Microwave Systems—Then and Now—Examples at the 50th Reunion of the MIT Radiation Laboratory

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(*Invited Paper*)

Abstract—**The delivery by the British in 1940 of a cavity magnetron operating at S-band (10 cm) sparked an intensive effort in the US in response to three urgent wartime system requests. The MIT Radiation Laboratory was established by NDRC; and from this sprang an intense and successful program in microwave components and systems. Because of space restraints, this paper briefly describes the successes attained in two of the three projects; "firecontrol" and "navigation." The paper then skips to the current situation, the impact of advances in technology, both in the microwave field and in complementary fields essential to the design of modern "microwave systems." Three examples are briefly reviewed: the Army Patriot, the Navy Aegis, and the AF Navstar or GPS navigation system.**

TODAY we are celebrating the 50th anniversary of The Radiation Laboratory. The Radiation Laboratory at MIT was a World War II response—the world was threatened by Nazi dictatorship—scientists and engineers responded, dropping their normal pursuits to join the war effort. Two happenings in 1940 brought about the establishment of the Radlab: the establishment by President Roosevelt of an independent civilian research and development agency, the National Defense Research Committee, or NDRC, and the dispatch by Prime Minister Churchill of a special mission to the United States headed up by Tizzard.

The United States was not yet at war; and England, alone on the Nazi western flank, was being heavily bombed and was facing an iminent invasion. The Tizzard mission asked for U.S. help in three specific areas: 1) a microwave airborne intercept radar; 2) a microwave gunlaying antiaircraft radar; and 3) an electronic navigation system of long reach. In return they brought with them a revolutionary microwave oscillator tube called the cavity magnetron —a tube which could produce short pulses (a microsecond long) at high powers (in the order of tens of kilowatt peak power) at microwave wavelengths of 10 cm (3000 MHz).

While the microwave art in the United States in the fall of 1940 was not without its advocates, there was essentially no industrial equipment base and no commercial component base. In fact, even "pulsed circuitry" and its commercial component base were essentially lacking—devotees being limited to early longer wavelength researchers at the Signal Corps and Naval Research Laboratories and to physicists working in the area of cosmic rays and nuclear physics, who often abused radio vacuum tubes and cw components to achieve their ends.

The pulsed microwave magnetron opened up new vistas and it started the microwave revolution which continues to this day. The short wavelength (high frequency) permitted narrow radar beams; a 6 ft paraboloid reflector produced a 3 degree beam—giving an angular resolution at a distance of 10 miles of about a half mile. This sharpness of beam gave angular discrimination and substantial relief from ground reflections (ground clutter) when looking for aircraft in the sky. The short pulses also separated out nearby reflections which often were very strong, permitted range resolution of multiple targets (to a few hundred yards), and provided accurate measurement of the target range, say to 20 yd. The high peak power of the magnetron was essential for the design of radar systems with detection ranges of aeroplanes out to distances of hundreds of miles—assuming that receivers of appropriate sensitivity were available. Finally, there was the promise that microwave equipment in the 10 cm range was not effected by clouds or rain; so that truly all-weather and day-and-night operability was assured.

The above characteristics of microwaves were here enumerated because they were the principal drivers in the design of microwave radar systems. Other speakers will, I am sure, address microwave theory and microwave components in far greater detail. My assignment was to dwell on microwave systems. However, such an assignment goes far beyond the limits of time here available. Henry Guerlac, the official historian of the Radlab, finished his *Radar in World War II* in 1947. It was posthumously published (1171 pp.) in 1987 as volume 8 of the History of Modern Physics [1]. A far more concise history of radar to the year 1960 was included in the celebration of the tenth anniversary of the founding of the Lincoln Laboratories [2]. To bring the record up to date—say to 1990 is gargantuan. I have had to somehow draw a boundary to

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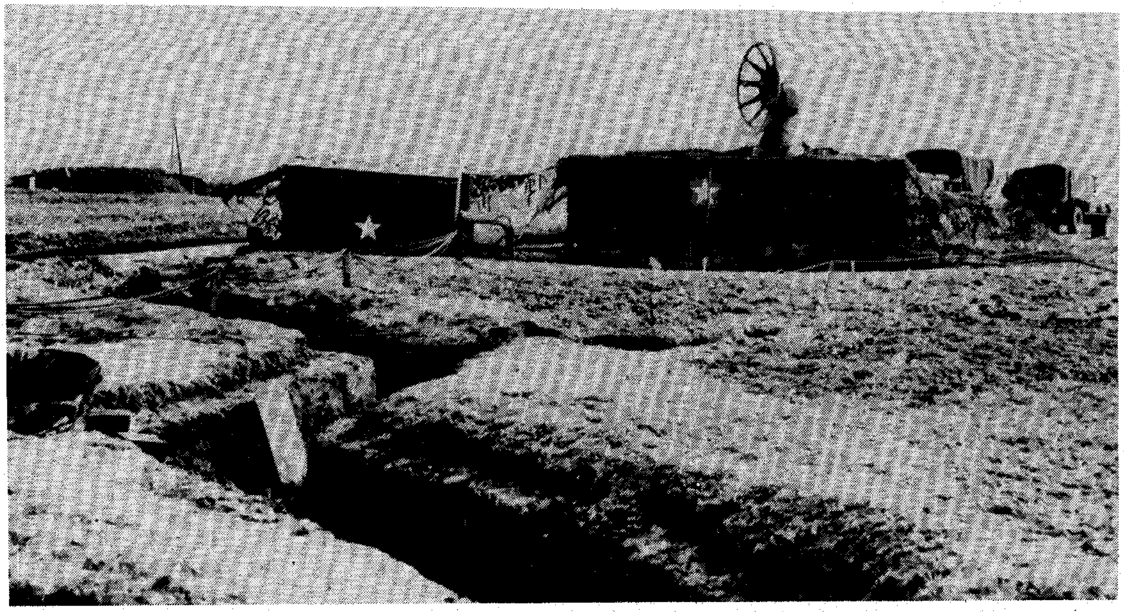

Fig. 1. SCR-584 anti-aircraft radar at war in Western Europe, 1944.

this talk and also to skip from then to now. So this is not a history nor is it a complete compendium of microwave systems—as a matter of fact, I let the IEEE Aerospace & Electronics Systems Magazine of October 1990 [3] set the limits—essentially Radlab Projects 2 (gunlaying) and Project 3 (navigation)—limited further to the time intervals "then and now." I must admit that very important microwave system applications such as bombing radars, ground avoidance radars, blind landing systems, anti-submarine warfare systems, etc. will get short shrift. Nevertheless I shall fill in some of the gaps by referring to pertinent technology advances.

