Distant Early Warning Line Radars: The Quest for Automatic Signal Detection

F. Robert Naka and William W. Ward

In the early 1950s, the threat of manned bombers carrying nuclear weapons across the arctic region was of paramount concern in continental defense. The 1952 Summer Study at MIT recommended the development of an early-warning radar line across the northern reaches of Alaska and Canada, from Cape Lisburne on the northwest corner of Alaska to Cape Dyer on Baffin Island on the east coast of Canada. It was an ambitious undertaking, particularly since the radar system had not yet been developed or designed and a new detection process had yet to be invented. Among other innovations the radar net was proposed to use automatic-detection techniques to reduce drastically the heavy manpower requirements and unacceptable time delays characteristic of manual radar operations of the period. After the U.S. Air Force accepted the Summer Study recommendation in December 1952, Lincoln Laboratory was contracted to deliver ten radar sets by 30 April 1953, a period of less than five months. F. Robert Naka was assigned the task of developing the automated radar signal processing and alarm system. The article reviews the primary author's experiences with this challenging radar project. While the technical problems sound primitive in view of today's radar capabilities, they were met and solved at a pace that was easily ten times faster than today's Department of Defense developments.

In 1951 the U.S. Air Force sponsored Project Charles, a study chaired by F. Wheeler Loomis that examined the ability of the Soviet Union to attack the United States with nuclear weapons carried by manned bombers [1]. The study noted the inadequacy of the evolving air-defense network to meet this threat and urged immediate attention to the problem.

The 1952 Summer Study group, chaired by MIT's Jerrold R. Zacharias, recommended that a network of surveillance radars be deployed north of the 70th parallel from Alaska across the northern reaches of Canada to Newfoundland [2]. This system, the Distant Early Warning (DEW) Line, was proposed as a critical component of defense against manned bombers attacking across the arctic circle, by providing early detection and warning to a central point in the United States.

The Air Force needed three to six hours advanced warning of an attack so that (1) Strategic Air Command bombers could more easily be dispersed to numerous airfields or be airborne to survive an initial onslaught, (2) air-defense interceptors could be deployed to maximize the defense, (3) civil aircraft could be better diverted from the more likely target areas, and (4) civil defense measures could be more effectively implemented.

In December 1952 the recommendation was accepted by the U.S. Air Force, and Project Lincoln was contracted to deliver ten sets of these radars by 30 April 1953. The delivery date had been selected so that the radar systems could be shipped to the northern sites in Alaska during the arctic summer season. Fortunately, the formal procurement procedures of today did not exist for the project; the development and deployment of the radars followed a simple pattern that had evolved from the operations of the Radiation Laboratory of MIT during World War II—"get it done." Herbert G. Weiss was designated the radar project leader for what was then called Project Counter Change (also called Project CORRODE) [3]. Jerome Freedman was assigned the task of modifying the selected radar equipment for stability and reliability in the arctic environment and to support automated radar-signal processing and alerting operations. F. Robert Naka was assigned the task of developing the automated radar-signal processing and alarm system, which involved researching the manual detection process used by operators. The Western Electric Company, a branch of AT&T, was assigned to handle the complex support logistics for this deployment in the extreme environment of the arctic region. The initial station was at Barter Island on the northeast corner of Alaska.

The conventional manning of standard radar stations of the period was impractical for the extreme operational environment of the DEW Line sites. At the time, a line comprising standard air-defense radar stations required several hundred personnel per station, an unsatisfactory approach because of the need for an extensive and expensive logistic supply system. Each standard radar station had ten to fifteen operators who viewed the radar output on plan position indicator (PPI) displays. One set of operators detected and tracked incoming aircraft, another set tried to identify the aircraft, and a third set guided fighter aircraft to intercept the unidentified aircraft.

With the DEW Line, only the first two functions, detection and verification of attack, were necessary. A total manning of only ten personnel per station was the objective, which put special emphasis in the DEW Line project on improvements in operator functions and the use of more automated processes. Much of the early effort involved research on the human functions in radar site operations (see the appendix entitled "Humans as Radar-Signal Detectors").

The DEW Line was based on the premise that small groups of people could be deployed to remote radar sites in the far north and could work at other tasks while listening for radar targets. The use of automated detection, including the generation of audible alert signals, accomplished two goals for the project developers. First, it reduced the number of personnel required at each site. Second, it compensated for the recognized unreliable detection capabilities of humans in situations of low-probability targets.

Deployment Concept

The initial deployment concept for the northernmost DEW Line was a single line of radars across the northern land mass of North America from the western end of Alaska to the eastern end of Canada, a distance of some 2500 nmi, as shown in Figure 1. In addition, a Mid-Canada Line and a Pine Tree Line along the U.S.–Canada border were also developed (see the discussion on the Flutter radar later in this article). Standard air-defense stations, having the ability to direct interceptor aircraft, were deployed in Alaska, Canada, and the continental United States [4].

The DEW Line eventually comprised fifty-seven ground radar stations extending from Cape Lisburne in the northwest corner of Alaska to Cape Dyer on Baffin Island in Canada's east coast. It was later extended through Greenland in the east and through the Aleutian Islands in the west. The initial DEW Line became operational in 1957.

The DEW Line was a central part of an extended configuration of ground-based, ship-based, and airborne radar systems to guard the North American continent. Over the Atlantic, the Navy's Airborne Early Warning and Control (AEW&C) WV-2 aircraft barrier, a seaward extension of the DEW Line based at Argentia, Newfoundland, extended as far as the Azores from 1956 to 1965 [5].

Over the Pacific Ocean the DEW Line comprised a chain of radars running south through Alaska to the Aleutian Islands. An offshore airborne-early-warning (AEW) barrier was flown by Navy WV-2 aircraft operating from Midway Island from 1957 to 1965. These flights covered much of the territory north to-

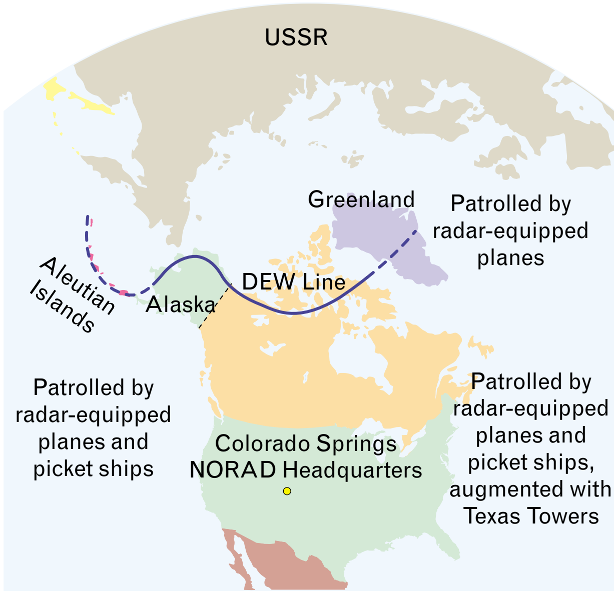

FIGURE 1. The Distant Early Warning (DEW) Line extended from Cape Lisburne on the northwest corner of Alaska to Cape Dyer on Baffin Island on Canada's east coast. It was augmented over the Pacific Ocean by an airborne-early-warning line from Alaska to Hawaii (and later to Midway Island) and over the Atlantic Ocean from Argentia, Newfoundland, to the Azores. A central communications point for the DEW Line, in Colorado Springs, Colorado, later became known as the North American Air Defense Command (NORAD).

ward the Aleutians. The remaining stretch of ocean was guarded by radar picket ships.

Air Force AEW–barrier efforts used RC-121 (later EC-121) aircraft operating from Otis Air Force Base, Massachusetts, and McClellan Air Force Base, California. They provided inshore coverage along with radars on three Texas Towers, radar picket ships, and a few Navy blimps, until the Navy went out of the lighter-than-air business in 1962.

One hundred forty-two Navy WV-2s carried the AN/APS-20, an S-band search radar lacking airborne-moving-target-indication capability (AMTI). They also carried the AN/APS-45 nodding-beam X-band height-finding radar.

The Air Force's AEW&C efforts began with essentially the same equipment. In time, the S-band search radar, carried on 73 EC-121s, was replaced by the UHF AN/APS-95, the production version of the Lincoln Laboratory–developed AN/APS-70. This replacement provided AMTI and a displaced-phase-center-antenna function (DPCA). For more information on DPCA, see the article in this issue entitled "Displaced-Phase-Center Antenna Technique," by Charles Edward Muehe and Melvin Labitt.

DEW Line Operational Requirements

The DEW Line surveillance radars were placed about every 100 nmi, depending on terrain, with gap-filler transmitter stations placed at halfway points between each pair of surveillance radars [6]. Several radar sites were designated as main stations, and the remainder were called auxiliary stations. Lateral communications connected auxiliary stations to main stations; suitable communications links (mainly tropospheric scatter technology) connected main stations to a central point in the United States that later became known as the North American Air Defense Command (NORAD), a joint U.S.–Canadian command.

The operational function of the line of radars was to detect a penetrating bomber or a raid of bombers with a certainty of at least 99.9% by the time the aircraft crossed the line of radars. The line of radars reported the location, track direction, and time of bomber detection to NORAD.

Search Radar Development

Because the demanding schedule did not allow sufficient time to design and build a completely new radar system, Freedman directed the review of several existing radars for their possible modification and application to the DEW Line. Two of the limited choices available were the S-band AN/CPS-6B and the L-band AN/TPS-1D, World War II–derivative systems that were then current. The AN/CPS-6B used a distinctive V-shaped beam pattern for simultaneously measuring range and altitude. It also had a greater range capability than the AN/TPS-1D, but it was much larger and more complex. The AN/TPS-1D, a simpler and lighter scanning and search radar, was selected because it came enclosed in a few small metal crates that were man-transportable. In addition its manufacturer, Raytheon, was near Lincoln Laboratory in the Boston area.

The Bell Telephone Laboratories independently developed and deployed a new antenna for the far-

Table 1. Operating Characteristics of the AN/TPS-1D (Mod C) Search Radar [7]

Frequency range	1220–1350 MHz
Peak power output	160 kW
Average power output	~400 W
Pulse rate	400 pulses/sec
Pulse width	6.0 μsec
Range	1000 yards to 160 nmi
Antenna radiation pattern	
Horizontal (azimuthal) (originally 3.6°)	2.8°
Vertical from 0° to 30°	cosecant^2 (elevation angle)
Receiver noise figure	11.7 dB
IF bandwidth and frequency	5 MHz at 60 MHz
Presentation types	5- and 7-in PPIs with 20-, 40-, 80-, 160-nmi range scales
Required prime power	8.5 kW
Approximate weight (uncrated)	4800 lb
Total volume (uncrated)	1000 ft^3

north installations to improve the range and altitude performance of the DEW Line search radars. This combination was designated the AN/FPS-19.

Radar System Design Parameters

The design modifications to the AN/TPS-1D involved much more than adapting radars to the extreme arctic sites. The operating characteristics, shown in Table 1, had to be modified for the specific demands of the detection problem. In particular, the radar parameters had to be carefully related to automation of the signal processing and the need for audible alerting.

