defense requirements for long-range target detection and tracking of large numbers of targets, the ADC version was the more demanding. Joint meetings of Air Force Systems Command (AFSC), TAC, and ADC resulted in a compromise joint Specific Operational Requirement (SOR). In 1963 the joint TAC/ADC SOR 206 entitled "Airborne Warning and Control System (AWACS)" was issued.

Under SOR 206, the overall system integration function was to be supplied by an airframe manufacturer who would procure a radar from a radar manufacturer. Three airframe suppliers began to develop airframe and system concepts in response to the SOR. These were:

- \* The Boeing Company (707)
- \* The Douglas Aircraft Company (now McDonnell Douglas) (DC-8)
- \* The Lockheed Georgia Company (C-141)

Seven radar contractors expressed interest in providing a radar for AWACS and began to develop radar concepts. Bob Cowdery, who had worked on the APQ-81, was put in charge of the Westinghouse effort. He was the manager of subsequent AWACS-related programs well into the production phase. Bill Skillman, who had been involved in the early pulse Doppler development, was the radar system engineer. He continued that role through the subsequent AWACS-related programs well into the 80's.

The Air Force Aeronautical Systems Division (ASD) at Wright-Patterson AFB at Dayton, Ohio, collected preliminary proposals from all these companies and presented them to Headquarters AFSC and Headquarters USAF. It was decided that the Air Force Scientific Advisory Board (SAB) should be convened to determine the feasibility of an airborne radar to achieve the downlook detection and tracking performance required. All other subsystem technologies to be used in the projected AWACS system were considered as proven and off-the-shelf.

The SAB met in August 1963 and concluded that the feasibility of the radar technology had not yet been fully established. Specifically, the Board determined that the radar technology needed to obtain sufficient subclutter visibility had not yet been proven.

ASD then began to formulate the Overland Radar Technology (ORT) Program to demonstrate that sufficient subclutter visibility could be obtained. During this period the radar contractors played a major role in rapidly advancing the required technology. At Westinghouse low sidelobe antenna technology was demonstrated, and a high power transmitter appeared feasible. As a result, the Department of Defense (DoD) approved and funded the ORT program in 1964.

## **OVERLAND RADAR TECHNOLOGY (ORT) PROGRAM**

In early 1965 Airborne Instruments Laboratory (AIL) was awarded a hardware-excluded contract to survey and evaluate the radar concepts of all of the radar contractors. The Illinois Institute of Technology's Research Institute (IITRI) was selected to provide additional analysis and evaluation. These evaluations resulted in the selection of Hughes, Raytheon, and Westinghouse to demonstrate scaled versions of their concepts in EC-121 aircraft. These radars ran the gamut of waveform possibilities, since the Raytheon approach used Low PRF techniques (unambiguous in range, ambiguous in Doppler), Westinghouse used High PRF (unambiguous in Doppler, highly ambiguous in range) and Hughes took the middle ground, using Medium PRF (ambiguous in both Doppler and range)[5]. In addition, General Electric was to supply flight test data of the APS-111, a Low PRF radar being tested at that time by the Navy in the E-2A, primarily over water. The ORT radar contractors got under way with contract award in February 1966.

Each radar contractor installed its radar in an EC-121, Super Constellation, a propeller-driven aircraft (Figure 2). Although the radar contractors had originally proposed different RF operating frequencies, the Air Force obtained only one frequency band allocation at S-band, so all radars were designed to operate in this frequency band. The radar design was scaled so the

clutter would be the same amplitude as in the higher flying, higher speed jet aircraft to be used for the production version of AWACS. One major difference was the location of the antenna. At this time the leading candidate for the antenna location was in a pancake rotodome supported on pylons above the fuselage. In the EC-121 the antenna had to be installed in the existing radome flush against the aircraft's belly at the wing root. The Westinghouse antenna was designed as large as possible for this radome, the size of which was determined by an engineer crawling into the radome with a tape measure. The antenna was mounted on the existing rotary coupler (rotary joint) (Figure 3). The transmitter, receiver, and other radar and test equipment were installed in the cabin (Figure 4).