The history of Radlab gunlaying radar systems, beginning with the conical scan automatic-tracking XT-1 system has been described at some length [1], [3], [4]. The XT-1 went into production as the SCR-584, (Fig. 1), with nearly 2000 sets delivered in time to have a major impact on the war. Its success resulted from: 1) high degree of performance; 2) high reliability; 3) field support; and 4) versatility for adaptation to other military requirements. During the four years of the Radlab, practically every element of the Radlab had contributed. Peak power climbed from 40 kW to one MW; matched filter receivers helped to increase range to four times specification value, the TR box made possible a compact antenna theodolite mount, the stub supported demountable coaxial lines permitted reliable and quick disconnect essential to equipment mobility, the invention of the Plan Position Indicator (PPI) freed the equipment from a separate acquisition radar, the so-called N-squared gate to negate enemy chaff was rushed into model production at Radlab and field installed by personnel of BBRL (British Branch of the Radiation Laboratory).

The high reliability was a product also of the Radlab component and systems groups and of industry. Nothing was left to chance and the Signal Corps-Radlab-industry cooperation was beyond reproach. It was an example of what Vannevar Bush wrote: "an effective professional partnership of scientists, engineers, industrialists, and military men, such as was never seen before, which exemplified the spirit of America in action at its strongest and best" [5].

But a radar is only a part of a system—a gunlaying system includes a radar for target acquisition and tracking, a computer to establish tracks and to make fire-control predictions, and the guns and the shells with their fuses. The Radlab shared in all these aspects of the system. Accuracy of position data and their transmission from the SCR-584 to the M-9 computer (a Bell Telephone Laboratory electric analogue computer) were fundamental. In fact parts of the computer where mounted within the SCR-584 to reduce data transmission errors. Computer aim point prediction required computing velocity from position data; and since the tracking of finite size aircraft targets was inevitably accompanied by "noise," the optimum averaging of tracking data was shared between the radar system and the computer designs.

Adaptation of the versatile SCR-584 to fit other military operation requirements demonstrated the fundamental theorem that a new capability leads to new solutions. Perhaps the most outstanding modification to the SCR-584 system was replacing the M9 electrical firecontrol computer with automatic electrical plotting boards, first two-dimensional, and later three-dimensional. Such a marriage was readily accomplished, because the precision computer azimuth, elevation, and range potentiometers were already in the SCR-584 radar. Now the SCR-584 system could track a plane and on a map continuously present to the operator in the SCR-584 an accurate track of the airplane. When the plane carried a Radlab radar

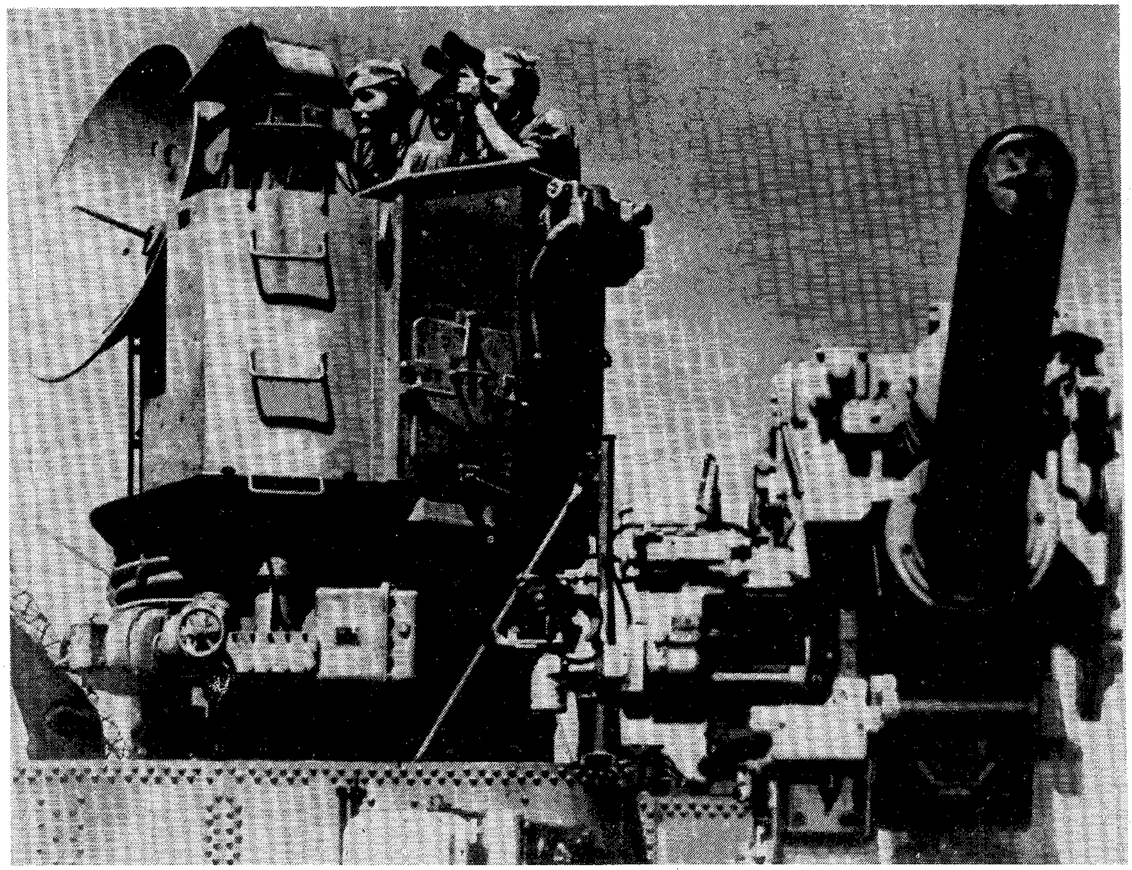

Fig. 2. The topside portion of the Navy GFCS-Mk 56 showing the nutating X-band search and tracking antenna, the optical target acquisition scope and the optical tracking scope next to the 5 inch-38 gun.

beacon, the range was extended to the line-of-sight and the pilot could be given instructions on where to fly to reach his target and/or how to fly to return to his base without being shot down by "friendly fire." Further, if you removed the pilot from the plane and used the radar beam as a secure communication link, you had an accurate pilotless cruise missile. As the war in the continent was coming to an end, some 200 Rosebud beacons had been modified at Radlab for installation on unmanned B-17 and B-24 drones, the first U.S. cruise missile. As the production beacon, the APW-11, was designed for installation on the American version of the German V-1; it was later used with the plotting-board equipped SCR-584 (designated AN/MPQ-1) for scoring practice SAC bombing runs and finally, during the Vietnam War, the system was used for control of the B-52 bombing of Haiphong and Hanoi.