Psychological testing of the ability of humans to detect audible radar signals set the time on target at 250 msec, which led to a requirement that the antenna, which had a horizontal beamwidth of about 4°, be rotated at 2 rpm for the early-warning application instead of the conventional 6 rpm for air defense. This requirement had the salutary effect of increasing the total radar-signal power integrated, and hence increasing the range performance of the radar.

On the other hand it meant that the range-gate band had to be wider to ensure that an aircraft would be illuminated at least once per scan. For an aircraft flying at a radial speed of 300 knots the band of contiguous range gates had to have a width of 2.5 nmi or 30 μsec. For the 2-μsec AN/TPS-1D pulse, that meant 15 gates per band. Signal-processing and display equipment limitations allowed only one gate per band, forcing the radar designers to accept a mismatch loss. Even with only one gate per band (six gates per radar), each radar required an extensive amount of hardware, including two eight-foot-tall relay racks of signal-detection equipment known as the Radalarm X-1, as shown in Figure 2.

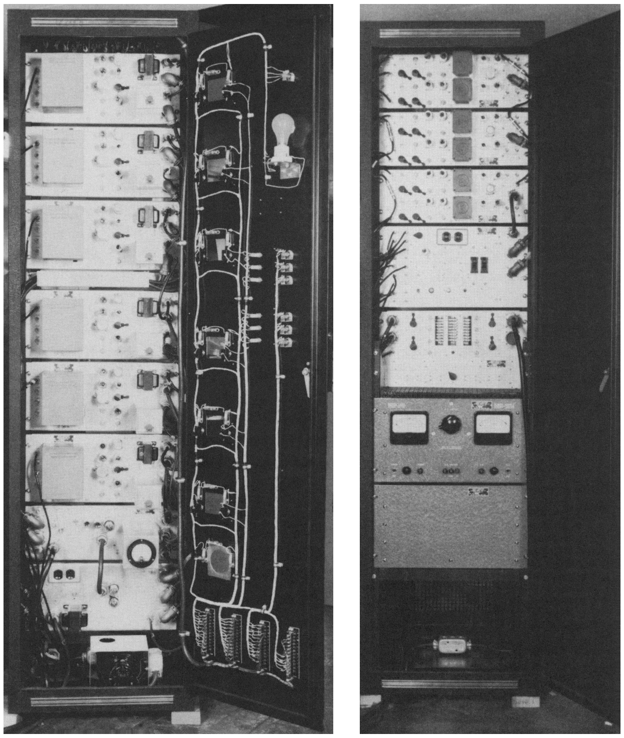

FIGURE 2. First-generation range-gate cabinet and audio-alarm cabinet for the Radalarm X-1.

There were two major electronic modifications to the basic AN/TPS-1D that reduced the effects of vibration and temperature change on its ability to perform reliably: (1) the increase of the pulse length from 2 to 6 μsec, and (2) the modification of its stable local oscillator (STALO), a crystal-controlled highly stable oscillator.

In consultation with Raytheon, Lincoln Laboratory personnel examined the operating characteristics of the microwave power source—the 5J26 magnetron. It was determined that reliable performance could be achieved with up to a 6-μsec pulse length at reduced peak power while maintaining the same average power. By retaining the same pulse transformer, this arrangement required a change only to the pulse-forming network. Nevertheless, because the pulse-forming network was enclosed in a high-voltage oil-insulated can, a replacement can had to be ordered. A simple change like this complicated the procurement of spare parts for field operations in the far north.

The stability of the STALO required considerably more effort to correct. The radar operated from a 400-Hz prime power source. As simple a device as an air-cooling fan produced levels of vibration unacceptable for stable operation, which made it necessary to replace the existing fan with a 60-Hz fan bolted to the exterior of the metal housing crate. In addition the STALO was removed from the interior of the radar housing and provided with a thermally insulated box for temperature stabilization. Further shock mounting was required to isolate the STALO from vibrations, even those from people walking near the radar. The power supply for the STALO was changed to 60 Hz and the STALO tuning motor was modified to be battery-driven when the frequency was changed.

As noted, the radar was modified to lengthen its pulse to 6 μsec for a 7-dB range gate-to-pulse-length mismatch loss. Other parameters such as the pulse-repetition rate were kept the same, although a number of equipment changes were made to provide a more rugged radar capability. Two AN/TPS-1D radars shared a common antenna to improve operational reliability by providing a functioning radar and a fully operating spare. These are shown in Figure 3.

Another important concern of the DEW Line project was appropriate protection of the radar systems from the extreme weather conditions of the arctic circle. This concern led to the development of special radomes, which are discussed in the appendix entitled "Rigid-Space-Frame Radomes."

Signal Processing, Display, and Detection

With the gates set at 30 μsec, the researchers turned their attention to developing an audible signal to alert the human operator of possible detections. A simple approach that had been tried at the MIT Radiation Laboratory [8] was to sample and hold the voltage of the signal-and-noise stream, the so-called boxcar circuit. That circuit had, however, a $(\sin x)/x$ amplitude response that favored signals in the 0-to-200-Hz region, whereas humans hear better in the 500-Hz region. It was decided therefore to employ linear amplification of the bands from 0 to 800 Hz. That approach required a filter to severely attenuate the pulse-repetition frequency and its multiples, and to also suppress the scanning modulation of approximately 5 Hz as the antenna beam swept past the target. The filter notch was made wider—approximately 20 Hz—to ensure that instabilities in the radar would

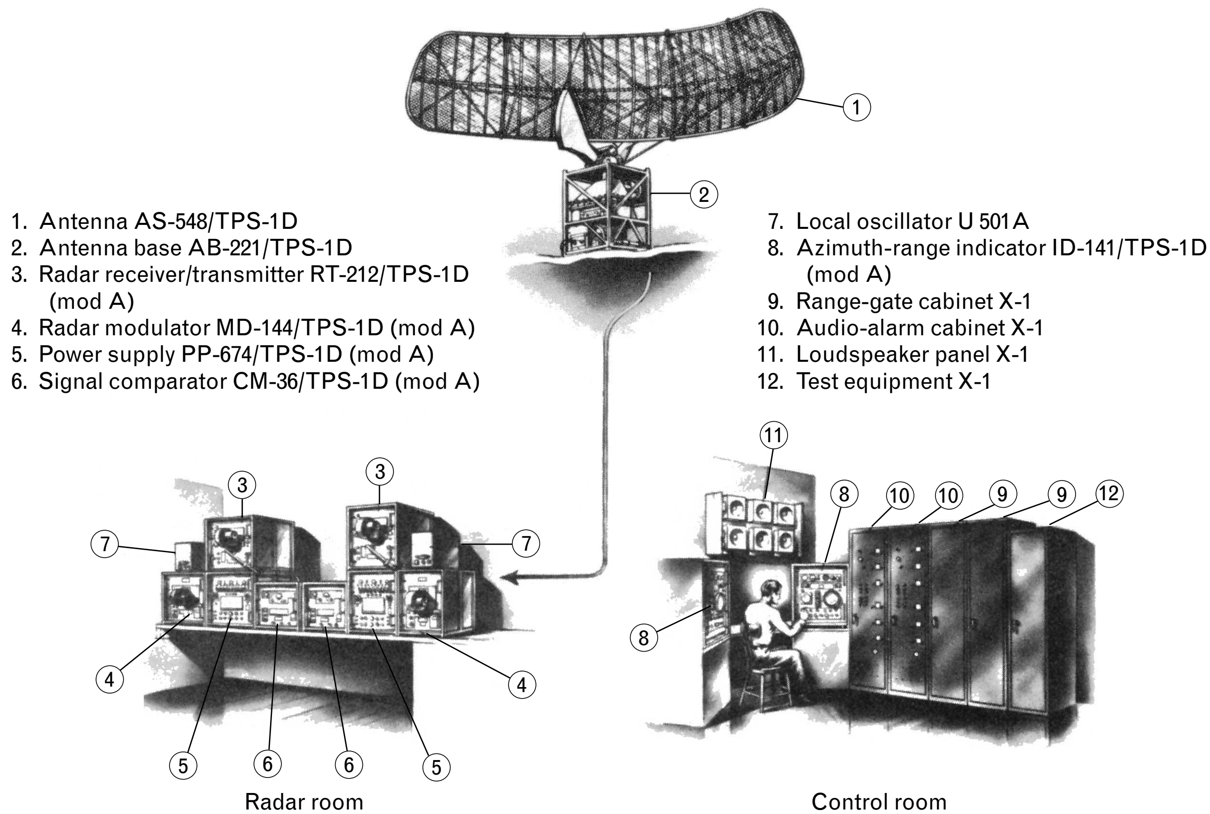

FIGURE 3. A station complement of Automatic Alerting Radar X-1 consisting of two AN/TPS-1D radars sharing a common antenna, two Radalarm X-1 equipments, and a human detector/operator.

not corrupt the display. The filter was designed and produced at the Bell Telephone Laboratories in Murray Hill, New Jersey. Figure 4 shows the filter characteristics.

Concern about the unreliability of operators on the low-probability watch, particularly when they were engaged in other tasks, led to investigations into a backup alarm circuit employing some type of automatic threshold device called a radalarm even though it might perform more poorly than a human operator.

The first few generations of radalarms relied on the commercially available Simplytrol to implement the threshold-decision function of the mechanized radar observer. A Simplytrol meter relay was placed in parallel with the output to the human operator. The Simplytrol was essentially a D'Arsonval-movement milliammeter with one or two adjustable needles in addition to the current-indicating needle. In the radalarm application the meter was driven by a current proportional to the output of the radar receiver. When that current became large enough so that the indicating needle touched the single upper-threshold needle, electrical contacts on the two needles were closed, signaling a detection. Figure 5 shows a single channel of the signal-detection equipment with the Simplytrol meter relay at the lower right.

The Simplytrol meter relay had the added value that the output noise level could be displayed and the voltage gain of the circuitry set to provide the appropriate probability of detection and false-alarm rate. A procedure for setting the noise level and threshold was devised by Naka and described in *Lincoln Laboratory Manual 1* [9]. A signal-generation test-equipment module was designed and produced to accompany the manual.

The Simplytrol meter relay has a mass, a spring (constant), and a circuit resistance. The suitability of the meter for a signal-detection device was analyzed in two steps. First, Leon Bess made a theoretical analysis of the detection of signals by such a device.

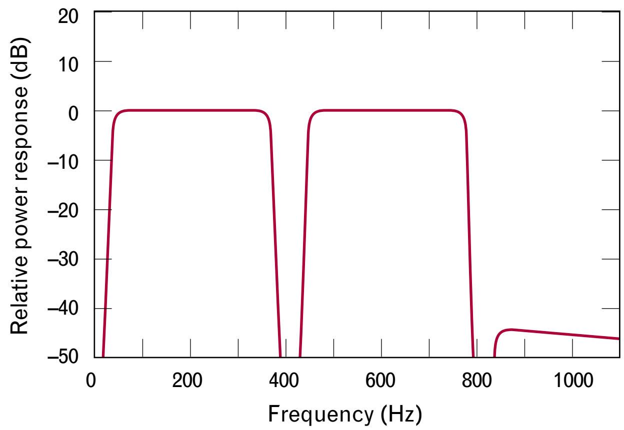

FIGURE 4. Frequency-response characteristic of toroid filter assembly for the modified AN/TPS-1D radar (Mod C). Note the bandpass between 400 and 800 Hz with the steep rejection notches for the pulse-repetition frequency of 400 Hz and the first harmonic at 800 Hz.

