Eighth Air Force B-17s bombing Germany, 1945.

Everett Collection/Shutterstock

THE INVENTION OF MICROWAVE RADAR

By David Hughes

The long-wavelength, ground-based radar on the East Coast of England helped save the day during the Battle of Britain in 1940, directing Spitfires and Hurricanes to German bomber formations.

At the time, the development of a lightweight radar on aircraft to find other aircraft, submarines, and targets on the ground was going nowhere. Transmitting high-frequency microwave radiation required more than 20 watts of power to see things far enough away to be useful on combat aircraft.

Then, a couple of brilliant young physicists came into the picture. The two men had never designed a radar and knew little about engineering. They didn't know how devices being used thus far to power these types of radars worked, so they sat down one afternoon and sketched out a new type of magnetron to do the job. It was one of the most important inventions of the Second World War.

There would be many uses for airborne radar, but at least two had war-winning potential.

The British knew that if they could develop an airborne radar to detect a submarine on the surface many miles ahead, it could put an end to the Nazi U-boat menace that was trying to starve their island nation into surrender. In 1940, they had little interference from ill-equipped British surface warships or anti-submarine aircraft. By 1942, when the U-boats were in their prime, they were sinking merchant ships faster than they could be built.

The story of how Britain developed a device that can fit in the palm of a hand, and how the Americans rallied to design new radars to exploit it is told in *Blind Bombing, How Microwave Radar Brought the Allies to D-Day and Victory in World War 2*, by Norman Fine. The book won a silver medal at the 2020 Independent Book Publishers Association's awards. The book brings to life the scientists, military, and political leaders who made this happen, as well as the technology they developed. Fine is an engineer, but he does not get lost in dry technical detail. He always explains why what he is writing about matters to the outcome of the war. His writing skill no doubt benefits from his role as editor and publisher of an annual engineering design guide in the 1990s.

MIT Tackles Airborne Radar Design

The story also stars the Massachusetts Institute of Technology (MIT), which played a crucial role in shaping airborne radar during the Second World War.

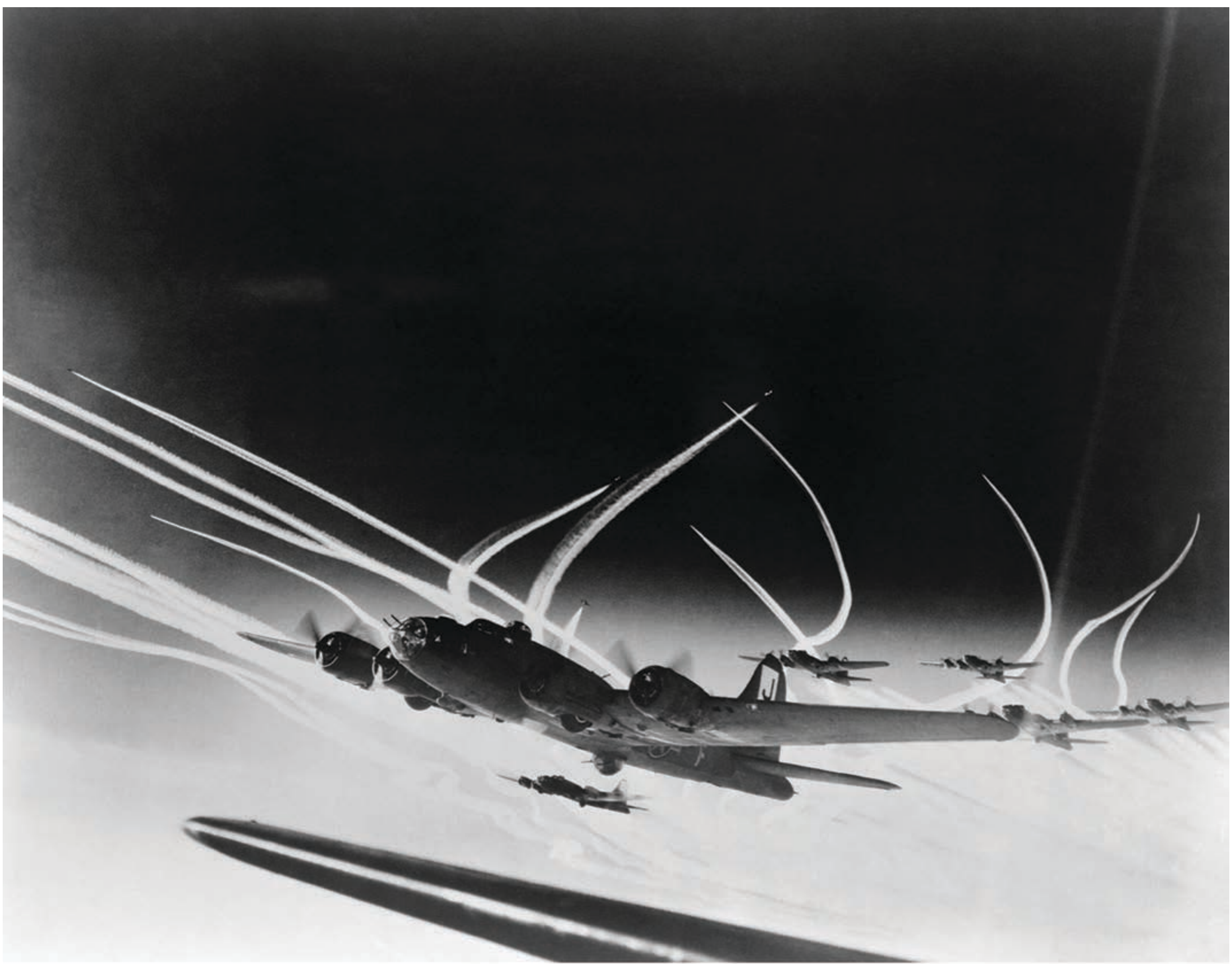
Fine grew up in Boston during the war. One day, an uncle took him to MIT's open house for children interested in science. That was the day Fine decided to become an engineer, even though he later attended Dartmouth, a liberal arts college, rather than MIT. During his freshman year at Dartmouth, a legendary English professor – who was a friend of poet Robert Frost – liked the papers Fine submitted so much that he told the teenager he should become a writer. That was the last English course Fine ever took, but he eventually combined his passion for engineering with writing.