The three dimensional plotting board also found unique applications. Early in the war, the Radlab experimental predecessor, the XT-1A, had demonstrated that artillery shells and bombs could be tracked. The data so taken was used by the Army Aberdeen Proving Grounds to improve their ballistic tables. However the same concepts were applied to tracking enemy mortar shells, and even missiles (with appropriate scaling factors). And, indeed, the system was applied to back-track mortar shells in Italy and Nazi V-2's launched from western Germany. Several SCR-584, modified with larger dishes and range scales, were located in Holland and Belgium from where they back-tracked to the launch points. Fighter-bombers were dispatched and the launch pads destroyed. The V-2's stopped coming until the Nazi developed and built mobile launchers. You will, obviously, recognize the similarity of these events to the application of the Patriot system to the tracking and shooting down of the Iraq SCUD missiles—more on this later.

The self-oscillating magnetron as originally invented by the British and further developed in the U.S. and used by Radlab in its WW-II radar systems was not a coherent source. That is, there was no phase relationship between successive pulses and therefore no use could readily be made of the phase of reflected received pulses. Had there been a stable oscillator followed by a pulsed amplifier transmitter, in which the transmitter phase was locked, the use of Doppler processing in discriminating moving targets from fixed clutter could have been applied, and indeed, the time period between the demise of Radlab and now is characterized by the use of such phase-locked amplifiers.

Yet several Radlab efforts to reduce ground clutter should be mentioned: the use of delay lines to cancel out repeating echoes that did not move (Moving Target Indicator or MTI); getting rid of near-by clutter (often very large but sometimes small, like sea gulls) using sensitivity

Fig. 3. The Army Patriot phased-array search and tracking antenna with the IFF, ECCM, and missile guidance antennae (courtesy of Raytheon Corporation).

time control; the use of vertical polarization to reduce sea-clutter and of rotary polarization to get rid of rain clutter.

An interesting application of phase cancellation by the SCR-584 is worthy of mention. If the SCR-584 was pointed at a cross-road, the conical scan turned off, and the range gate appropriately set, it was noticed that the phase of the reflections from a moving truck relative to the fixed reflections at that point would make the total reflected signal fluctuate as the relative phase of the reflected signal from the ground and the truck changed (interference).

If now an earphone was connected to the gated signal, one could "hear" when a truck passed. Similarly, one could "hear" a man walk across a field held in view by the radar. These examples, plus observing when an aeroplane dropped chaff while being tracked demonstrated what a human operator could add. Today, we can substitute computers for much of this; but for the time-being, let us call it human "signal processing."

The referenced *IEEE Systems Magazine* [3] also describes in some detail the Navy GFCS Mk56. I shall not spend much time on this system—I must get on to the "now" phase of my talk. Nevertheless, as stated before, a Microwave System consists of more than a radar. The radar becomes a major component. The GFCS Mk56, (Fig. 2), is included here, not so much for the additions to the microwave art—although it was X-band (3 cm wavelength) and 0.1 μs pulses, both of which improved performance and anti-jam features, but because it was the first time that a complete and complex radar firecontrol system was designed under a single systems engineering management—with the Radlab in full technical control.

To summarize the "then" of Project 2, World War II had started with on the whole ineffective anti-aircraft fire. The introduction of the SCR-584 and the associated NDRC developed electrical computer (by Bell Telephone Laboratories) and the NDRC developed proximity fuse (by the Applied Physics Laboratory) revolutionized the art with not only all-weather day-and-night capability but also orders of magnitude battlefield demonstrated improved effectivity against aircraft and cruise missiles. The Radlab developed GFCS Mk56 had been started later, and two Radlad prototypes had been installed when the war ended. Thus it did not get to see action: but if it had, its unique systems design would have been very effective against torpedo planes and kamikaze attacks.

The four decades following the disbandment of the Radlab in 1945 have been characterized by continued technological advancements. In the microwave technology, all sophisticated military radar systems now employ phase-locked amplifiers (e.g., traveling wave tubes) instead of free running oscillators. New materials called ferrites, and other techniques were developed to provide accurately controlled phase shifting of microwaves in waveguides. Large multiple transmitting arrays of many antennae replaced single radiators and reflectors. Active arrays were built with each antenna having its own solid state amplifier. By controlling the phase to each antenna (or groups of antennae), the direction of the narrow beams from such large arrays could be controlled over wide angles. Thus, without using mechanical motion, the radar beams could be steered over wide angles even between individual pulses. The mechanical conical scan used in the WW-II automatic tracking radars could be replaced by monopulse electronic control steering. In fact, scanning for search over wide angles could be interweaved as desired with accurate angular tracking. To provide these steering functions requires fast processing control.