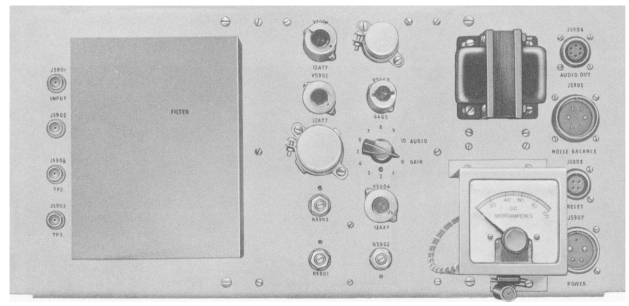

FIGURE 5. Automatic-signal-detection channel X-1 showing the filter on the left, the audio output transformer on the upper right, and the Simplytrol meter relay on the lower right. The Radalarm X-1 included six of these signal-detection channels.

Second, measurements were made of how the device responded to a step-voltage input. Bess extended the analysis of J.I. Marcum [10] and E.J. Barlow [11] to include the parameters of the detection device. This analysis showed that the circuit needed a time constant corresponding to the time-on-target of 0.25 sec; the measurements showed the meter relay to have the equivalent time constant of about 0.25 sec.

The principles described above were implemented in the design of the radalarm circuitry. A block diagram of one of six channels of Radalarm X-1 is shown in Figure 6. Bipolar video echoes from the 6-μsec transmitted pulses were fed into a 30-μsec gate whose range delay was adjustable from 0 to 120 nmi.

Bipolar video was obtained from the modified AN/TPS-1D radar, which had a superheterodyne receiver. Following the preamplifier connected to the antenna, the radar carrier frequency containing signal and noise was downshifted to the intermediate frequency (IF) of 60 MHz by mixing it with the STALO

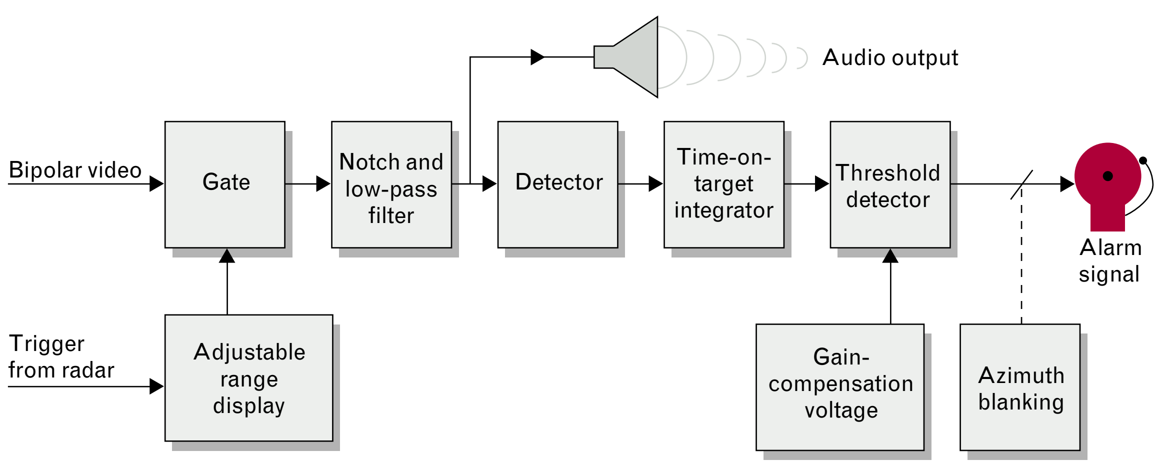

FIGURE 6. Radalarm X-1 channel block diagram. Coherent bipolar radar video containing 6-μsec echo pulses and noise is fed into a 30-μsec range gate that can be adjusted to cover any range swath. The delayed and gated video is fed into the filter whose characteristics are shown in Figure 4. The output is fed in parallel to an audio speaker for human signal detection and to an automatic-signal-detection channel. First the signal is passed through a phase detector, followed by a time-on-target signal integrator and a threshold detector. The threshold detector has video gain compensation so that the false-alarm rate can be set. A radar signal that exceeds the threshold closes a switch that rings an alarm bell. Azimuth-blanking circuitry prevents neighboring friendly radar signals from tripping the alarm.

frequency. After amplification through the IF strip the signal and noise were shifted to a zero carrier-signal base band to obtain bipolar video (as opposed to conventional unipolar video) by mixing them with the output of the coherent local oscillator (COHO) through a phase detector.

Following the gate, the video was fed into the notched low-pass filter whose characteristics were shown in Figure 4. The output was split and fed in parallel to a loudspeaker (for audible-signal detection by the human ear) and to circuitry for automatic signal detection. The time-on-target signal integrator and threshold detector were embodied in the Simplytrol meter relay. The threshold detector closed the switch on an alarm bell. The alarm bell activation could be interrupted by azimuth-blanking circuitry to eliminate interference from friendly radars or other electromagnetic emitters.

False-Alarm Rate, Signal-to-Noise Ratio, and Probability of Detection

Radar signals are detected in the presence of receiver noise. (Radar signals also compete with clutter signals from the ground, sea, rain, or aurora, but only receiver noise will be treated here.) If signal plus noise exceeds a certain threshold the signal is said to be detected. Sometimes a signal at or above the threshold is missed because of a dip in the noise level. These two conditions give rise to a probability of detection. A false alarm occurs occasionally when the noise exceeds the threshold.

The appropriate parameters to consider are the noise level, the threshold level, and the signal-to-noise ratio required to achieve a desired probability of detection. The noise-level to threshold-level ratio determines the interval between false alarms, or inversely the false-alarm rate. The radar signal-to-noise ratio must be calculated to obtain a desired probability of detection. The two references [10, 11] employed to make that calculation are described in Reference 3.

For the DEW Line radar a false-alarm rate of one false alarm per day was desired. The number of decisions per day is then the number of azimuthal positions per antenna revolution (360/3.6) times the number of gates (6) times the revolutions per minute (2) times the number of minutes per day (60×24), which equals 1,728,000 decisions per day. Naka devised a procedure for adjusting the radar receiver to receive one false alarm per day (false-alarm probability $P_{fa} \approx 6 \times 10^{-7}$) that is described in Reference 10.

The ultimate design goal is for the automated radar operator to detect with extremely high probability (>0.99) the aircraft crossing the radar's coverage. However, the radar doesn't have to achieve this high probability on every scan of the beam across a target. A probability of detection P_d of 0.9 for each scan, for example, will be acceptable. One can consult Figure 7 and learn that the signal-to-noise ratio in the radar receiver must be at least 13 dB to meet the requirements for P_d and P_{fa}. Using the well-known radar equation [12], we can determine that for a B-29 airplane (nose-on-L-band radar cross section of 14 dBsm) entering the coverage volume of an Automatic Alerting Radar X-1, the range for 90% probability of detection on a single scan is about 70 nmi.

It takes 0.25 sec for the antenna to move by one beamwidth in azimuth. During that time the radar transmits 100 pulses. Just as for a human operator watching a PPI display, the video signal that is detected from the IF signal passes to an integrator, which yields an integration of the most recent 100 received signal-plus-noise values in each range gate. That smoothed signal is monitored by the threshold-crossing detector, which makes a target/no target decision every 0.25 sec.

The threshold detector could have been an analog device such as the Simplytrol meter relay used in the Radalarm X-1. It could also have been a digital device such as the sliding-window detector described in the article "Radar Signal Processing," by Robert J. Purdy et al., in this issue. (The measured probability-of-detection performance of the automatic-detection equipment as a function of signal-to-noise ratio for various false-alarm rates is discussed in the appendix entitled "Humans as Radar-Signal Detectors.")

Flight Test of Automatic Alerting Radar X-1

Today, the calculation discussed above would be an acceptable description of the radar's performance. At the time of the DEW Line project, a flight test with an aircraft flying a controlled path was necessary to confirm the calculation. James W. Meyer led a team

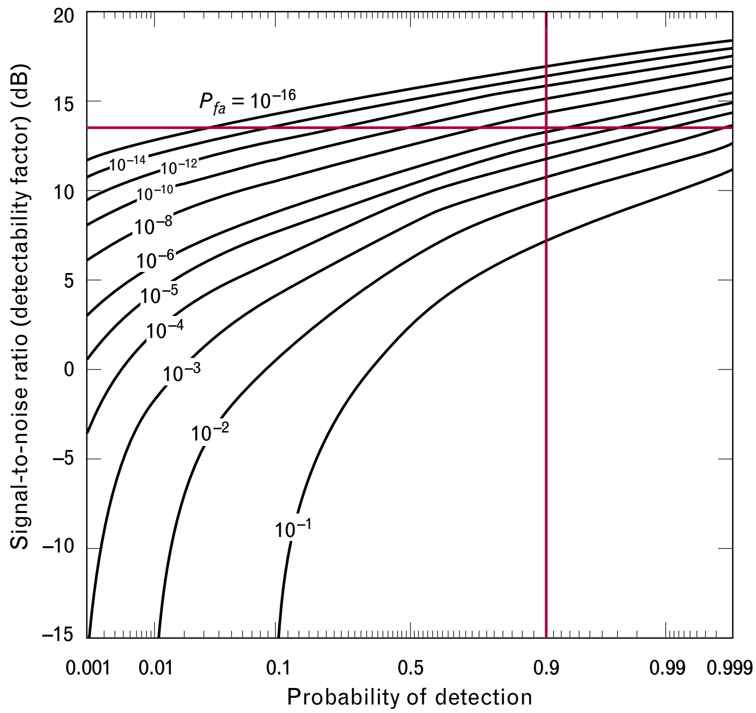

FIGURE 7. Required signal-to-noise ratio (detectability factor) for single-pulse detection. The red lines are drawn for a probability of detection of 0.9 and a probability of false alarm of 6×10^{-7}, giving a required signal-to-noise ratio of about 13 dB. Adapted from Reference 13.

that conducted flight tests for the visual PPI detection of a propeller-driven B-29 bomber as a function of altitude. The results in Figure 8 show a range performance of about 70 nmi and an altitude performance of about 35,000 ft by fitting the vertical antenna pattern to the data. For radar sites separated by 100 nmi this coverage is uncomfortably marginal, particularly when we consider the lower radar cross section of the B-47 jet bomber. The coverage is improved somewhat by antenna-pattern lobing over smooth or reflecting terrain, as shown in Figure 9(a), but that is achieved by sacrificing low-altitude coverage at the midpoint between radar sites.