Later in his career, Fine and an associate founded and ran a high-tech company once he became an expert in solid-state display technology. Four years out of engineering school, he helped design the RBDE-5 radar bright display equipment for the FAA while a consultant to Raytheon.

The Battle of Britain began, and in August 1940, President Franklin D. Roosevelt was in a quandary about what to do about the Nazi conquest of France, and the threat to invade England. It was 16 months before the attack on Pearl Harbor, and Roosevelt and other American leaders wondered if Britain would surrender. He sent emissaries to find out. As the British fought back against the Luftwaffe's attacks on the Royal Air Force and on London, it slowly became clear that British Prime Minister Winston Churchill was never going to quit.

America was starting to rebuild and expand its military in anticipation of being drawn into the war, and its own forces had too few tanks and airplanes for proper training. Sending the tanks and airplanes rolling off the production line to Britain in 1940 to help them avoid losing the war only made sense if the island nation was not going to be conquered by the Nazis. It began to look like that would not happen.

Meanwhile, Britain had some top-secret military systems in development, but not enough scientists, engineers, and manufacturing capability to bring them to maturity. The priority was on whatever was rolling off the production line at the moment in Britain because systems that might not be ready until 1942, couldn't help England survive in 1940 and 1941. This is when America, not yet at war with Germany, came in. In a radio talk a year before the Pearl Harbor attack, Roosevelt said America was the arsenal of democracy.



Everett Collection/Shutterstock

Fighters protecting a B-17 formation leave contrails, 1944.

At the time, the development of a lightweight radar on aircraft to find other aircraft, submarines, and targets on the ground was going nowhere.

James Steidl/Shutterstock

B-17 in clouds, illustration.

A New Powerful Transmitter for High Frequencies

The effort to design a new type of transmitting tube to power airborne radar occurred in November 1939, two months after Adolf Hitler invaded Poland to start the Second World War. John Randall, who later won a Nobel prize for helping crack the code on human DNA, and Harry Boot were physicists "unencumbered by preconceived notions," as Fine wrote. They sat down and, in a single afternoon of collaboration, "sketched out a new type of magnetron to generate microwave frequencies at never-before-seen power levels." In three months, they built a prototype in a shop. The device was no bigger than a hockey puck, even though glass tubing, vacuum pumps, and electronics surrounded the newborn resonant cavity magnetron in the lab.