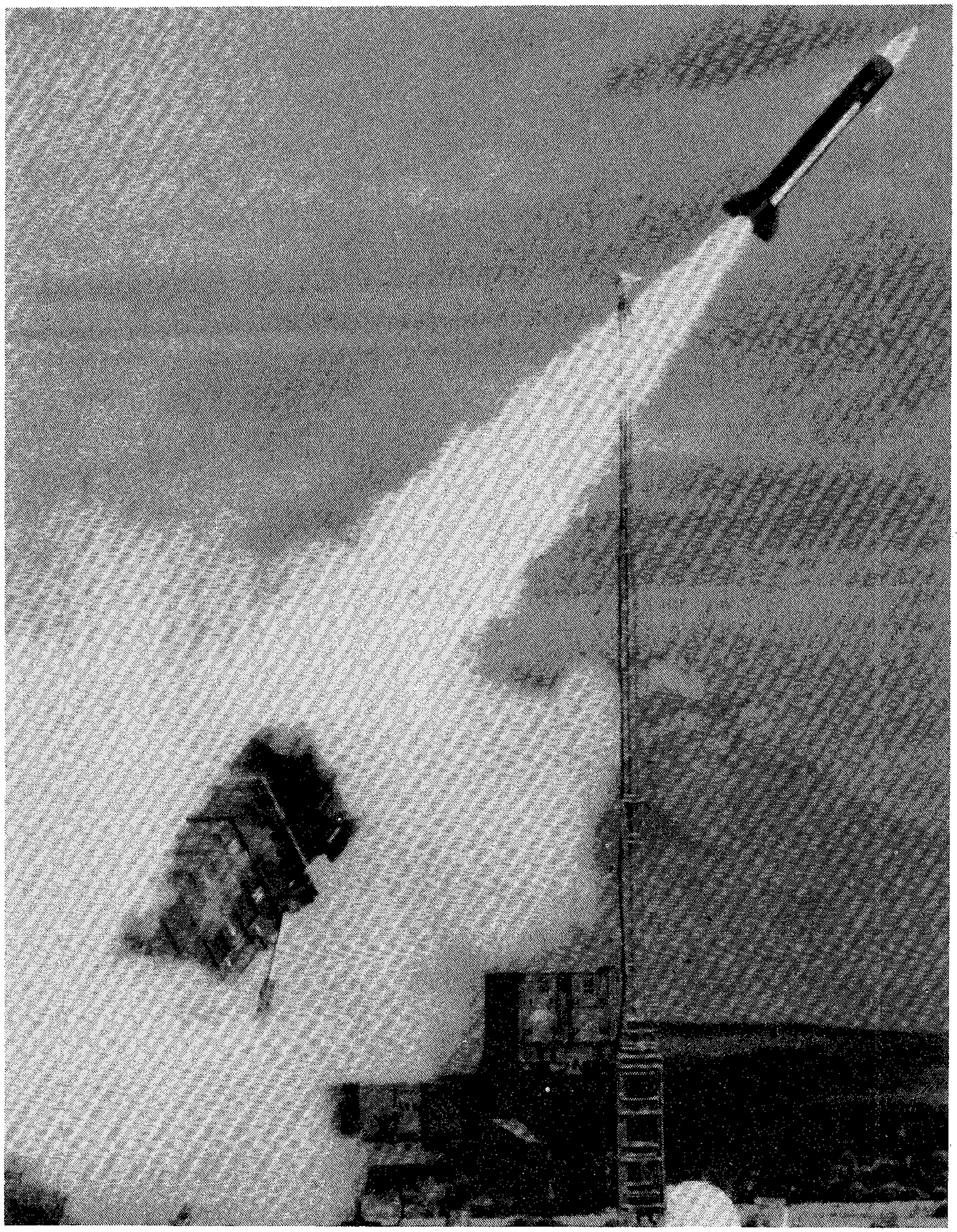

Fig. 4. The Patriot launcher and missile (courtesy of Raytheon Corporation).

Other major contributing advances to modern radar systems were: 1) the invention of the transistor and the subsequent solid state integrated circuits; 2) high speed digital computers and their programmable software. Today, the control of modern high performance radar antennae is done by such computers operating through phase shifters; and the signal processing of the return echoes, which in WW-II was done by operators, is now largely done by sophisticated computers programmed as needed to automatically identify targets of interest, establish tracks, and even make command decisions to control the weapons. The operator no longer views the direct radar signals on the scope but instead bright displays of track data furnished by the computer with superimposed collateral data and maps.

A complete system also needs the weapons. In WW-II, the weapon of choice was the rifle or gun. While these were effective against targets moving in straight paths, at least for times intervals comparable to the time-of-flight of the bullet, the technology for controlled missiles did not exist during WW-II. This issue was addressed during WW-II by the Radlab. In response to a query from Vannevar Bush dated October 3, 1944, Radlab stated that guided missiles could in principal be considered as replacements for guns. Four approaches were identified: 1) a homing missile; 2) a beam rider; 3) tracking both the target and missile and sending flight instructions; and 4) "missile tracks the target and continuously solves the collision problem." It was concluded that the technology to design such missile systems did not then exist and "no concrete results could be expected in less than five years." [6]. Now, 46 years later, it can be reported that all the necessary technology has been developed; all the approaches and even combinations have been fielded.

The army's current primary anti-aircraft system is called the Patriot. Developed by Raytheon, the Patriot is both an anti-aircraft system and anti-tactical ballistic missile system. The radar antenna, transmitter and receiver are shown in Fig. 3. The phase controlled antenna array has 5161 elements, it is approximately 12 ft in diameter and radiates at *C*-band (wavelength about 6 cm). The antenna stays fixed, but its scan coverage and sequences are controlled by a digital computer in the engagement control station. The Patriot missile weighs 2000 pounds and measures nearly 18 ft in length. Four such missiles are carried in a mobile launcher, (Fig. 4). A typical Patriot Fire Unit consists of eight launchers.

Whereas the WW-II SCR-584 could track only one target at a time, over a hundred separate tracks can be simultaneously maintained by the Patriot radar and processing computer. From these the computer selects the targets in accordance to previously programmed priority plans and assigns the missiles.

The missiles are launched into a fixed direction. They steer into a computer controlled direction. The missile is command controlled in midcourse using track data of both the target and missile (scheme 3). When the missile gets close to the target, the system switches to previously mentioned approach 4)—that is collision control from tracking data acquired by the radar receiver on the missile. As was done in the Sparrow air-to-air missile and in the Hawk ground-to-air missile, in the terminal portion of its flight, the missile radar is semi-active; the ground transmitter illuminates the target, but the receiver is on the missile. The Patriot ground radar also provides a very secure communication link to the missile (as was done in the cruise missile control by the SCR-584 in WW-II). This same communication link also allows all the missile steering computation to be done by the very versatile digital computers in the ground control station. This system concept provides great versatility. It simplifies the electronics in the missile and reduces missile costs. Finally, a number of missiles can be simultaneously in flight engaging different targets, or, if desirable, as demonstrated against the SCUD, several missiles can engage the same target in sequence.

Corresponding in function to the Army Patriot is the Navy Aegis system and its radar component designated AN/SPY-1A, developed by the Johns Hopkins Applied Physics Laboratory. Like the Patriot, the SPY-1A radar uses a phased array antenna system, about 12 ft by 12 ft. Four such antennae are mounted on cruisers of the Ticonderoga class as well as on destroyers of the Arleigh Burke class, (Fig. 5), giving 360 degree azimuthal coverage. The antennae are fixed, the transmitted peak power is 4 to 6 MW at *S*-band (10 cm). High speed digital computers control the antenna phasing and perform signal processing and track maintenance. Like the Patriot, the complete operational cycle is automatic without operator intervention unless such action is specified because of the situation. The Aegis system computer control system also operates the electronic warfare elements, on-