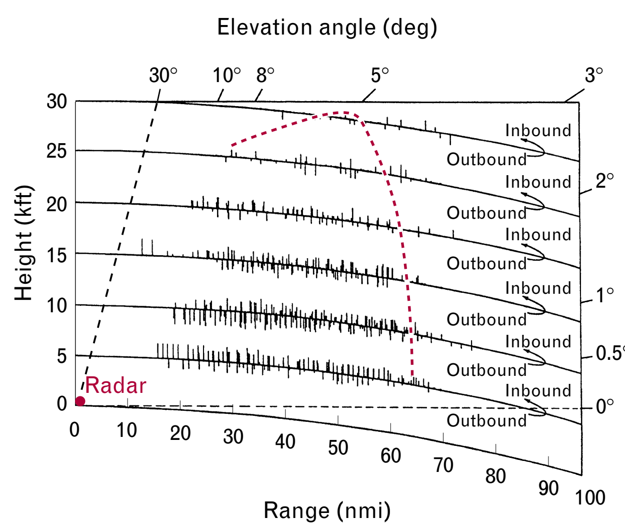

FIGURE 8. Measured coverage diagram of modified AN/TPS-1D radar. Bars above the altitude lines show inbound B-29 bomber detections; bars below show outbound detections. Three different bar heights denote strong, medium, and weak signal strengths. The antenna pattern (red dashed curve) has been overlaid for an approximate fit. The radio horizon is equal to 4/3 the radius of the earth.

Concept of Operations

The concept of operations for air-defense radars was to have one false alarm each time the antenna rotated (at 6 rpm), or to have one false alarm every ten seconds. Subsequent antenna scans determined whether the detection was a false alarm or a target. The probability of detecting a real target for a single radar scan

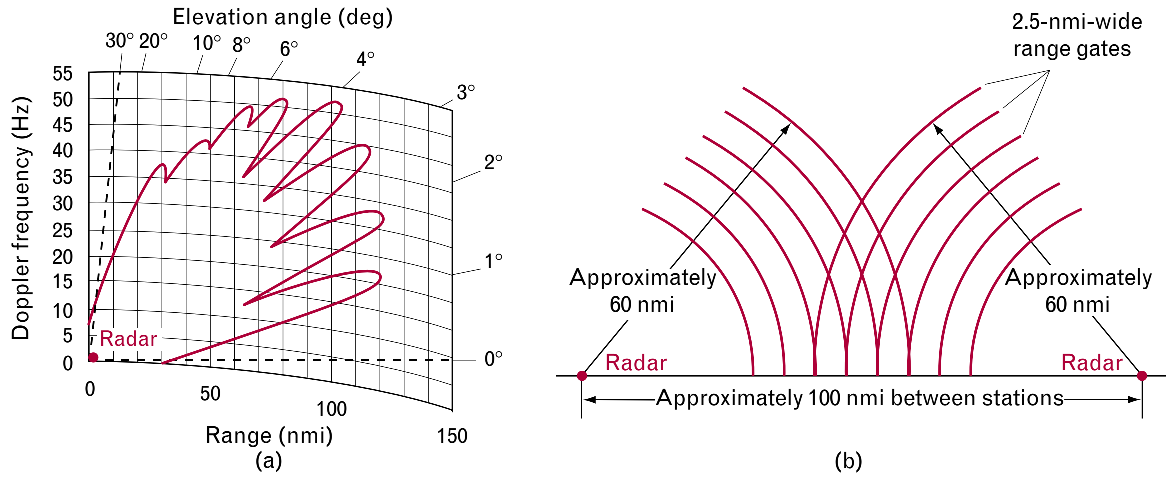

FIGURE 9. (a) Coverage of Automatic Alerting Radar X-1 over smooth terrain, showing antenna-pattern lobing from specular reflections of electromagnetic energy for 90% detection of B-29 aircraft. The radio horizon is equal to 4/3 the radius of the earth. (b) The horizontal coverage showing the six 2.5-nmi range gates set arbitrarily out to a range of 60 nmi from two radars separated by 100 nmi.

was expected to be 90%. The establishment of an aircraft track from a series of radar scans raised the probability of detecting a real target to 99% or better.

Performance of the Total Deployed System

The range gates were set approximately, as shown in Figure 9(b), depending on the terrain. Over rough terrain the vertical coverage was that shown in Figure 8. Over smooth terrain specular reflection of the radar energy occurred, producing the lobing pattern shown in Figure 9(a), with the first lobe having a detection range of 120 nmi or twice that occurring over rough terrain. The farthest gate was set at 60 nmi, inside the 70-nmi performance of the radar system, to account for the vertical antenna-pattern coverage. The cumulative probability of detection was the ultimate index of the radar system's ability to detect penetrating aircraft before reaching the line between radar sites. The completion of the flight tests permitted this calculation.

In the summer of 1953, two of the ten systems produced by Lincoln Laboratory were shipped to domestic sites near Streator, Illinois, where the total system could be checked out and the crews trained. One concern during this time was whether the radar crews could tune the radar COHO correctly to feed target bipolar video to the radalarm circuitry—a delicate adjustment that allowed the COHO to produce a video signal "butterfly" needed to detect a target. That the crews were trainable was proven by a successful test flight discussed later in this article.

Mistakes that occurred during training ultimately led to positive outcomes. For example, although site personnel were instructed to connect the radar to a prime source of stable power, they gave priority to the communications system and instead connected the radar to the source that ran the heating and ventilating compressors. Consequently, starting up compressors triggered many false alarms, and the crews reported that the radars were not working. In the far north, the same problem did not occur because the connections were made properly.

Figure 10 shows a calculation of the performance of the domestic DEW Line made by Naka and verified by limited flight tests. For example, when the target aircraft is 40 miles from radar #1 and 70 miles from radar #2 the cumulative probability of detection, using data from both radars, is in excess of 99%.

Low-Altitude Bistatic-Fence Radar Development—The Flutter Radar

The DEW Line radars were spaced about 100 nmi apart. With a range performance of 70 nmi over nonreflecting terrain there was a low-altitude gap halfway between stations of about 2000 ft below which an aircraft could fly undetected. Over reflecting terrain the

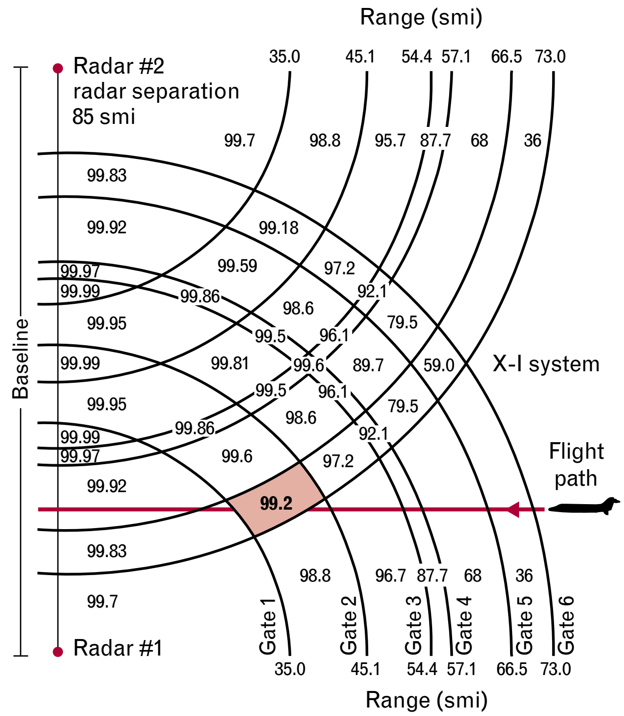

FIGURE 10. Cumulative probabilities of detecting a B-29 aircraft crossing the baseline between the domestic radar sites near Streator, Illinois. The shaded area indicates that when the target aircraft is 40 statute miles (smi) from radar #1 and 70 smi from radar #2, the cumulative probability of detection from both radars exceeds 99%.

gap extended to about 4000 ft. The Canadians at their National Research Council in Ottawa had been experimenting with a bistatic system for their Mid-Canada Line. In this system, the transmit and receive antenna beams were pointed toward each other to take advantage of the strong forward-scatter reflection from an aircraft crossing the line connecting the transmitting and receiving sites. However, at Lincoln Laboratory that design was felt to produce too many detections of low-flying birds flying perpendicular to the baseline. The signal-modulation frequency from birds flying between the two sites along the line connecting them would be near zero. All other bird flight paths would produce higher-modulation frequencies. The highest-modulation frequency was produced by birds flying directly toward a transmitter and receiver along the line passing through the two sites, but outside the transmitter/receiver baseline. Therefore, in plan view the antennas were offset in angle from each other relative to the baseline, as shown in Figure 11. A high-pass filter was also inserted in the signal-detection equipment to minimize detection of signals from

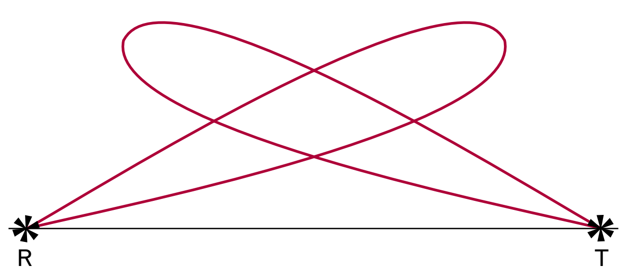

FIGURE 11. Plan view of the horizontal orientation of antenna patterns for the Flutter radar. This configuration allowed the radar to reject signals from birds but detect signals from faster-moving aircraft.

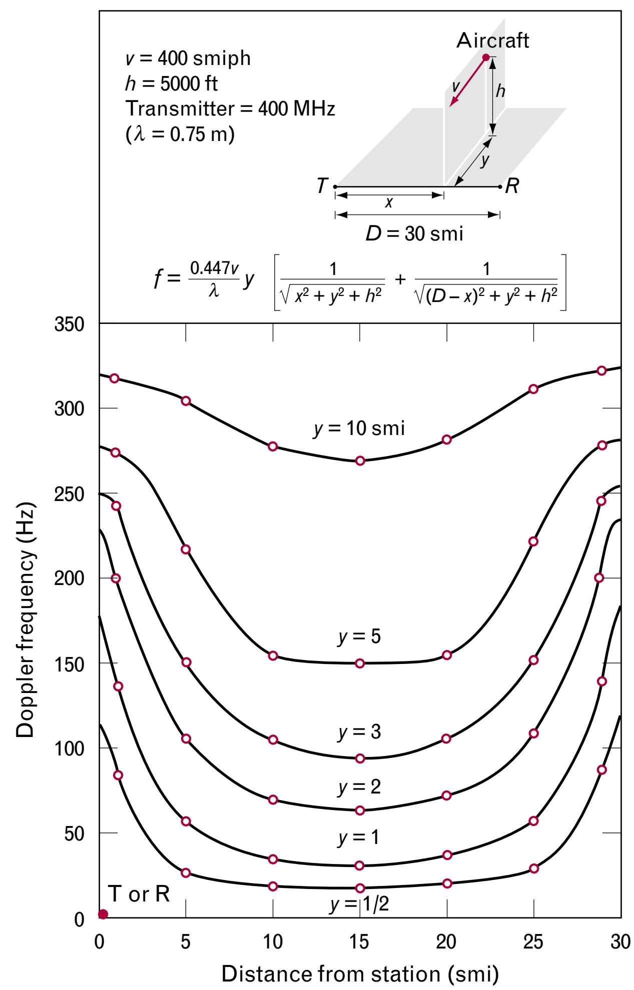

FIGURE 12. Doppler frequency versus distance from a transmitter T or receiver R station for aircraft flying perpendicular to the baseline.