"If the device worked according to their theory, clouds of electrons would be boiled off a heated source (the cathode) running down the centerline of a hole bored through the center of a solid copper cylinder (the anode)," Fine wrote. "The field from a magnet wrapped around the copper cylinder would nudge the electrons to whiz around the cathode in a circular path as they migrated toward the anode."

Electrons passed narrow slots leading to small cylindrical chambers (cavities) that would vibrate (resonate) at microwave frequencies, just as air molecules do passing a slot in a police whistle.

The researchers fired up the new type of magnetron and it got hot – a good sign. They purchased an automobile headlight and turned the magnetron on to power it, but the headlamp incinerated in a flash of smoke. They searched for larger headlamps and found the magnetron incinerated everything they connected to it. In short, it worked beyond their wildest imagination. Klystrons up to that point were creating only 20 watts of power for microwave radiation. This device generated 2,500 times more power, or 50,000 watts, at the 10-centimeter microwave wavelength.

During the spring of 1940, Britain's General Electric company produced the first dozen resonant cavity magnetrons. Their work was so secret that Taffy Bowen, one of Britain's principal radar designers, didn't learn about it until June 1940, when all 12 devices had been fabricated and tested.

Churchill Shares Weapons Secrets with America

That summer, Churchill made a momentous decision to share Britain's top-secret weapon work with the United States. He wanted American scientists, engineers, and manufacturing experts to use US government funds to help turn dreams into reality when it came to jet engines, rockets, predictors, atomic fission, the cavity magnetron, and the equipment being used to break the German Enigma machine communication code. There would be no strings attached.

On September 19, 1940, Bowen walked into a room at the Wardman Park Hotel on Connecticut Ave., in Washington, D.C., and handed American scientists the British resonant cavity magnetron No. 12. The Americans doubted the device could produce the amount

Catwalker/Shutterstock

B-17s escorted by a P-51 Mustang, stamp.

of power the British were claiming, so they took it to Bell Telephone Laboratories in Murray Hill, N.J., and fired it up. They were astonished to find it worked as advertised.

The Americans turned to a microwave radar committee chaired by an amateur scientist, Alfred Loomis, to carry the ball forward. Loomis was good at everything he did in life, including earning a living in the law and on Wall Street, where he became wealthy investing in utility stocks. He sold all his stock right before the Wall Street market crash of 1929. However, Loomis's first loves were science and math. He eventually set up a university-level laboratory in a house he owned in an exclusive suburb of New York City named Tuxedo Park. In the 1930s, MIT students spent their summers at the house working on experiments with Loomis.

The idea that he was an "amateur" scientist gives no credit to the fact that he was hanging out with the top physicists of the day, including atom bomb movers and shakers Max Planck, Neils Bohr, Enrico Fermi, and Albert Einstein. Fine wrote that Loomis had the bearing of a four-star general in civilian clothes.

The Birth of the MIT Radiation Lab

Bell Labs wanted to develop the radar sets the US needed. However, Loomis had a different idea and steered the work to MIT, which set up a cross-disciplinary organization named the Radiation Lab or "Rad Lab." The name was meant to suggest atomic energy, which would fool any spies into thinking their work wouldn't come to fruition during the Second World War. The Rad Lab was soon developing airborne radars in a matter of months, which would influence the outcome of the war.

At a meeting of the American Physical Society at MIT in 1940, attended by 900 scientists, MIT recruiters worked the hall. Bright, young physicists were needed to man the fledgling Rad Lab, and MIT recruited them by the dozens at this conference.

The physicists who joined the lab worked on radar system designs until they had hand-fabricated systems with the required combat capability. They then flew with US military aircrews to flight test and improve the systems before they were turned over to companies for manufacturing. Scientists worked on fabricating a system with a single antenna that could both transmit the microwave signal and receive the echoes.

Two months after receiving the British cavity magnetron, Bell Labs produced the first five devices made in America. By January, the first microwave radar was working on an MIT building roof and picked up echoes from the Boston skyline across the river. A month later, a US Army/Boeing B-18 bomber was turned into a flying laboratory. As work progressed, the B-18 was flown to New London, Conn., to look for submarines on the surface. It was September 1941, three months before the Pearl Harbor attack, and a year after the meeting at the Wardman Park Hotel, when an anti-ship radar observed a submarine conning tower 15 miles away.