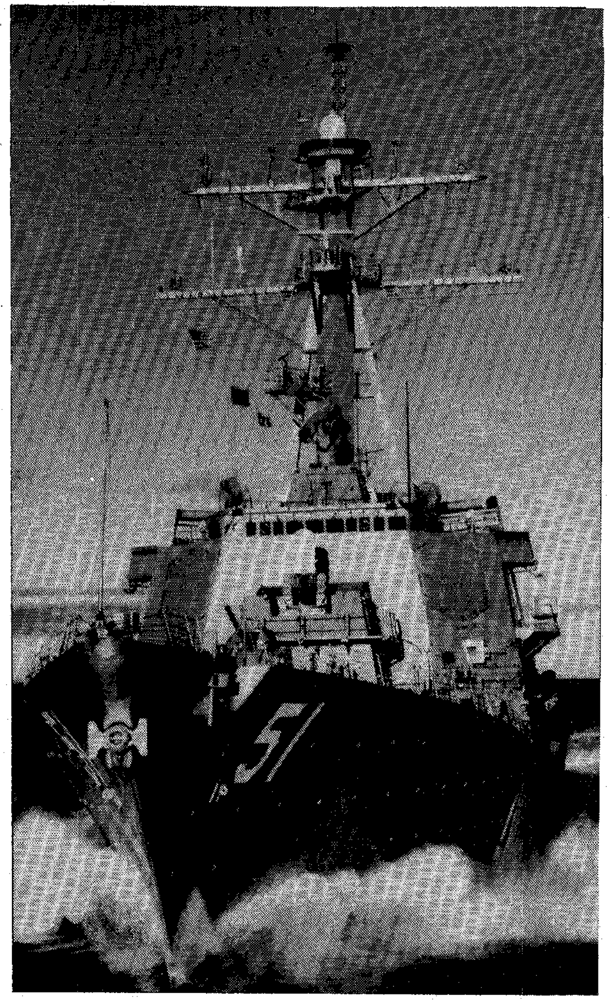

Fig. 5. The Navy Aegis System on the USS Arleigh Burke destroyer showing two of the four phased array antennae of the SPY-1D radar (courtesy of the Raytheon Corporation).

board sonar, etc. It also controls the firing and midcourse guidance of the Standard Missile against airborne targets and the Harpoon Missile against underwater targets.

Finally, I promised a short discussion on Project 3 of the Radlab, Loran—long range navigation—then and now. The Radlab effort is reported by J. A. Pierce in the *IEEE Aerospace and Electronic Systems Magazine* ([3], pp. 16–36). Pairs of transmitters were built along shores, hundreds of miles apart. These transmitted pulses at frequencies between 1700 and 2000 kilocycle—corresponding to wavelengths of about 150 m—certainly not in the microwave region. These low frequencies were chosen to provide long range propagation—say 700 nautical miles by so-called ground propagation over sea water during the day. At night, use was also made of sky waves, that is reflections from the ionosphere, thereby increasing the range to 1400 nautical miles. The pair of stations operated at different frequencies, but the pulses were synchronized in time. A user receiving the pair of signals established a line of position. As shown in Fig. 6, if the two pulses arrived simultaneously, the user was on the perpendicular bisector—that is equidistant from the two

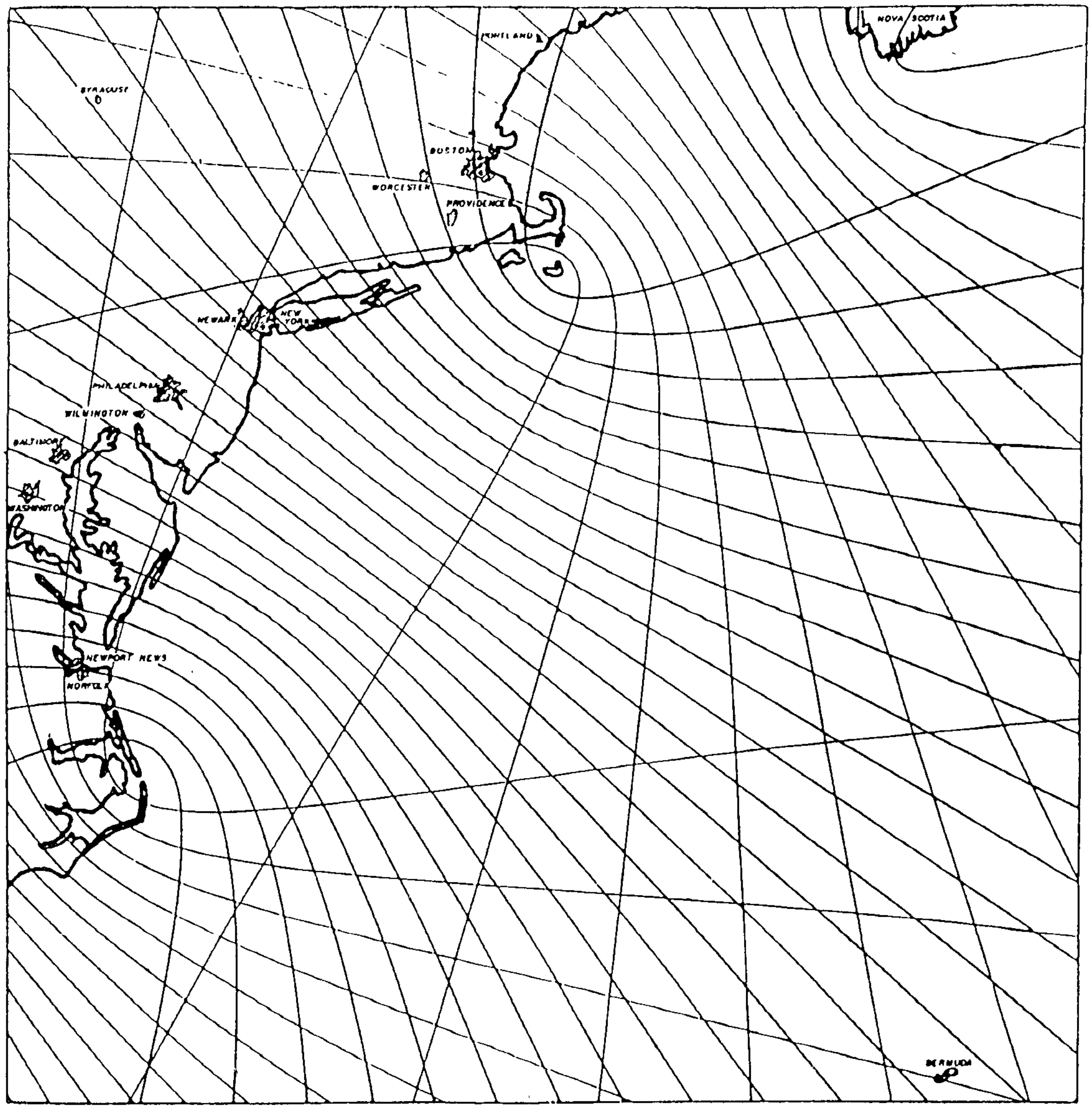

Fig. 6. A simplified Radlab Loran chart. Readings are made to 1/200th of the spacing of lines in the figure.

stations. If the signals arrived at a time-spaced interval, the user was on a line of position represented by a hyperbola. If the process is repeated using a third station, or another pair, then the two intersecting lines of position determine the position of the user.