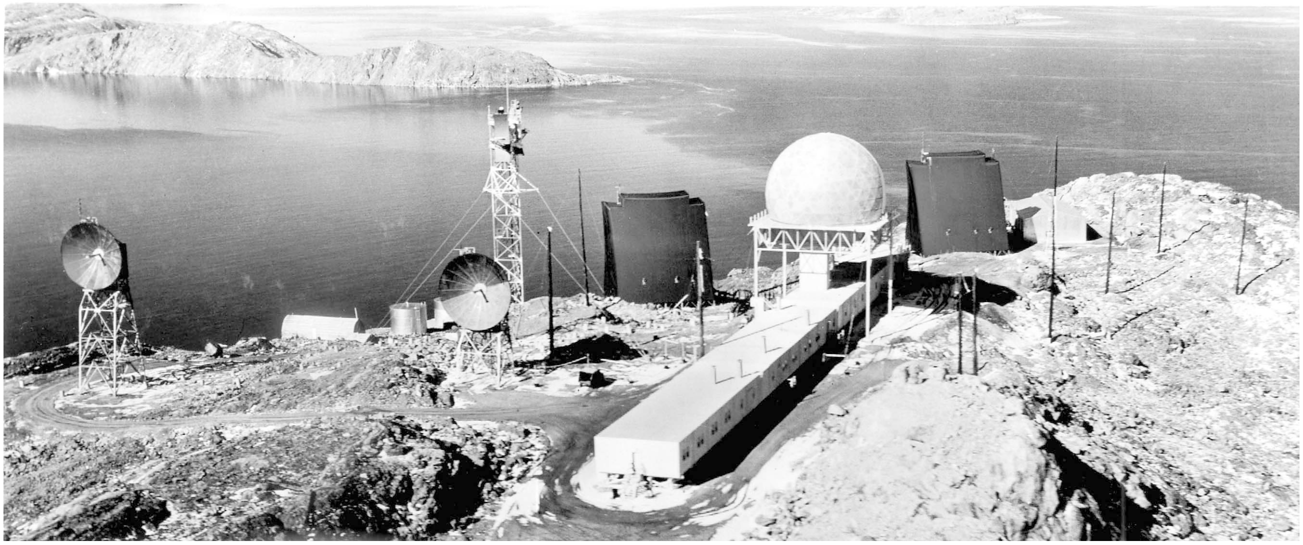

FIGURE 13. A representative DEW Line radar station at Baffin Island, Canada. The rotating antenna of the L-band AN/FPS-19 radar is housed in the 55-ft-diameter rigid-space-frame radome, which straddles the "railroad-train" array of wanigan shelters in which the station's crew lives and works. The two fixed receiving antennas of the UHF AN/FPS-23 bistatic Flutter radars are mounted on the tall tower in the middle of the picture, each aimed toward an adjacent unmanned Flutter-radar transmitting site. At left are two circular paraboloidal antennas for communication with other stations along the line. Visible at the right are two rectangular paraboloidal reflectors of an AN/FRC-47 terminal for longer-range communication. Both communication systems rely on UHF tropospheric scatter. (Image property of AT&T Archives. Reprinted with permission of AT&T.)

birds. For a transmitted frequency of 400 MHz an indication of the Doppler frequencies to be expected is shown in Figure 12. The horizontal antenna pattern was of cosecant-squared form, as specified by the principal author. The antenna was designed by Leon Ricardi and the project was run by Edwin Sloane.

A total of 60 Flutter radars, designated the AN/FPS-23, were deployed on the DEW Line with an unmanned transmitter station between each adjacent pair of manned surveillance Automatic Alerting Radar X-1 stations. Figure 13 shows an aerial view of a representative DEW Line site.

Lincoln Laboratory Contributions

Automatic Alerting Radars and Radalarms

As explained earlier a number of compromises were made in the design of Automatic Alerting Radar X-1 and the accompanying Radalarm X-1. The most serious compromise was the antenna pattern. The experimental system antenna was replaced with that from an AN/FPS-8 that gave greater range and altitude coverage. In addition, Radalarm X-3 was developed to overcome some of the shortcomings of X-1. With the automatic alarm circuitry replacing the human operator of audible signals as the primary detection agent, use of the boxcar circuit enabled the replacement of the large Bell Telephone Laboratories filters, and many more gates were added. The range gate of Radalarm X-3 was shortened to 15 μsec to reduce the gate-to-pulse-length mismatch by a factor of two. Further, to widen the detection band, three gates were set 15 μsec apart to improve their cumulative probability of detection against the B-29 and to ensure that the faster-flying B-47 would be scanned at least once. Six range-adjustable triplets were designed and housed three each to an AN/TPS-1D module; one such module is shown in Figure 14.

Radalarms X-4 and X-5 were designed for the AN/FPS-3 to improve the cumulative probability of detection of penetrating aircraft. Finally, Lincoln Laboratory developed a 600-MHz experimental radar called Sentinel that optimized all its operating parameters, listed in Table 2. The Sentinel radar is also discussed in the sidebar by Edwin L. Key in the accompanying article "Early Advances in Radar Technology

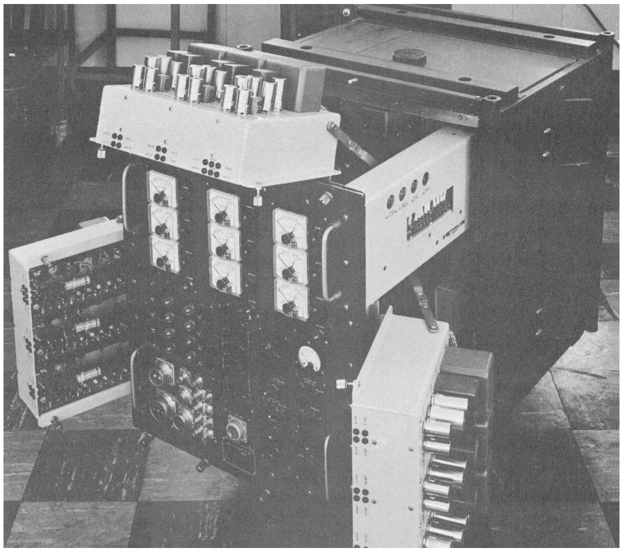

FIGURE 14. Raytheon preproduction prototype of the Radalarm X-3. It contains three detection bands, each containing three range gates. Note the many vacuum tubes with their metallic heat-conducting covers.

Table 2. Parameters of the Sentinel Radar

RF Frequency	570–630 MHz
Peak power	150 kW
Average power	3 kW
Pulse length (detection)	40 μsec
Pulse length (threat analysis)	5 μsec
Pulse compression	
Barker 13-segment code compressed to	39 μsec 3 μsec
Transmitter output tube	Klystron with 62-dB gain
Pulse-repetition frequency	500 pulses/sec
Receiver noise figure	<6.5 dB
Antenna aperture	45 ft $\times$ 25 ft

for Aircraft Detection," by Donald L. Clark. The Sentinel radar had a detection capability in excess of 250 nmi on small jet-fighter aircraft. It was a fully coherent master-oscillator/power-amplifier (MOPA) system employing a klystron power amplifier. Forty-μsec range gates covered the entire interpulse interval to assure signal detection. Key designed and installed a 13:1 pulse-compression subsystem to obtain better resolution after aircraft signal detection.

A cursory examination of the performance of the human operator on a PPI versus the automatic alarm circuitry showed they had about equivalent capability. Sometimes a blip would appear on the PPI without an automatic alarm and sometimes the automatic alarm would occur without the observed blip. Most of the time both detected the same signal.

The coverage diagram of the Sentinel radar, the AN/FPS-3, the Automatic Alerting Radar X-3, the modified X-1 with the Bell Telephone Laboratories antenna (AN/FPS-19), and the X-1 are shown in Figure 15. The Sentinel system is purposely over-designed to be able to withstand loss in range capability caused by either maintenance degradation or the necessity of compromising some of the parameters for technical or logistical reasons. The Air Force acquired the Sentinel radar, designated it the AN/FPS-30, and deployed four systems manufactured by Bendix across southern Greenland as an extension of the DEW Line.

The components developed for the Sentinel radar were used in other radar developments. For example, the klystron power amplifier was adapted for the 600-MHz Frequency-Diversity Air Defense Radar, the AN/FPS-28. For additional information about the radar see the sidebar entitled "The Air Force Frequency Diversity Radar Program" in the article "Long-Range UHF Radars for Ground Control of Airborne Interceptors," by William W. Ward and F. Robert Naka, in this issue.

Lincoln Laboratory's first radalarms worked, but they did not endear themselves to the operating crews at the DEW Line radar sites. With the bistatic AN/FPS-23 UHF Flutter radars, many false alarms were caused by birds and bush pilots flying through the radar beams. These radars were phased out after a few years. In the case of the AN/FPS-19 L-band search radars, radalarm systems were turned off, most likely because of operator problems in tuning the COHO. The advent of the AN/FPS-30 Sentinel radar with its MOPA design brought an improved capability to the DEW Line extension across southern Greenland.