Meanwhile, the MIT Rad Lab had grown by 300% in the previous four months to 140 people with 90 physicists and engineers. Fabulously wealthy oil man John D. Rockefeller gave MIT a gift, offering to pay everyone's salaries at the Rad Lab for the first 10 months of its existence.

Microwave Radar Finds U-Boats on the Surface

An airborne radar – which could spot a German U-boat on the surface from more than 20 miles away – sealed the fate of the German submarine war against merchant ships resupplying Britain. A 10-centimeter wavelength microwave radar could do the job of seeing such a small radar cross-section, but it took lots of development work to get one into service. As the systems were readied for deployment on a limited basis for use in combat, the scientists determined that the results would be disappointing if the equipment showed up without technical manuals and proper training for pilots, navigators, bombardiers, and mechanics.

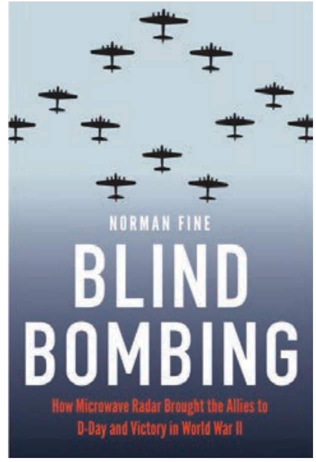
By the time Pearl Harbor was attacked, the MIT Rad Lab had an anti-submarine radar mounted in the bulbous nose of a Consolidated Aircraft B-24D Dumbo, named after the Disney character of the same name. The Pentagon showed little interest in the project.

Loomis's influence in the government was aided by the fact that he was Secretary of War Henry Stimson's cousin. He arranged for Stimson to fly on Dumbo from Washington, D.C., to see how the radar worked, and it managed to spot a ship on the water. "That's good enough for me," Stimson said.

The next day Stimson sent a note to Gen. George Marshall, the Army chief of staff, and Lt. Gen. Hap Arnold, head of US Army Air Forces. Stimson told them he had seen the new radar at work and asked, "Why haven't you?" The Army then asked for 10 Boeing B-18 bombers to be fitted with the Rad Lab's ASV-10 system. On April Fool's Day 1942, one of them found three U-boats at sea 50 miles from Boston and sunk one with depth charges.

In Britain, Squadron Leader Humphrey Leigh was frustrated by the lack of success using long wavelength airborne radar to find submarines. These radars were not as discriminating as the microwave units in development. However, it was possible at times to locate U-boats on the surface in the Bay of Biscay at night as they recharged their batteries while leaving their bases in France for the North Atlantic. In the dark, the depth charges often missed their targets. Leigh came up with the idea of putting a carbon arc searchlight on the aircraft to light up the submarines as if they were in broad daylight right before dropping depth charges on them. The combination of airborne radar and the Leigh light made it much more dangerous for U-boats on the surface at night.

By May 1943, the tide of the U-boat war had turned. Very long-range B-24s with MIT microwave radar could fly to the middle of the