The first Westinghouse flights revealed that the sidelobe clutter was considerably larger than had been calculated from the free space antenna patterns. Theorizing that the elevation pattern was degraded by reflections from the fuselage and wing root, radar absorbent material was glued over these metal surfaces within the radome. Subsequent flights showed that the sidelobe clutter was now more in line with the predictions. Because of the austere nature of the program, a single receiver was time-shared, emulating a large number of gates in the interpulse period. This increased the dwell time so much that the antenna could not scan. As a consequence, all flights were performed with the antenna aimed at a fixed azimuth. Clutter data was recorded in flight and thresholding in the sidelobe clutter region was performed on the ground. Target detection performance was evaluated by adding a synthetic target to the recorded clutter data and thresholding the combined signal.

As a result of the ORT flights, which ended in late 1966, Raytheon was dropped from the competition since: [6]

"Data collected...indicate that 'discretos' present a real problem for a high-resolution, low-PRF radar..."

AIL also reported:

"...the basic conclusion of the ORT Scaled Radar Evaluation--the Westinghouse and Hughes radar techniques can provide useful in-clutter detection capability for AWACS."

The GE radar in the E-2A was still in the running at this time, but was not evaluated in the ORT program.

## **CONCEPT FORMULATION STUDIES**

In parallel with the ORT program, ASD awarded concept formulation studies in September 1966 to two airframe/system integration contractors (prime contractors) - Boeing and Douglas - and to four radar contractors: General Electric, Hughes, Raytheon, and Westinghouse. These studies not only established overall system and radar concept definition, but provided study, analysis, and antenna/radome tests necessary for establishing the airframe-to-radar interface definition. A rotodome configuration was chosen by Boeing and Douglas. In this configuration the antenna is fixed to the circular rotodome that is mounted above the fuselage and rotated as a unit to obtain the required 360-degree coverage. Mounting the Identification, Friend or Foe (IFF) antenna back-to-back with the radar antenna permitted use of a large antenna

to increase the IFF range to match the radar's range capability. The prime contractors each built one-seventh scale aircraft models complete with radomes (Figure 5). Hughes and Westinghouse built one-seventh scale model antennas. Testing with the antennas installed in the radomes enabled the primes to measure antenna/radome radiation patterns, aircraft blockage, and other data. Sufficient data was taken to permit preliminary calculation of the clutter environment in which each radar would operate. This data led to further refinement of the antenna and radome designs to improve the subclutter visibility in the sidelobe clutter regions. During the scale model testing it became apparent that proper radome design was crucial to the attainment of low sidelobes in the installed configuration. Radome support structures in front of the antenna caused large azimuth sidelobes. The upper surface of the radome can cause high elevation sidelobes if the reflection is not sufficiently low. Also, due to the nature of the phased array construction, high elevation beam angles caused a spurious downward lobe that could create large sidelobe clutter. All these effects were recognized and solved during this program.

Also concurrent with the ORT Program, a refinement of operational concepts and requirements was generated. This resulted in ROC-ADC/TAC-1-66 in September 1966. This provided a much more realistic statement of requirements from the user's standpoint.

These studies and tests were completed in mid-1967. AFSC then moved the AWACS System Program Office (SPO) from ASD to the Electronic Systems Division (ESD) at Hanscom AFB near Boston, Massachusetts. Analysis of the flight test data continued into 1968. At that time AIL recommended that the low PRF approaches of Raytheon and GE "should not be considered as AWACS candidates." [6]

Now with the tests complete and feasibility of the AWACS concept demonstrated, the Air Force was poised, ready to move ahead into the Contract Definition Phase of the AWACS program. All they had to do was convince DoD and Congress to send money. There was no high-level "champion" for the AWACS program. While the ducks were being lined up, Hughes and Westinghouse were put under contract to develop critical technology for AWACS: the AWACS Support Program.