The accuracy of the system was in the neighborhood of 1 to 2 miles, depending on the angle of the lines of position intersection, atmospheric noise, but also on the vagaries of radio propagation at 2 MHz. Nevertheless, because it operated in all weather and day and night, the system was a huge success. It used the best current technology and met the desired performance.

After the war, other systems, but still using the difference of arrival time were developed: some like Omega at even lower frequencies to give world coverage albeit with reduced accuracy; others like Loran-C at higher frequencies to give better accuracy but limited by line of sight to short distances.

The advent of space technology in the 1960 period provided new opportunities for navigation systems, the possibility of both world coverage and accuracy. A number of system using satellites as the source of radiation were proposed; and one, the Transit, soon became operational. However the analogy to the original hyperbolic Loran is best represented by the Navstar or GPS (Global Positioning System), a system conceived at The Aerospace Corporation, and now becoming operational.

Navstar uses a constellation of 18 satellites in three sets of 12 hour orbits, (Fig. 7). All satellites are tracked by master ground stations; and the orbits are carefully determined to an accuracy of a few feet. Each satellite also carries a number of atomic clocks. When necessary, corrections in the orbit data and to the clocks are injected in each satellite by the ground stations.

In effect, these satellites become what stars are to the stellar navigator; but, because they transmit in the mi-

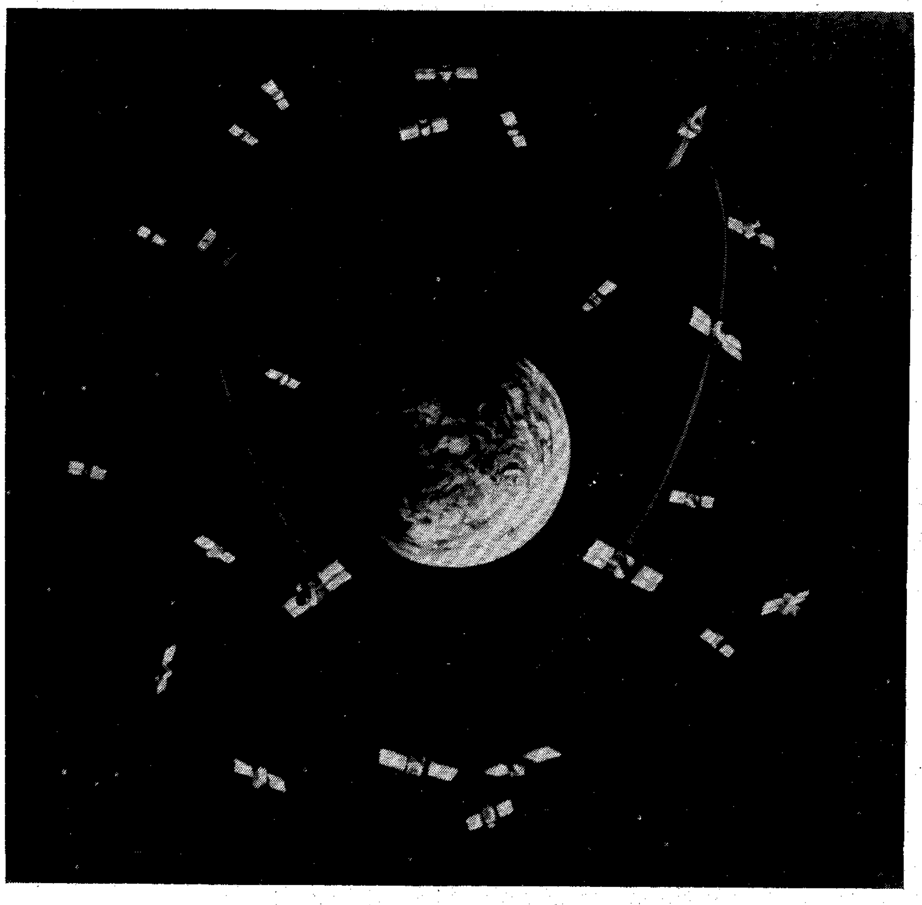

Fig. 7. The three 12-hour orbits of Navstar/GPS satellites. At least four satellites are in view at any place on earth (courtesy of The Aerospace Corporation).

crowave region, L-band (about 30 cm wavelength), their radiation penetrates the ionosphere in all weather conditions. However the electron density of the ionosphere changes with corresponding slight changes in the velocity of propagation. So two adjacent frequencies are radiated from each of the satellites; and the difference in arrival time at the platform receiver provides the data for making corrections in the propagation velocity—a concept first used in the Transit satellite system. All satellites transmit continuous signals, all at the same frequency; each satellite modulates its transmission over a 20 MHz bandwidth with its characteristic message which, in the open mode, is repeated at short intervals. The user acquires the satellite message by correlating the message with the stored message in the user's receiver. Because of the wide bandwidth, the user in effect performs a pulse compression equal to the reciprocal of the band-width, that is accurate to about 50 ns. This advanced technology rejects both multipath problems as well as unwanted signals which might be present at the same frequency band near the user. In the simplest user equipment, (Fig. 8), a single channel L-band receiver queries four satellites in sequence. The unit also has its own clock—not very good, just a common quartz controlled watch—its reading is referred to as pseudo-time. It also has a compact microchip computer and a digital catalogue of all the satellite codes. In this one channel user equipment, the unit sequentially matches the signal codes from four satellites in view and registers the time of arrival as measured on its somewhat inaccurate clock. There are four unknowns, three in user's position (latitude, longitude, and altitude) and one in the user's clock relative to Navstar's system time. The microchip computer then computes the four unknowns using the four observed pseudo-time arrival measurements. With modern technology, the entire user equipment including display is packaged in a hand held battery operated unit.