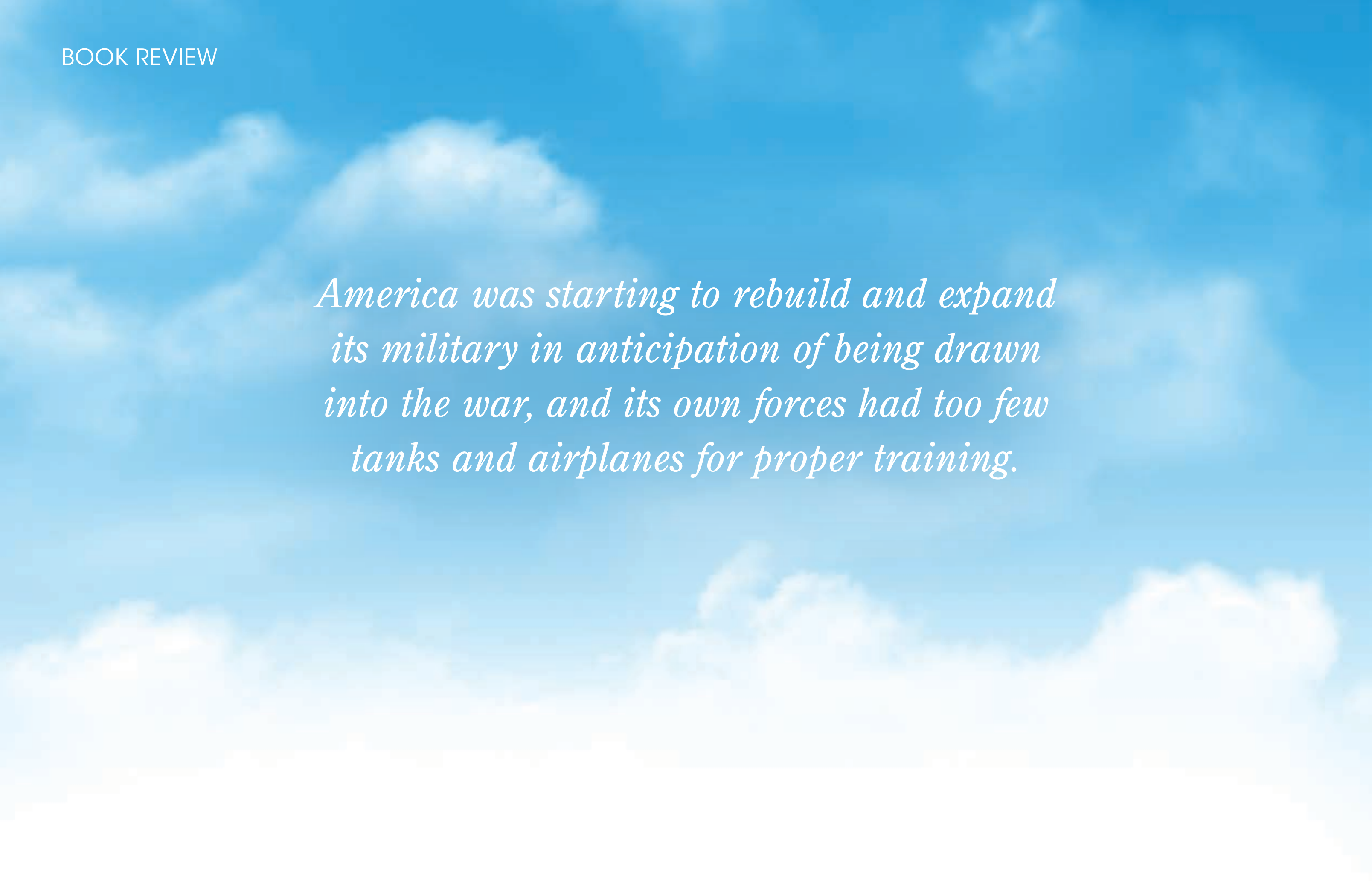


Potomac Books; Norman Fine

Blind Bombing book and author Norman Fine, whose uncle was a B-17 Mickey operator.

bomank76/123RF

A B-17 Bomber flying overhead in a Wisconsin air show in 2017.



America was starting to rebuild and expand its military in anticipation of being drawn into the war, and its own forces had too few tanks and airplanes for proper training.

North Atlantic in what was known as the Air Gap, where U-boats had been safe from air attack. From that point forward, aircraft sank a lot of U-boats. Of the 56 U-boats lost in May that year, aircraft sunk 27 or more. The new MIT microwave radar contributed to the German decision to withdraw all its remaining U-boats from the North Atlantic.

As the war continued, the Rad Lab staff grew to 4,000, including scientists, engineers, technicians, and mechanics. Half of all the radar systems developed and used by the Allies in the Second World War came out of the MIT lab. Scientists and engineers were constantly designing new microwave radar transmitters and receivers, multiplex circuits, cathode ray tube scopes, and other equipment. Of the scientists working at the MIT lab, nine would later become Nobel laureates.

Microwave Radar Sees Nazi Targets Through Clouds

Another radar system figures prominently in Fine's book, and it has a personal connection to him. When he became interested in writing about the MIT Rad Lab and microwave radar, he asked his Uncle Stanley, a B-17 veteran, if he knew anything about a microwave radar used on that bomber model. It turned out he did because Stanley had been an operator of that radar system on specially equipped B-17s, known as pathfinder aircraft in the bomb group he was assigned to in England.