## **AWACS SUPPORT PROGRAM**

Hughes and Westinghouse further developed the critical items for their proposed AWACS radars. They concentrated in the areas of antennas, transmitter tubes, signal processors, and system simulation. Westinghouse and GE developed a new high power low-noise klystron to use as the final power amplifier in the transmitter. A full-scale low-sidelobe antenna was built and demonstrated. The prime contractors performed system integration studies in parallel. This program continued at a low level until 1969 when the Air Force funded a full-scale Contract Definition Phase for the AWACS program. The Support Program continued into early 1970 and contributed essential technology to the Brassboard Program. The Air Force evaluated the Boeing and Douglas positions and awarded the AWACS prime contract to the Boeing Company of Seattle in July 1970. A "flyoff" of the competing Hughes and Westinghouse designs was funded beginning the "AWACS Radar Brassboard Flyoff." For the Air Force, the Brassboard Program

had a broader objective: to prove unequivocally that an operationally useful overland radar capability had been achieved.

## **THE BRASSBOARD PROGRAM**

Boeing, as prime contractor, established two separate engineering groups to follow the Hughes and Westinghouse radar programs. They also generated a Source Selection document that enumerated the critical radar performance and physical characteristics required. This document pointed out that the Source Selection authority was the AWACS Program Manager, and that he (with the help of a Radar Evaluation Board) would recommend to the Air Force which radar subcontractor should be selected for the Design, Development, Test, and Evaluation (DDT&E) and Production Programs. Each radar contractor received copies of this document.

The other major factors in the Radar Source Selection were the DDT&E and Production Program proposals. These were to be submitted to Boeing just before the conclusion of the Brassboard Program. The timing was such that Brassboard experience could be included by the radar subcontractors and that Boeing could judge credibility through comparison with test program performance.

Hughes and Westinghouse both built two radar systems, one for installation in a modified 707 aircraft for flight testing, and the other for testing in a radar lab at Boeing. Extensive data instrumentation was included in the flight test version. A separate data acquisition recorder was used by Boeing to collect data for competitive evaluation of the radars.

The Brassboard radars were designed, fabricated, tested, and installed in the flight test aircraft at Boeing in less than two years (Figures 6-8). This was rather incredible considering the complexity of the radar and instrumentation. During the design it became apparent that the analog Doppler filter bank using crystal filters, as used in all previous pulse Doppler radars, was unwieldy and could be replaced with a digital filter bank using the "Fast Fourier Transform" (FFT) algorithm recently rediscovered by Cooley and Tukey [7]. A prototype of this type of processor had been flown by Westinghouse in the F-15 competition in 1970. To measure the height of targets, Westinghouse selected the elevation scanning technique developed for the APQ-81. This required a bank of phase shifters to steer the beam electronically. To avoid excessive beam modulation which would increase the elevation sidelobes, the phase shifters had to be very linear. A unique rotary-field phase shifter was developed that met the linearity requirement. A high power klystron was selected as the transmitter tube.

Because of the "crash" nature of the program, most of the system debugging occurred at Boeing. To deal with the many problems that arose during the flight tests, both contractors shipped many of the engineers to Boeing so they would be available for trouble-shooting around-the-clock. Only a limited number of tests could be done on the ground, the real test came in the air. In the ground tests the radar appeared to be missing a substantial amount of sensitivity, but in the air the radar detected targets at close to predicted ranges. The sensitivity issues were promptly forgotten when the ground clutter was found to be roughly ten times the predicted magnitude.

The first order of business was to be able to work in the ten times larger clutter environment than the radar had been designed for. Adequate stability of the transmitted frequency was crucial to avoiding performance degradation due to instability sidebands on the received clutter. A crash effort resulted in a redesigned master oscillator that provided adequate stability and was installed soon after flights began.