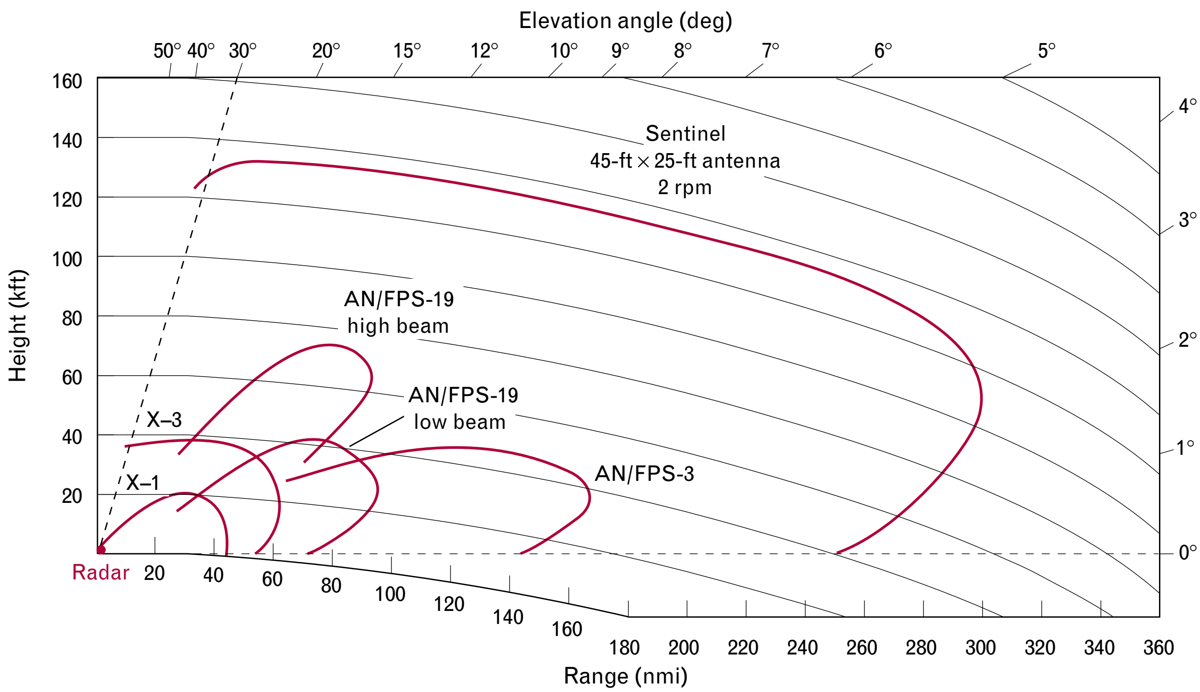

FIGURE 15. Coverage diagrams for the Sentinel, AN/FPS-19, AN/FPS-3, and Automatic Alerting Radars X-3 and X-1 on a B-47 aircraft. The radio horizon is equal to 4/3 the radius of the earth.

Signal Detection in Noise

In addition to developing the first automatic analog radar-signal detection equipment, research and development of the DEW Line radar contributed to a better understanding of the detection of signals in noise. At that time there was considerable confusion about how the human eye detected targets while viewing a PPI display. For example, at first scientists thought that the signal pulses were integrated twice, once by the PPI phosphor and again by the human eye. Psychological tests showed that integration occurred only once and that the electronic device, the human eye, and the human ear had essentially the same detection capability.

Also, the effect of the range-gate to radar-pulse-length mismatch led to an understanding of the PPI-display mismatch. The PPI, a video tube, had about 250 spots along a radius. If a PPI is set for a range from 0 to 250 nmi the pulse length of the radar must be 1 nmi or 12.3 μsec to match the spot size. The spot acts in the same manner as a range gate. Lincoln Laboratory personnel therefore advised radar air-defense operators that, when searching in areas delineated and displayed by range, it was better to have operators assigned different range areas rather than to have all PPI settings the same. If five operators were each to search a range interval of 50 nmi, thereby covering the range from 0 to 250 nmi in range segments, each of the operators should set up a different range delay on the PPI and expand his display to cover only 50 miles. This arrangement would permit the display of a radar pulse as short as 0.2 nmi without a mismatch.

Ballistic Missile Early Warning System

The ideas produced during the development of the DEW Line radars led to setting the parameters of the AN/FPS-50 Ballistic Missile Early Warning System (BMEWS) fixed-antenna search radar. The early experience led to an understanding of the interaction between the certainty of detection, the number of scans needed for a given target trajectory, the probability of detection per scan, and the false-alarm rate. By then the importance of the *PA* product (average transmitter output power *P*) × (antenna receiving aperture area *A*) had been pointed out by Edwin L. Key. Holding radar-target cross section, probability of detection, and false-alarm rate (system noise temperature) constant, then

$$R^4 \propto \frac{PA}{d\Omega/dt},$$

where R is the range and $d\Omega/dt$ is the rate at which the radar scans solid angle.

Concluding Remarks

In the early days of the Cold War and of Lincoln Laboratory a number of technically challenging initiatives were taken that proved to be very fruitful. In the nearly fifty years that have elapsed, the research and development cycle has become very systematized in the interest of delivery of a desired system on time and within cost. The authors suspect that the decision to proceed on the DEW Line radars, based on their slender promise of success, would not be permitted today. Lacking such commitment, ten sets of equipment could not have been produced and delivered in a period of only five months.

Although the Soviet Union did not attack the United States with manned bombers, the DEW Line demonstrated our resolve to defend our nation, as did the BMEWS. The DEW Line project was an outstanding early example of a small group successfully meeting a clearly specified goal on a demanding schedule.

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APPENDIX A: HUMANS AS RADAR-SIGNAL DETECTORS

RESEARCH ON RADARS FOR the Distant Early Warning (DEW) Line began in July 1951 in the Presentation group of Project Lincoln (the precursor to Lincoln Laboratory). The group, led by Joseph C.R. Licklider with Herbert G. Weiss as assistant leader, comprised an even mixture of psychologists and engineers who worked to optimize the interaction of humans and radar-signal processing devices, in particular the ability of humans to detect and track radar returns on a plan-position-indicator (PPI) display [1, 2]. The engineers in the group often served as guinea pigs in the tests conducted by the psychologists. It was an exciting time of research as new data and ideas about the human being as a radar operator emerged quickly.

Three key topics that affected the development of the DEW Line search radars are discussed: (1) human radar-signal processing and detection, (2) the effects of low-probability watch operations, and (3) detection of audible radar signals.

Human Radar-Signal Processing and Detection

In the summer of 1951 Project Charles was in session. In its report the committee chaired by F. Wheeler Loomis reviewed the international situation, in particular the ability of the Soviet Union to deliver nuclear weapons by aircraft to strike the United States [3]. The committee recommended two approaches to aircraft detection and tracking: (1) use people to establish the tracks of aircraft by studying a series of ten scan-by-scan rapidly developed photographs of a radar PPI and (2) use the Whirlwind digital computer to accomplish the same task.

The first approach, proposed by Edwin H. Land, involved an early form of the Polaroid Land Camera; the second approach represents the way we track aircraft today. In the scan-by-scan still-picture presentation an operator locating a target would not be able to note the successive times when the radar detected the target, which limited the operator's ability to smooth and project track positions. The critical man-machine interaction issue was how accurately humans could process, detect, and locate aircraft radar signals to establish tracks. A simplified method of locating aircraft was modeled by changing the PPI display. If the PPI were rotated backward so that the range strobe remained stationary, then targets emanating from the strobe appeared to move. By establishing a hairline, the operator could mark the time of the targets' passing under the hairline by pressing buttons.

Two experiments testing this approach were run by F. Robert Naka (electrical engineer) and Barbara B. Welles with assistance from William Carpenter [4]. In the first experiment a ten-element keyboard for range was in front of a display with dots representing radar targets flowing toward the keyboard and under a hairline. The job of the operator was to press the appropriate key when the dot crossed under the hairline representing time, and hence determine the azimuth of the target. The results showed an error distribution so broad that a more fundamental test was run in which a single dot crossed under a hairline and the operator pushed a hand-held button on the end of electrical wires. Note that in this case the operator could anticipate the time of the crossing so that it was reasonable to expect the operator's timing of the crossing to be a best estimate.

Figure A shows the results as reported in Reference 4. The standard deviation was calculated to be 250 msec, a surprisingly large value. Lincoln Laboratory employee William J. McGill, a psychologist who later became president of Columbia University, pointed out that a similar error was noted by astronomers working for colleagues of Kepler in the timing of zenith crossing of the planets. Of course, at that time the students employed for these measurements were thought to be incompetent. In the context of radar detection, a timing-estimation error of 250 msec at a range of 200 nmi and a typical strobe (antenna) rotation speed of 6 rpm would produce an azimuthal position error as large as 31 nmi.

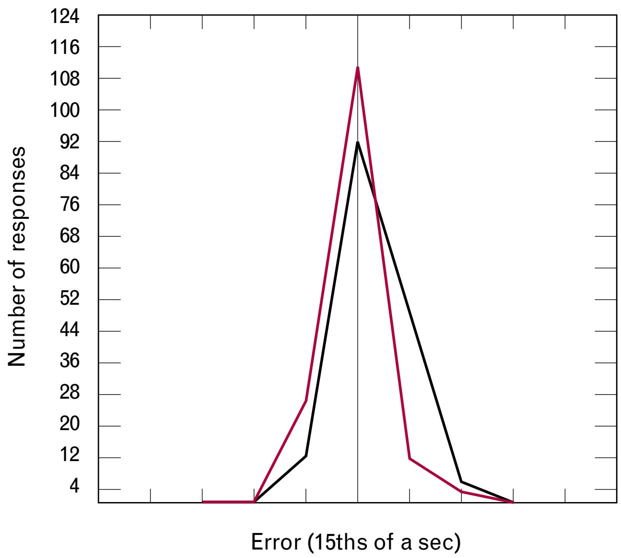

FIGURE A. Response of human eye-hand coordination from two different test personnel.

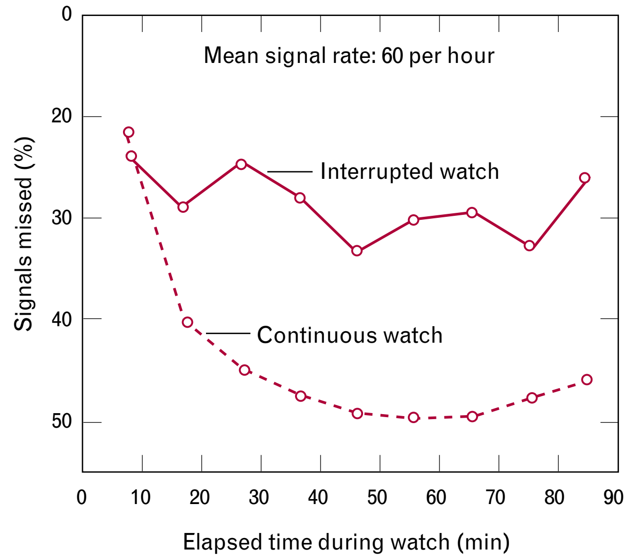

FIGURE B. Effect of frequent brief interruptions on test personnel on signal detection in a ninety-minute watch.

Low-Probability Watch

The problem of inaccurate estimates by human observers was compounded by the difficulties of maintaining observation of displays to detect low-probability events. Radar operators at the operational air-defense site at North Truro, Massachusetts, missed many radar target signals on the PPI. Psychologists observing radar PPI operators noted that in a darkened operational room the most likely cause of missed signals was that the operators had fallen asleep twenty minutes into the watch, although no operators would admit to dozing off.

A simple test confirmed this hypothesis. A voltmeter served as the display for an operator; the pointer/needle of the voltmeter had only two possible positions. When the pointer read zero the operator did nothing and when the pointer read midrange the operator pushed a button. A small darkened room, approximating the radar display room, was used for the test. The average rate of signal appearance was set at 60 per hour. The results in Figure B show that 40% of the signals were missed after 20 minutes. A further test both determined whether the operator had fallen asleep and served to interrupt the watch: the operator was required to push another button to indicate acknowledgment of a small light that lit intermittently.