The new system operated in a high-frequency microwave area known as X-Band from eight to 12 GHz, and it was designated "H2X." When the first B-17 was equipped with this system in August 1943, an Army Air Force colonel who looked at the clunky-looking radome on the bottom of the fuselage said, "That radome looks Mickey Mouse." From then on, the B-17s with this radar were called Mickey planes, and the person controlling the radar was the Mickey operator.

The new H2X radar was designed to help American bombers find targets in Germany when cloud cover was a heavy overcast. Up until that point, American bombardiers had to see the target on the ground to drop bombs using an optical Norden bombsight. If bombardiers couldn't see the target due to clouds, the mission was scrubbed.

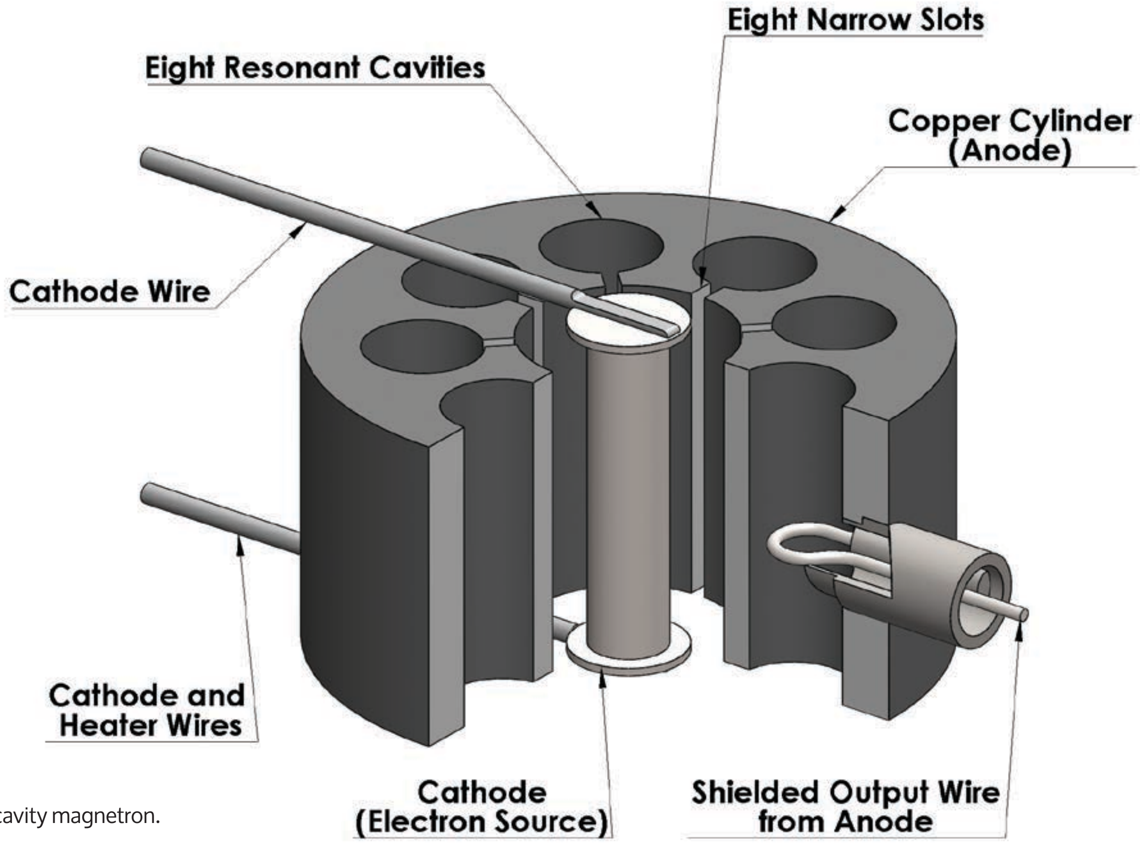
The big problem for the US Eighth Air Force in England at the time was that cloud cover was so constant over Germany they could only launch missions about seven days a month or even less in the winter. This was frustrating to the leaders of the Eighth Air Force even though they swore by the utility of the Norden bombsight for the daylight bombing they conducted when cloud cover was not a problem.