A totally unexpected phenomenon was the appearance of a strong, slowly decaying signal in the receiver immediately following the transmitted pulse. This signal was at the carrier frequency, sometimes called  $F_0$  (F-zero) and the phenomenon was dubbed "Fo Ringing." This signal saturated the receiver for a number of range gates which reduced target detectability. In-flight observations showed a cyclic variation of the Fo Ringing with the antenna rotation, repeating twice per rotation. This pointed to the rotary coupler (rotary joint) that brought the signal from the transmitter in the cabin to the antenna in the rotodome. It was found that small errors in construction permitted energy to leak into a volume of the rotary coupler that acted as a resonant cavity, storing up energy during transmission, and reradiating into the receiver when the transmitter was turned off. Fortunately, Westinghouse had procured a backup rotary coupler of different design so a quick switch solved this problem.

With these major performance detractors out of the way, attention turned to optimizing target detection. The ORT program had demonstrated that Constant False Alarm Rate (CFAR) circuitry could provide detectability with low false alarm rates in the sidelobe clutter regions of Range-Doppler space. Thus, similar CFAR design was used in the Brassboard radar. However, it soon became apparent that a large number of false alarms were occurring at the "edges" of the clutter. The most severe edge is at the nadir, the region of the surface directly beneath the aircraft. At ranges less than the aircraft altitude there is no sidelobe clutter. As range increases beyond this, sidelobe clutter is received from a relatively large area around the nadir. The large reflectivity of most terrains near normal incidence further increases the clutter return. Thus the sidelobe clutter has a very large spike at the altitude line, then tapers off rapidly. The narrowness of this spike frequently appears as a target to the CFAR, causing an apparent target at the same range as the altitude. Simply blanking short-range targets was not a solution because the Westinghouse radar used High PRF techniques. The variable nature of these clutter detections caused "ghost" targets to appear at other ranges. These ranges were predictable, so a "patch" was put into the software to blank detections in narrow bands of ranges near the radar altitude, and the various ghost ranges, but only at the nadir clutter Doppler frequency. Thus very little useful target space was blanked.

One of the key factors in the radar evaluation was the detection range, so numerous flights took place with controlled targets to evaluate the "blip-scan" ratio, or the probability of detection as a function of range for both of the radars. This was easier said than done! Since aircraft were used as targets, the change or fluctuation of the radar cross-section with aspect angle, called amplitude scintillation, creates a randomness in the detections as the geometry changes. This effect is usually handled by obtaining sufficient data that the variation can be averaged out. However, as the flights progressed, there appeared to be strong target fluctuations that were correlated over a number of scans, leading to the suspicion that some other phenomenon was involved. To isolate the causes of the observed fluctuations, a nonfluctuating

target was created by hooking up a frequency-offset target repeater to an antenna mounted on an aircraft. Strong fluctuations were seen in this "nonfluctuating" signal. These fluctuations could only be caused by multipath interference in the atmosphere! At least one pre-ORT study had pointed out the difficulty of comparing radars due to atmospheric effects. But up to now, the effect had been neglected. No solution was possible to this problem, the performance evaluation had to recognize that the performance was affected in unpredictable ways by the atmospheric fluctuation.

A number of other changes were made on the basis of analysis of flight test results. Fortunately the signal processing computer was programmable (vs hard-wired core memory in the APQ-81) so that an average of one software patch was installed every day to fix bugs and improve performance.

Near the end of the flight test period, Westinghouse decided to freeze the configuration, fly lots of hours, and collect lots of data to show consistency in performance. The radar performed very reliably, permitting good data to be collected. Forty-nine Brassboard flights were made, and approximately 300 flight hours were logged.