The Navstar satellites also transmit a military-use-only modulated signal which is cryptographically secure, (Fig. 9). The accuracy of this channel was designed to meet mapping and targeting accuracies. Jet aircraft and other fast-moving vehicles carry four or more channel receivers to provide for simultaneous and continuous reception of signals, as well as signal processing giving continuous position, velocity and world-wide system-time. In more sophisticated units, the Navstar receiver is integrated with inertial navigation units with synergistic benefits in navigation accuracy. The military units provide for world-wide location accuracies to better than 20 yd and time to better than a tenth of a microsecond.

The Navstar signals, like all aids to navigation, are supplied to the public without a user charge. The accu-

Fig. 8. Commercial one-channel hand-held GPS receiver and position and course computer - position accuracy about 25 yd (courtesy Magellan Systems Corporation).

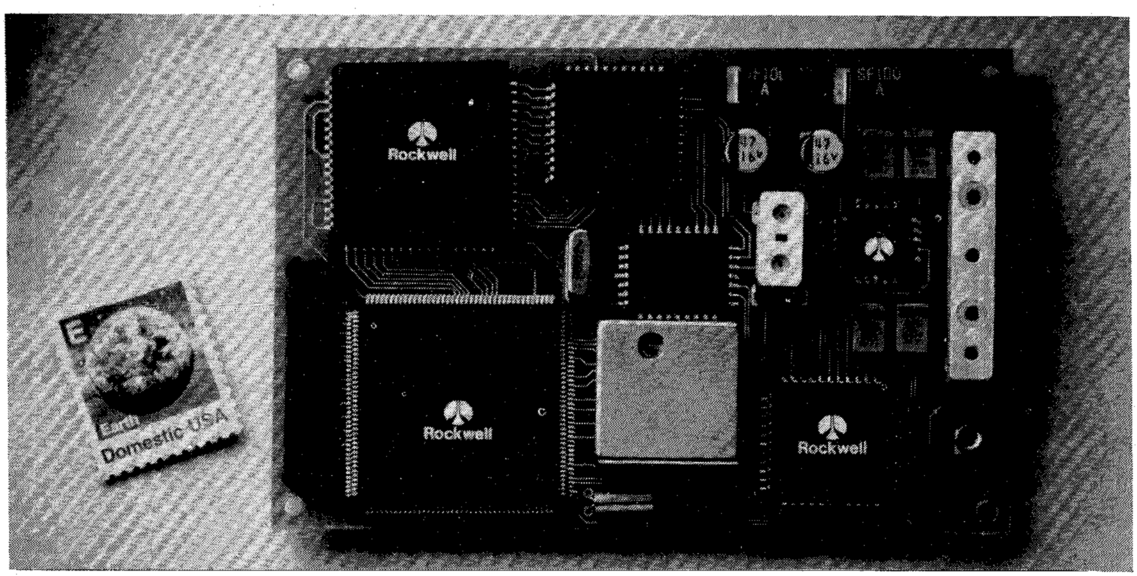

Fig. 9. Militarized 5-channel GPS receiver for incorporation by original equipment manufacturer, OEM (courtesy Rockwell International).

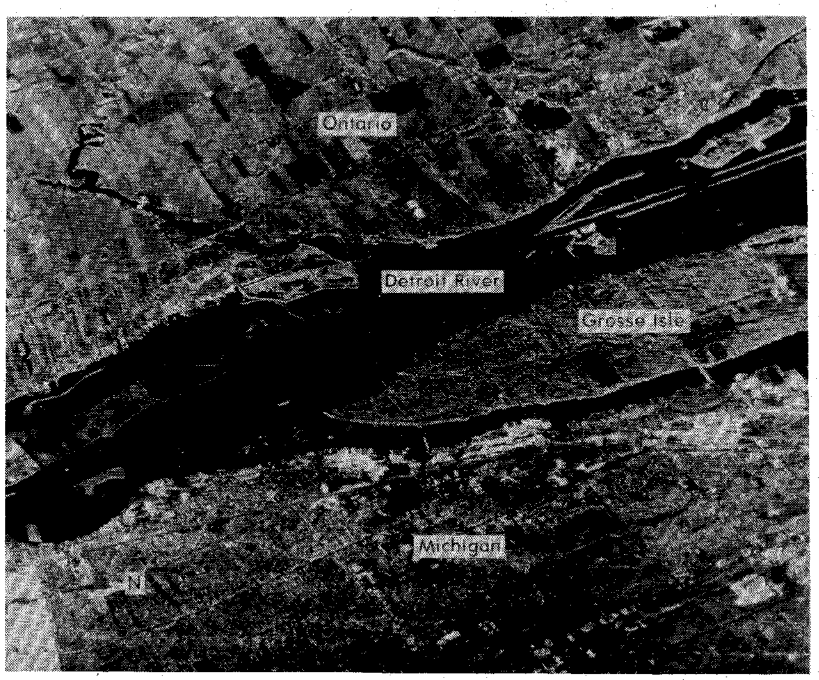

Fig. 10. Strip-map produced in real-time by airborne synthetic aperture radar (SAR) with 20 ft resolution (courtesy ERIM).

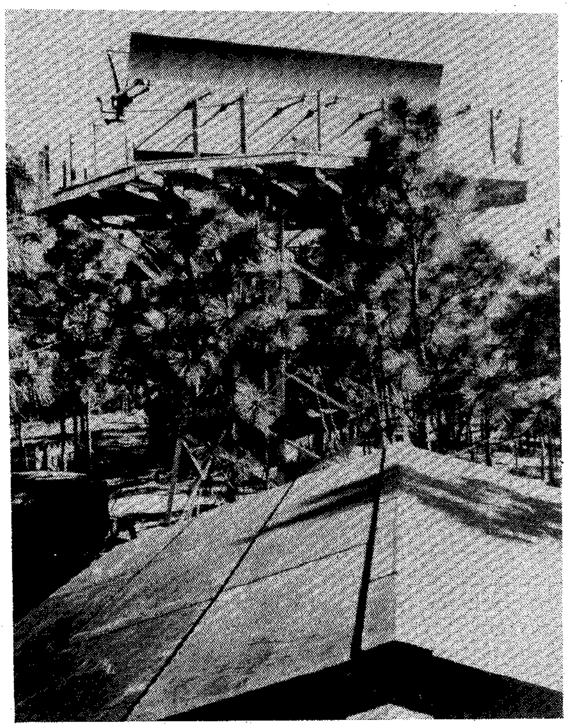

Fig. 11. World War II Radlab MEW surveillance radar on a 25 ft tower.