As with earlier anti-submarine radar, the H2X in development at the Rad Lab suffered from a low priority for parts and supplies due to a lack of interest from the US Army Air Corps.

When the commander of the Eighth Air Force heard about the H2X in the spring of 1943, he sent his pilot training and navigation leaders from England to MIT, where they ran into Prof. George Valley who was leading the project. They inquired as to how soon they could procure 20 radar bombsights and have them fitted in 12 B-17s.

Valley was surprised because up to then, it seemed that "nobody wanted the damn thing." Valley offered to take 20 microwave radars built for other purposes off the production line and retrofit them to the H2X configuration, which took about five months, and the program took off from there.

karandaev/123RF



Cutaway of cavity magnetron.

Potomac Books

In September 1943, the Eighth Air Force made its first radar-guided air strike on a German port city where U-boats were being assembled. Post mission analysis showed that a lot of bombs hit the target. By early 1944, B-17s with H2X led all missions so they could take over if clouds obscured the target.

Uncle Stanley Became a Mickey Operator

Fine's Uncle Stanley was one of the inexperienced Mickey operators thrown into combat on missions like this one. On his plane's first mission, he led a formation of B-17s flown by highly experienced combat aircrews. The job of the Mickey ship was to mark the target with bombs and flares so other B-17 crews could release their bombs at the right moment. The least experienced member in the entire wing of bombers was dropping bombs to signal the release point for other highly experienced crews. Fine's uncle just hoped he did not screw up – he didn't. He became one of the most trusted Mickey operators in the Eighth Air Force.

The Mickey ship always flew in the lead of a formation of B-17s which was the most vulnerable location. Luftwaffe pilots had determined that the best way to attack a B-17 formation was head on, diving on the lead bomber from 12 o'clock high. A Mickey crew had to brave this lethal threat on every mission flown.

In 1944, half of the bombs dropped by the Eighth Air Force used radar. During all of the Second World War, 61% of the bombs dropped by American B-17s were on Mickey missions, even though the H2X radar was not used until late 1943.

In the first five months of 1944, the Eighth Air Force mission was critical for the upcoming D-Day invasion of Europe. The American B-17s were out to destroy as many of the factories making Luftwaffe aircraft as possible to protect the invasion scheduled for June. By bombing nearly every day using radar with poor target visibility, the Eighth Air Force could force the Luftwaffe fighters into the air. America had just introduced the very long-range P-51 fighter, which used drop tanks to accompany B-17 formations deep into Germany. When the Luftwaffe fighters came up to attack the B-17 formations, P-51s were standing by to shoot them down. As a result, by D-Day, the Allies had achieved total air superiority over Europe, and the invasion proceeded without much interference from the air.

Fine noted that, "One year after the war ended, American historian James Phinney Baxter III, writing as the official historian of the U.S. Office of Scientific Research and Development, called the resonant cavity magnetron 'the most valuable cargo ever brought to our shores.'" Raytheon made a million of these magnetrons in partnership with MIT – 80% of the total manufactured.

In 1945, Raytheon engineer Percy Spencer noted that a chocolate bar melted in his pocket while he was working on a microwave radar. He performed some tests which led to the invention of the microwave oven.

In 1946, the MIT Rad Lab's successor was the Research Laboratory of Electronics, an inter-departmental laboratory serving as an incubator for new research directions at the university. One graduate research assistant in the electronics group in the early 1950s was physicist Robert N. Noyce. He co-founded Fairchild Semiconductor in 1957 and invented the first monolithic integrated circuit – a silicon chip that could be mass-produced. He later co-founded Intel in 1968 and was called The Mayor of Silicon Valley. His achievements in semiconductors helped form a path forward for airborne radar.

jiawangkun/123RF

MIT campus in Cambridge, Mass.

Honeywell Weather Radar is Automated Today

Fast forward to 2021, and airborne weather radar used on airline and business jet aircraft do not use a magnetron; they use computer chips. The transmitters in Honeywell's very high-frequency X-band weather radars use gallium nitride transistors to amplify radio frequency signals generated digitally. These radars operate in the 10 GHz range, a wavelength of about 1.5 inches. X-band provides a tight antenna beam width and acceptable attenuation.