Flight test results, the steadily advancing state-of-the-art, and life-cycle cost considerations converged on a proposed radar configuration for DDT&E that was responsive to the full-up AWACS requirements. In October 1972, Westinghouse was selected as winner of the radar competition and the flight system moved into the System Integration Demonstration (SID). There were six flights totaling 36 hours to demonstrate Airborne Tracking in which the radar operated with the full set of mission avionics. This was accomplished by November 1972, paving the way for the authorization of full-scale DDT&E in January 1973. Following SID, a number of flights in the Washington, D. C. area demonstrated the radar capabilities to many high-ranking Air Force personnel as well as members of Congress.

## **MORE HURDLES TO LEAP**

The decision to proceed into DDT&E was not without controversy. Some argued that there was no need for bomber defense or airborne early warning or airborne interceptor control, or even interceptors. Suggestions were made that AWACS was vulnerable and could not be defended. It was claimed that electronic countermeasures (ECM) would render the radar useless. The large number of targets in the European theatre would saturate the tracker.

As a result of all these allegations, in mid-1974 the Senate Armed Services Committee requested the Secretary of Defense to provide certification of the performance of AWACS in the jamming environment of Central Europe. The Defense Department's Research and Engineering branch convened the "AD HOC committee on AWACS ECM Resistivity" to investigate the ECM performance of the AWACS Radar. The committee was chaired by Dr. Harold Smith of the University of California's Livermore Laboratories. The Smith Committee made use of in-flight antenna pattern measurements and "ground-flooder" ECM tests, plus much other analytical data. The conclusion by the end of 1974 was that there was a solid basis for certifying the viability of

the AWACS performance in an ECM environment. As a result, the Secretary of Defense certified to Congress that the performance of AWACS in ECM was adequate to meet the projected threat.

## **TRANSITION TO PRODUCTION: DDT&E**

In DDT&E the Brassboard radar was extensively redesigned into a production configuration. This was necessary since the Brassboard was designed primarily for ease of flight testing with only secondary consideration to weight and reliability.

The hardware was completely repartitioned and relocated. The receiver and data processing equipment was repackaged and installed in the cabin (Figure 9). The transmitter was put into smaller packages and installed in the cargo hold (Figure 10). The antenna was redesigned so that the phase shifters used to scan the beam were much more accessible than in Brassboard (Figure 11). Extensive redundancy with automatic switchover using built-in test and fault isolation obtained the high level of reliability and ease of maintenance needed to provide adequate availability of the AWACS aircraft.

In early 1975, the first production buy was authorized after extensive Congressional debate. Flight testing of the production radar began at the end of 1975. The new design revealed some new problems to be solved.

One surprise was the return of Fo Ringing. The production rotary coupler was designed so that it could not produce Fo Ringing. After considerable testing and head-scratching the transmitter power amplifier tube was found to be the culprit. The cooling of this tube was "improved" in the redesign by a considerable increase in the diameter of the collector cavity. This cavity, beyond the RF path, collects the spent electrons and dissipates their energy. At its new size, this cavity had a resonance near the bottom of the radar operating band so that when operating at the lower frequencies the energy stored in this cavity leaked into and saturated the receiver just as occurred with the Brassboard rotary coupler. Subsequently, the diameter of the collector cavity was increased, moving the resonance away from the radar band, substantially reducing the Fo Ringing.

## **PRODUCTION PROGRAM**

The first production radar, now the AN/APY-1, was delivered in October 1976, 23 months after production go-ahead. The airplane (707) in which it was installed, now called the E-3A or Sentry (Figure 12), was delivered to the U.S. Air Force in March 1977, only four months behind the original program schedule. In May 1978, with six AWACS in the inventory, the Air Force declared that the AWACS program had reached Initial Operational Capability (IOC). Later radars included a Maritime Surveillance Capability (MSC) to provide detection of ships. The entire fleet was retrofitted with an improved design radome to reduce clutter and improve angle accuracy. The radar has an outstanding in-flight availability of over 95%.