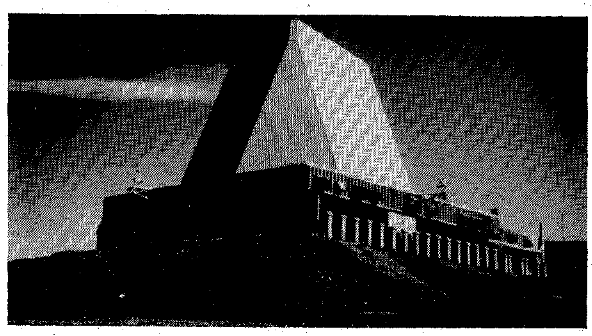

Fig. 12. AF Pave Paws radar at Thule, Greenland (courtesy of the AF Space Command).

racy of the open channel can be purposefully degraded from that of the military channel. However actual use of commercially available units have demonstrated accuracies of the order of 30 yd. If current planning is realized, the Navstar will be fully operational worldwide (with satellite spares in orbit) by 1995; and afterward all other forms of electronic navigation systems supported by the U.S. government will be phased out.

As reported in the press [7], by 1995, the DoD will have purchased some 10 000 militarized GPS receivers—and the number is expected to grow to about 100 000 by the end of the century. The Persian Gulf War dramatically demonstrated the military worth of the GPS. While only 15 satellites were in orbit (instead of the full configuration of 21 satellites), the derived location data was available all day for ground troops and almost all day for three-dimensional users. To fill the gap of available military receivers, tens of thousands of commercial receivers were supplied-particularly to ground troops in the Gulf War-Desert Storm. As reported by the *Armed Forces Journal International* (*AFJI*) [7], "Any lingering doubt about GPS's profound military utility were swept away during Operation Desert Storm. AF B-52 bombers were aided in locating assigned land targets by airborne GPS receivers sets. The Navy stand-off land attack missile (SLAM)...relied on GPS...The AF deployed its two JSTARS with GPS to spot (accurately locate) ground vehicle convoys... A senior Army source told *AFJI* that the Army's XVIII Airborne Corps and the VII Corps relied on GPS to keep track of their locations during the encirclement of Iraq's Republican Guard."

We are here today celebrating the 50th anniversary of the Radlab. My assigned task was to speak about "Microwave Systems—Then and Now." Little did we dream, back in the days of Radlab, how the field of microwaves would grow. In this talk I tried to carve out a piece of the subject matter—small enough to be manageable. In the process I have left out much—and I will not make any further apology. Certainly a more complete discussion would have included the many airborne systems like the current Airborne Early Warning (AWACS) systems. Then too, the high resolution synthetic aperture airborne, (Fig. 10), and spaceborne radars deserve extensive discussion. I shall only tease you by showing a real-time high resolution (20 ft) radar picture of the lower Detroit River.

Surveillance radar too have grown from the Radlab MEW (Fig. 11) to the gargantuan DEW (Distant Early Warning) radar (84 ft in diameter, 2560 active elements, over 2000 simultaneous tracks) which stands watch in Thule, Greenland for warning of possible incoming ICBM (Fig. 12).

Non-military microwave systems and equipment have also penetrated many new civilian applications: weather forecasting, air-turbulence and wind shear monitoring, and from microwave cooking to MRI medical diagnostic equipment.

In 1940, the Radlab started its work with the magnetron operating at 10 cm wavelengths. Before the war was over, radars in the X-band (3 cm) were operational and experimental equipment was flying in the K-band (about 1 cm). In the intervening years, the frequency range has been extended to mm waves and to the infra-red and visible regions—such radars being called lidars.

What will the next 50 years bring? I cannot be sure; but I am sure that our host, the IEEE Microwave Technology and Techniques Society, will continue to grow and prosper. Thank you for inviting me to your meeting.

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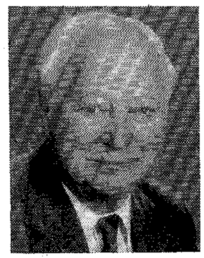

Ivan A. Getting (SM'46–F'54–LF'80) was born in New York City on January 18, 1912. He was an Edison Scholar at MIT from 1929 to 1933 and received the D.Phil. from Oxford University as a Rhodes Scholar in 1935. The next five years he was a Junior Fellow at Harvard University.

He retired as President and Trustee of The Aerospace Corporation on September 10, 1977 and currently serves as President Emeritus. He joined the organization as its first president on August 1, 1960. For the previous nine years, he was Vice President of the Raytheon Company. He has also served as Director of various organizations including Northrop, Verac, and Associated Universities. He was Director of the Division of Fire Control and Army Radar at the Radiation Laboratory of MIT from 1940 through 1945. Concurrently, he was the head of the Naval Fire Control Section of the OSRD, Member of the Combined Chiefs of Staff Committee on Searchlight and Fire Control, and Special Consultant to Secretary Stimson. From 1945 to 1951, he was a professor in MIT's electrical engineering department with a year's leave of absence during the Korean War to serve as Assistant for Development Planning in the Air Staff. Among his many contributions are the following: The so-called Compton-Getting effect; the first high-speed binary counter; the Cerenkov high-energy particle detector and the first automatic tracking radar, SCR-584.

He has served on numerous Government committees including the U.S. Air Force Scientific Advisory Board (SAB); the Signal Corps Advisory Council; the Undersea Warfare Committee of the National Research Council; and the Defense Department's Research and Engineering Advisory Panel on Electronics; Chairman of the Limited Warfare Panel of the President's Science Advisory Committee (PSAC) from 1961 to 1964; and from 1966 to 1971 was a member of that Committee's Naval Warfare Panel, and Chairman from 1971 to 1973. He also served as consultant to the National Security Council. In addition, he is active as a consultant and is a member of the Scientific Advisory Board, the National Research Council, and the Board of Trustees of the Environmental Research Institute of Michigan (ERIM).

Dr. Getting is a Fellow of the American Physical Society, and Honorary Fellow of the American Institute of Aeronautics and Astronautics. He is a member of the American Academy of Arts and Sciences. He was elected to the National Academy of Engineering in 1968. He served on the IEEE Board of Editors from 1947 to 1953 and was President in 1978. Among his awards are the Naval Ordnance Development Award in 1945; the President's Medal for Merit in 1948; Honorary D.Sci. degree by Northeastern University in 1956 and by the University of Southern California in 1986; and the Air Force Exceptional Civilian Service Award in 1960. In 1975, he was awarded the IEEE Pioneer Award and the Kitty Hawk Award from the Los Angeles Chamber of Commerce, and the IEEE Founders Medal in 1989. He is a Registered Professional Engineer in Massachusetts.