Detection of Audible Radar Signals

In the spring of 1952 engineering attention turned to audible tones produced by propeller modulation of radar signals by bombers such as the B-29. This possibility had been investigated at the MIT Radiation Laboratory [5]. At Lincoln Laboratory an AN/TPS-1D L-band radar was employed to investigate the detectability of such signals. A variable-position range gate of about 6 μsec was set up to track the 2-μsec radar pulse in order to eliminate the noise from the total interpulse interval. The range gate did not optimize signal detection of the 2-μsec pulse, but was set longer to ease signal tracking.

When the Summer Study group began meeting, audible propeller-modulated signals from random aircraft were piped to the group to illustrate the technique. When an aircraft was tracked the audible signal was a low drone. If the signal was arranged as a radar-signal-detection technique the detected aircraft sounded more like a burp. Although audible-signal detection and discrimination was widely employed by sonar operators, the technique had not been extended to operational radars.

The B-29 was slowly being replaced by the jet bomber B-47. Because it was believed that the USSR would soon have jet aircraft capability, investigations were also conducted into obtaining audible signals from the Doppler modulation of the radar signals caused by the radial motion of the target aircraft and perhaps by the rotation of the turbine blades themselves. There was even the possibility that this audio technique might enable radar operators to identify aircraft by type. To exploit this phenomenon it would be necessary to employ a coherent radar that would remain stable without the need for frequent tuning. The development of stable coherent radars is discussed in the main text of this article.

Prior to and during the development of Automatic Alerting Radar X-1, psychological tests were conducted. The radar system was designed to follow three principles: (1) the listener is most sensitive to a signal masked by noise in a region near 500 Hz, (2) only noise in a frequency band near the signal masks the signal, and (3) signals should be at least one-quarter second in duration for the maximum detectability.

Comparison of Signal-Detection Methods (Psychological Tests)

After the design of the analog automatic-detection equipment a more quantitative measure became possible so that visual- and auditory-signal detection were measured against the electronic capability. Figure C shows a bar chart of automatic-alarm signal detection versus relative PPI visual-signal detection; Figure D shows human audible-signal detection versus relative PPI visual-signal detection. The number of samples is displayed in each bar and the relative PPI visual-signal intensity scale is arbitrarily estimated by the human operator. Although a large number of samples would be necessary to compare the three signal-detection methods, the data show that these methods are roughly comparable.

Because the preceding tests did not measure false-alarm rate and probability of signal detection at the same time, a test comparing audible-signal detection and the automatic-detection equipment was conducted for different false-alarm rates shown in Figure E. A false-alarm rate of two per hour was selected both for the human operator and the automatic detection equipment. For the latter method, this rate occurred when the threshold was set at 35 for the given level of noise. The curves show the detection

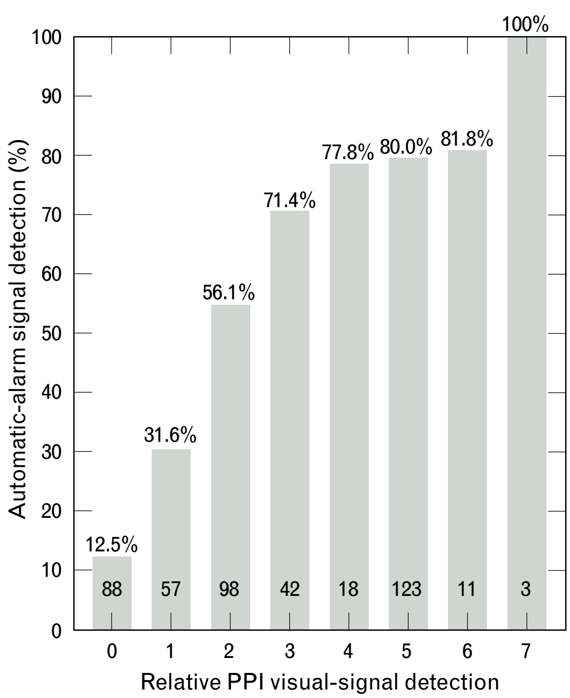

FIGURE C. Comparison of automatic-alarm detection versus relative PPI visual detection of radar signals. The signal strengths range from 0 (no observation) to 7 (PPI saturated). The number of samples is displayed in each bar.

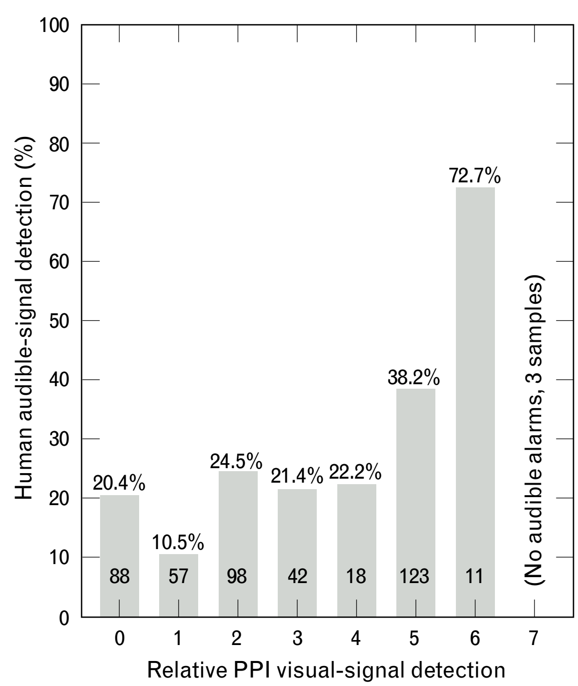

FIGURE D. Human audible-signal detection versus relative PPI visual detection of radar signals. The signal strengths range from 0 (no observation) to 7 (PPI saturated). The number of samples is displayed in each bar.

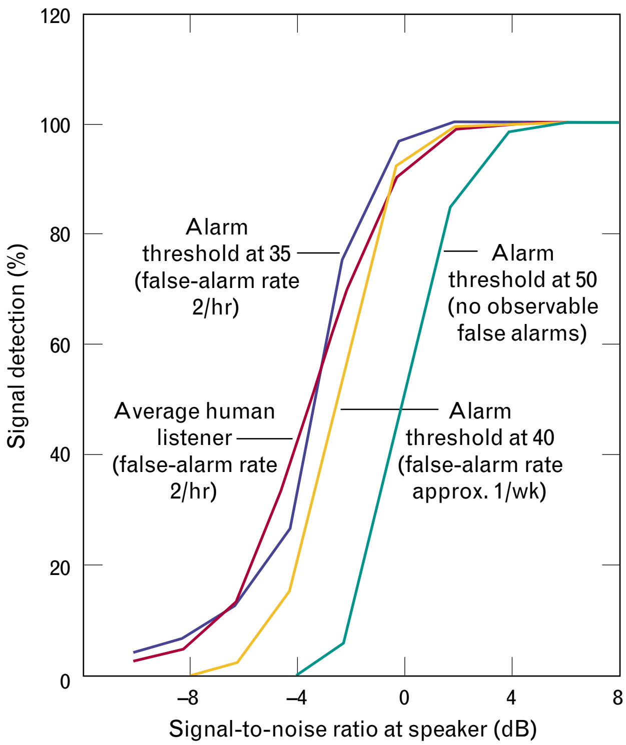

FIGURE E. Comparison of probability of radar signal detection for aural and automatic electronic detection of radar signals versus signal-to-noise ratio.

capabilities to be about equal for each method. In addition, equipment was tested over long periods of time to measure false-alarm rate and signal-detection capability. These curves follow those expected from the theory of radar signal detection

When the Sentinel radar development was completed, a cursory test of automatic alarm signal detection versus relative PPI visual-signal detection was conducted during a flight test of the Sentinel radar. Here the pulse length of 40 μsec was so long that the PPI spot size was smaller and no mismatch occurred. The two signal-detection methods were essentially equal in performance with some signals missed by the PPI and others missed by the equipment. Most of the time, both methods detected the signal.

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APPENDIX B: RIGID-SPACE-FRAME RADOMES

THE ROTATING ANTENNAS OF the DEW Line search radars needed protection from the high winds, ice, and extreme temperatures of the arctic environment to operate continuously as planned. Inflatable radar domes (radomes) made of thin, flexible materials had already been developed for use at temperate sites, but such shelters would not meet the needs of the DEW Line.

Inflatable radomes have several disadvantages. Essentially balloons, they must be maintained at an internal air pressure that is higher than the ambient pressure at the site, requiring reliable pressurization equipment. They can be entered only through air locks, and they deflect substantially in high-wind conditions. Furthermore, their surface coverings have relatively limited service lives.

Lincoln Laboratory solved the problem of sheltering rotating DEW Line radar antennas by developing a family of rigid-space-frame radomes that are essentially transparent at the radar frequencies of interest. This kind of shelter continues to be manufactured and used today.

Late in 1952 engineers from the Engineering Design and Technical Service division began discussions with R. Buckminster Fuller and Associates for the design and fabrication of two radomes based on his geodesic-dome concept. Fuller had already applied his philosophy and science, energetic geometry, to the fabrication of structures that achieve great efficiency in the use of construction materials and energy. A 50-ft-equatorial-diameter dome consisting of Orlon fabric over an aluminum frame had achieved almost two orders of magnitude reduction of total weight to enclosed volume by comparison with a minimum-design conventionally framed building. (Throughout this sidebar, radome diameter refers to the equatorial diameter.)

However, Fuller's domes (built up to 90 ft in diameter by 1952) were not designed to shelter radar antennas. The presence of a metal space frame around the radar antenna seemed at first to be an intolerable handicap. Lincoln Laboratory therefore contracted with Fuller and his associates (Geodesics, Inc.) for two domes constructed without metal space frames. Each dome was approximately a three-quarter-surface sphere with a 31-ft diameter. These domes were to be formed of joined polygonal panels of fiberglass-reinforced polyester resin. That material had high strength-to-weight ratio. Each panel was formed with flanges on its inner edges so that it could be bolted to its nearest neighbors.

The first of these radomes was delivered and erected atop Lincoln Laboratory's Building C in April 1954. It survived the estimated 110-mph winds of Hurricane Carol in August 1954 before being transplanted to the top of Mount Washington, New Hampshire, in October 1954, as shown in Figure A.

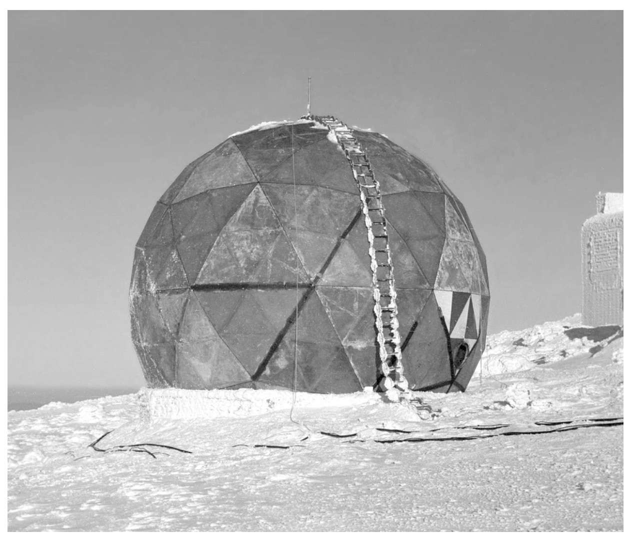


FIGURE A. Lincoln Laboratory's first 31-ft-diameter rigid-space-frame radome, used near the summit of Mount Washington, New Hampshire, for environmental testing. Most of the surface panels are equilateral triangles. Note that there is not much rime ice on the radome, compared with the nearby building. Any accumulated ice was easily removed by internal heating and dragging ropes across the radome's exterior.