## **AWACS WORLDWIDE**

The availability of the Maritime Surveillance Capability led NATO to the decision to procure an AWACS fleet, achieving IOC in 1983. The radar is designated the AN/APY-2. The NATO AWACS is the only military system owned by a group of nations. It is operated and manned by mixed crews from 13 nations. Saudi Arabia purchased a number of AWACS after a heated debate in Congress. Later, Great Britain scrapped its Nimrod radar development and purchased AWACS. France bought several also. Recently it was announced that Japan would also buy several AWACS.

AWACS has had numerous publicized deployments [8], starting with deployment to Saudi Arabia in 1979 for surveillance of the North/South Yemen conflict. Much praise was garnered for its operation in the Gulf War. Drew Middleton, military analyst for The New York Times, wrote: "They used to send in the Marines--now they send AWACS."

## **THE PIONEERS OF AWACS**

The development of AWACS began, in one sense, with the issuance of the Air Force requirements in SOR 206 in 1963. The combined efforts of many people in the Air Force at ASD, ESD, TAC, ADC, and others at Mitre, Boeing, and Westinghouse culminated in IOC in 1978. Many key individuals were instrumental in the ultimate success of the program. One of the earliest advocates for AWACS was Major Roy Mock who spearheaded the program at AFSC then as the Program Element Manager (PEM) at the Pentagon until his untimely death in 1966. Hans Peot was a key member of the ASD SPO. Hal Reece of ASC was prominent in the evaluation of technical concepts and encouragement to continue development. The Air Force Systems Program Directors all kept the program alive within the Air Force. Col. E. McRay was the first (66-68), followed by Maj. Gen. Ken Russell (68-73), then Gen. Larry Skantze (73-77).

Lloyd Shepherd, AWACS Technical staff at MITRE was a key technical advisor to the Air Force. Gus Cole, AIL, evaluated the ORT radars and later contributed much as a member of the Westinghouse team. Boeing Program Managers included Doug Graves and Mark Miller. Marv Eisenbach was Chief Engineer for Miller. Harry Dost of Boeing was responsible for the Westinghouse Brassboard team effort. Larry Norin crafted a radome that preserved the low sidelobes of the antenna.

Bob Cowdery was given the assignment to adapt the lessons learned in pulse Doppler and the APQ-81 into system applications. His efforts led to the ORT program and subsequently to the AWACS development and production. A small team of radar systems engineers assisting in this endeavor prepared endless technical reports and position papers to promote AWACS concepts. This group led by Bill Skillman was composed of John Giordano, Charlie Calhoun, Burt Stevenson, Bob Hendrix, John Lehmann and others. The Westinghouse team owes much to the leadership of Harry Smith, who managed the early development of pulse Doppler, and shared the Pioneer Award with Dave Mooney in 1984. The development of the APQ-81, led by Wayne Fegely, contributed much to the technology of AWACS. Bill Jones developed initial AWACS system concepts in response to SOR 206.

Jim Patton (Maj. AF ret.) was one of the authors of SOR 206 and later at Westinghouse contributed to our understanding of how the Air Force could use AWACS. Pete D'Anna helped with customer relations and education in the early days.

The Westinghouse team on the Brassboard program included Johnnie Pearson who headed the flight test program, Cliff Ryan who managed the hardware design and Jay Fay who coordinated the Baltimore and Seattle engineering teams. The late Lewis Heyser designed the high-power transmitter, based on his earlier APG-55 and ORT transmitters. The low-sidelobe antenna was designed by Phil Hacker and the late Dick McComas, improving on the technology demonstrated in the earlier ORT antenna. The rotary-field, ultra-linear phase shifters used to scan the beam were developed by Jerry Klein, working with Chuck Boyd at MAG. Dan Healey led the crash effort to obtain STALO stability. Tom Fell and Freeman Frugé were chief trouble-shooters in flight test. The software effort was led by Doug Lingle. Dave Mooney provided system analysis and chased the Fo ringing and other problems. Each of the unit designers took care to build in high reliability and incorporate built-in-test features.

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