"We think the big technology (improvement) not appreciated by many people is the (automatic) removal of ground returns," said Honeywell's chief radar engineer Brian Bunch. He is the senior technical manager for the radar, communications, navigation, and surveillance engineering group.

It used to be that pilots adjusted the antenna tilt manually to remove the ground returns and display just the weather ahead. This was a workload-intensive task for pilots, and if it was not done correctly, they could miss the presence of hazardous thunderstorm cells ahead.

The RDR 4000 and the newly released RDR 7000 do this automatically. The RDR 7000 has a smaller form factor than the 4000. There is a memory volumetric buffer that allows these systems to capture weather data and perform software analytics to display hazards to pilots on the flight path including hail, lightening, and turbulence.

Honeywell Predicts the Future with Radar Algorithms

There are also predictive features like the capability to predict a wind shear microburst on the flight path. A weather radar algorithm, for example, can predict when a thunderstorm cell will produce lightning. Hail is detected by examining how much water is present and where it vertically resides when correlated with temperature data.

The hazards are displayed to the pilots in a corridor along the aircraft's flight path at plus or minus 4,000 feet. The buffer can process weather data as far out as 320 nautical miles (NM) depending on the aircraft's altitude and the weather conditions. At 40,000 feet, the radar has a 200 NM horizon.

Honeywell engineers spend a lot of time on human factors, such as using color to represent different types of hazards ahead to the pilots. A lot of research went into displaying hail and lightning icons. Honeywell conducts studies on designs that can improve the decision-making capability for the pilot. The company's radar team always has a few tasks on the books to make further weather radar improvements. "We are not just trying to show pilots what is happening, we are trying to show them what will happen in the future," Bunch said.

All of this is a far cry from the 1940s when the MIT Rad Lab developed microwave radars for very specific tasks, such as sighting a U-boat on the surface or showing a B-17 Mickey operator a ground map of the target area. Even back then, training and human factor issues proved critical to getting the correct results, and pre-mission briefings included images for B-17 Mickey operators of what the target should look like on radar.

The legacy of the MIT Rad Lab continues. In 1951, its successor lab began research on continental air defense in work that spawned the MIT Lincoln Laboratory. This lab still researches communications systems, space technology, air missile and maritime defense, advanced technology, intelligence surveillance, reconnaissance capability, and other ATC issues. As of 2019, the lab employed about 3,500 people.

THE JOURNAL OF
AIR TRAFFIC CONTROL
OFFICIAL PUBLICATION OF THE AIR TRAFFIC CONTROL ASSOCIATION, INC.
Summer 2021 | Volume 63, No. 2

WHOSE FLIGHT IS IT ANYWAY?

Understanding Humans and Automation – and their Teamwork in the Stratosphere

Plus

- To 4DT or not 4DT: Is there really a question?
- The Impact of UAS and UAM on the Emergency Services Sector
- The Next Normal: Innovation Applied

THE JOURNAL OF AIR TRAFFIC CONTROL
OFFICIAL PUBLICATION OF THE AIR TRAFFIC CONTROL ASSOCIATION, INC.

Summer 2021 | Vol. 63, No. 2

Published for:

Air Traffic Control Association
225 Reinekers Lane, Ste. 400
Alexandria, VA 22314
Phone: 703-299-2430
info@atca.org
www.atca.org

Published by:

LESTER

140 Broadway, 46th Floor
New York, NY 10005
Toll-free phone: 866-953-2189
Toll-free fax: 877-565-8557
www.lesterpublications.com

President, Jeff Lester
Publisher, Jill Harris
Sales & Art Director, Myles O'Reilly

EDITORIAL

Managing Editor & Social Media Coordinator, Lindsay Risto

DESIGN & LAYOUT

Senior Graphic Designer, John Lyttle
Advertising Coordinator, Leticia Abas
Graphic & Online Media Designer, Mark Aquino

ADVERTISING

Sr. Account Executive, Quinn Bogusky
Sr. Account Executive, Louise Peterson
Account Executive, Allan Merluza

DISTRIBUTION

Administrative Assistant, Maryanne Li

Cover photo: profile_feodora52/123RF

ATCA members and subscribers have access to the online edition of The Journal of Air Traffic Control. Visit **www.lesterfiles.com/pubs/ATCA**
User name and password: **ATCAPubs** (case sensitive).

CONTENTS

ARTICLES

DEPARTMENTS