FIGURE B. On 25 February 1955, the radio-frequency (RF) loss of Lincoln Laboratory's second 31-ft-diameter rigid-space-frame radome was measured directly. The surface panels are irregular hexagons and pentagons. Improvements in fabrication technique made possible a weight reduction from 3900 lb (Figure A) to 2600 lb.

FIGURE C. A 55-ft-diameter rigid-space-frame radome installed atop an arctic tower at Thule, Greenland. Note the absence of significant radome icing.

It survived the winter of 1954–55 without damage and was subsequently moved for radio frequency (RF) testing to the Air Force Field Station at Ipswich, Massachusetts, and from there to Canada.

The second of these radomes was erected piece by piece atop Building C early in 1955. As shown in Figure B, a crane with a 140-ft boom was used to lift most of this 31-ft-diameter rigid-fiberglass space-frame radome from around the antenna subsystem of an L-band (1290 MHz) AN/FPS-8 search radar. An L-band AN/FPS-3 search radar atop nearby Katahdin Hill was the source of the test signals. The difference between the signal levels received with and without the radome yielded its one-way insertion loss (or attenuation). The loss was found to be negligible (within the 0.5-dB experimental error of the measurements). The only significant change in the antenna's performance was in its far-field sidelobe levels. Some of the close-in sidelobes were increased from 33 dB below the peak of the beam to 27 dB below it by the presence of the radome, an acceptable degradation. The results of this test showed that radomes of this kind of radar could shelter DEW Line radars without compromising their functions.

Lincoln Laboratory charged ahead under the leadership of Joseph Vitale to develop a family of rigid-space-frame radomes to meet the needs of the DEW Line radars as well as those of other Air Force installations. Figure C shows the first 55-ft-diameter radome installed at Thule, Greenland, in September 1955. It replaced the inflated radome that had been sheltering the antenna assembly of the AN/FPS-3 search radar there. The rigid radome did not deflect significantly during the high winds of a phase-3 storm (winds over 100 mph). The inflated radome covering the nearby antenna system of an AN/FPS-6 height-finding radar was distorted by those winds to the point that it could not safely be operated. The 55-ft-diameter rigid radome became the standard equipment for sheltering the DEW Line search radars.

Lincoln Laboratory's research and development program on radomes was expanded to include climatological studies, alternative choices of materials and configurations, detailed structural analyses, and extensive RF and mechanical testing of components

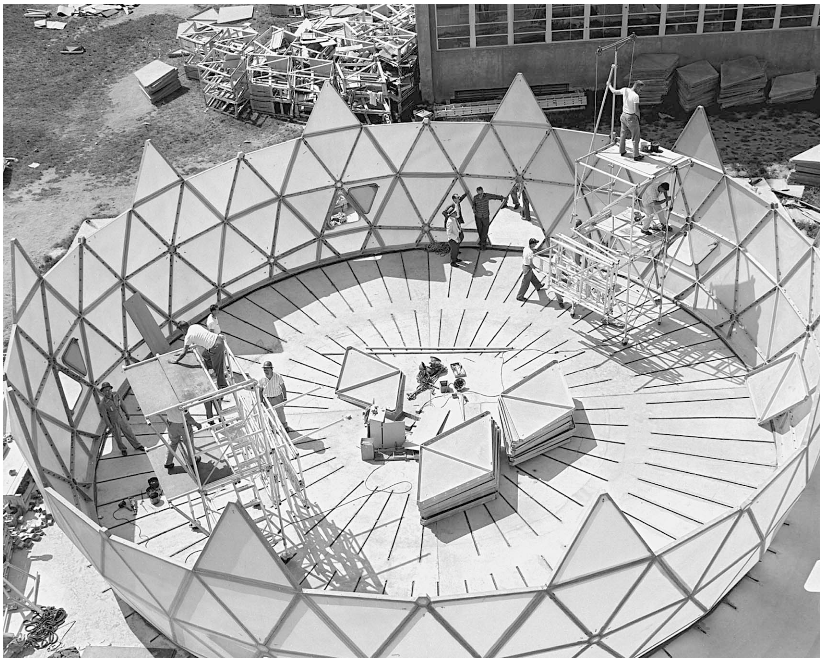


FIGURE D. A 55-ft-diameter radome being erected on the test pad between the easterly ends of Buildings B and D at Lincoln Laboratory. After the radome is complete, it can be loaded mechanically to simulate, for example, the effects of wind.

and subassemblies. Figure D shows the concrete pad to which complete radomes were bolted for mechanical qualification testing, which can be seen to this day between the easterly ends of Buildings B and D at Lincoln Laboratory.

Emboldened by the success of the 55-ft-diameter radomes, the Laboratory set out to design even bigger radomes that promised to be useful for sheltering large electromagnetic structures such as heavy-communication-terminal antennas and the antennas of the AN/FPS-49 Ballistic Missile Early Warning System (BMEWS) tracking radars. The Laboratory's first rigid radomes had achieved mechanical success by forming the space frame from the flanges of the panels themselves. It seemed timely to revisit Fuller's original conception of a metal space frame (for strength) covered by a suitable surface membrane. Tests were run with a scale-model radome and antenna, shown in Figure E. The results of these tests showed that practically all of the electromagnetic energy can be transmitted through the metallic screen if the size of the openings in it are at least of the order of a few wavelengths of the radiation concerned. If the openings are many wavelengths in dimension and if there is a marked degree of irregularity to the pattern of the mesh, the sidelobes of the antenna are not degraded to an intolerable extent.

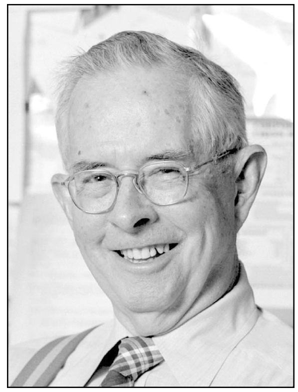
FIGURE E. Scale-model radome structure and antenna system under test to determine the far-field electromagnetic effects of having many metallic structural members in the near field of the antenna.

FIGURE F. The 150-ft-diameter rigid metal space-frame radome at Haystack Hill, Tyngsboro, Massachusetts.

Figure F shows the fruit of those investigations—the 150-ft-diameter rigid metal space-frame radome at Haystack Hill, Tyngsboro, Massachusetts. After the completion of the radome and the construction within it of a versatile 120-ft-diameter precision-surface steerable paraboloidal antenna, this facility swiftly became a radar and radio-astronomy observatory of major scientific and technological importance. The Haystack facility initially operated at X-band and subsequently supported research efforts at higher frequency bands. The surface covering of the radome has since been replaced because of weathering and to improve RF performance (lower transmission loss at higher frequencies, for example). The basic frame of the radome continues to serve well.

The completion of the Haystack radome was the culmination of Lincoln Laboratory's work in this field. By that time the new technologies had been transferred to industry. As is often the case, some of the people who worked on the radome project decided to make use of what they had learned while at Lincoln Laboratory. The Electronic Space Structures Company (ESSCO) of West Concord, Massachusetts, is a case in point. Under the leadership of Albert Cohen (a former staff member of the Engineering Design and Technical Services division), ESSCO has built, installed, and maintained many rigid-space-frame radomes throughout the world. For more information on the research results that have been produced by the equipment installed within the Haystack radome, see the article entitled "Radars for the Detection and Tracking of Ballistic Missiles, Satellites, and Planets," by Melvin L. Stone and Gerald P. Banner, in this issue.

F. ROBERT NAKA
joined Project Lincoln in June 1951 after completing his Doctor of Science degree (electron optics) at Harvard University. In 1954 Dr. Naka became associate leader of the Special Radars group. In 1956 he became the leader of the Heavy Radars group, where he led the development of the Boston Hill radar and was a member of the Air Force's Frequency Diversity Advisory group. In 1959 Bob joined the MITRE Corporation, which had been established a year earlier to head the Radar Systems and Techniques department. Subsequently, he became associate technical director, then technical director of MITRE's Applied Science Laboratories. In 1969 Bob became chief scientist of the MITRE Corporation. That same year, he reported to the Pentagon to become deputy director of the National Reconnaissance Office. In 1972 he joined Raytheon to be director of Detection and Instrumentation Systems, and in 1975 returned to the Pentagon to become Air Force chief scientist. In 1978 he joined Science Applications, Inc. as corporate vice president, and in 1982 he joined GTE Government Systems Corporation as vice president, Engineering and Planning, from which he retired in 1988. He now runs a small business, CERA, Inc., specializing in electromagnetic technology, as its president. He is a registered professional engineer in Massachusetts. Bob's honors include Member of the National Academy of Engineering, Fellow of the Explorers Club, and member of the honorary societies Sigma Xi, Tau Beta Pi, and the Druids (Omicron Delta Kappa) of the University of Missouri. He has received the U.S. Air Force's Exceptional Service Award four times. The University of Missouri bestowed an Honor Award for Engineering and the Faculty Alumni Award.



WILLIAM W. WARD
was born in Texas in 1924. During World War II he served in the U.S. Army Signal Corps, where he installed, operated, maintained, and repaired cryptographic equipment in the Pacific Theater of Operations. He received a B.S. degree from Texas A&M College, and M.S. and Ph.D. degrees from California Institute of Technology, all in electrical engineering. In 1952, he joined Lincoln Laboratory, where his first thirteen years were devoted to radar system engineering, including airborne-early-warning and ground-based surveillance radars, and space tracking and range instrumentation for NASA's Project Mercury and for ballistic missile testing. In 1965 he switched from struggling to solve problems that involve $(\text{range})^{-4}$ to working on more tractable problems involving $(\text{range})^{-2}$. That work has been in space communication, primarily in the development of systems that serve the diverse needs of the military and civil user communities by means of reliable links through satellites. He has helped to design, build, test, and operate in orbit Lincoln Experimental Satellites 5, 6, 8, 9, and two EHF Packages carried by host satellites FLTSATs 7 and 8. He has also contributed to the development of the operations centers associated with these satellites. Being blessed with a retentive memory, and having the collecting habits of a pack rat, he helped to prepare *MIT Lincoln Laboratory: Technology in the National Interest,* an illustrated history of the Laboratory published in 1995. He retired from Lincoln Laboratory in 1994 after long service as manager of satellite operations ("Keeper of Old Satellites"). He now putters around with a few old satellites that refuse to die, consults, writes, lectures, and raises vegetables in the summertime. He is a registered professional engineer in Massachusetts, a member of several professional societies, and currently a Distinguished Lecturer for the IEEE Aerospace and Electronic Systems Society.