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Modern RADAR: Theory, Operation & Maintenance—2nd Edition

A thorough handbook covering ALL aspects of EVERY modern radar system . . . from police and military units to satellites and astronomy—even guided missiles!

by Edward L. Safford Jr.

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TAB BOOKS Inc.
BLUE RIDGE SUMMIT, PA. 17214

Preface

It is with deep gratitude to you for your acceptance of my first edition of this work on radar that I offer this revision of this work. As the fields of science and technology advance with an almost unbelieveable acceleration, it is always an astonishment at how many new facets—pure gems of enlightenment—can be found to write about in this particular field. Even with the dazzling speed of electronic computers at hand, it becomes almost an impossibility to keep up with developments in any one field, such as this one of radar, much less to keep up with the whole field of science and engineering technology as a whole. And, yes, as an erudite person would observe, it *has* become an impossibility.

But I investigate and dig and pry into the realms of these wonderful fields of electronics, mechanics and computers for radar encompasses all of these. And we added to the still valid and important information contained in the first edition of this work in order that the book may be of more value to you. I mentioned in the preface of the first edition that Sir Robert Watson-Watt, in 1935, was asked to develop a radar-type death ray and that at that time the lethality of the instrument was to be attained by increasing the blood temperature of a pilot—who would invade the British Isles on other than a peaceful mission—to such a point that his blood would boil and thus end his assumed wartime efforts.

Well, time has passed, and I now find couched in scientific literature allusions to laser-type death rays that *are under develop-*

ment and, indeed, may have actually been produced for some limited applications. The method of producing the "abandonment of missions" of those who could—under certain circumstances—receive the benefit of a laser energy emission would not be a boiling of the blood, but the much more lethal device of simply evaporating the material upon which such an energy emission might impinge.

As I reread the initial preface, I also take note of the fact that transmission of power without wires was mentioned. That, too, under modern day concepts is "on the drawing board." Those wonderful scientists and engineers at NASA have drawn the blueprints for a space station which can draw energy, undiluted from the sun, and convert it to radar-type waves, which in turn would be beamed to Earth and converted into the kinds of power needed. That would be electricity coming from outer space without the use of wires! So the first step in this direction has been taken, although I still look forward to the day when I can drive an electric car almost anywhere without having to worry about batteries or recharging—it will be drawing power from the atmosphere around us.

And so it is that as I find the many new breakthroughs in science, I then look to their applications in the various fields. *Radar* is one such field. As the new concepts and developments appear, such as SAR, these developments are put to use. Yes, I will show you many trends and developments in this revised edition, of the radar field.

But since in radar, as in most other fields, the basic concepts always remain the same, we will continue to include these as good building blocks to understanding the newer trends. If you are familiar with them, then you might want to move ahead and look at the newer concepts. If you are not so familiar with the basic concepts of radar systems, then I urge you to study them and the devices used prior to moving to the newer ideas.

I also thank those most cooperative manufacturers and scientists who have contributed to this edition. I marvel at their capabilities and accomplishments and look forward to what they will bring forth very soon.

The development of radar was a series of steps in development and little discoveries which, one by one, combined to bring about the great systems as we know them today. We will review how it all came about. Then, as we progress through the subsequent chapters, we'll examine the later developments and, finally, the great systems themselves which have become such a vital and necessary part of our everyday life. We may not really be aware that all around us, in defense of our country, in the control of almost all aircraft, in insuring safe passage of ships at sea, in the work of our own home-town police forces, and even in our own home kitchens, radar is present in one form or another to help us lead the good, safe life, and opens the doorway to a future life which involves trips to the stars.

In planning this book, careful effort was made to follow a logical sequence so that your knowledge of the subject builds naturally as each chapter unfolds. We start with a review of the historical events which lead to the important developments which made radar, as we know it, possible. Then we build on these developments to review the various types of radar systems, learning how they differ in a general operational sense. Once we have a good understanding of the basic principles of radar, we can then begin our examination of radar systems currently in use, insofar as security restrictions will permit.

There are so many people and agencies who provided us with information, photographs and encouragement in the preparation of this work. We shall always be most humbly grateful to them. The list is impressive: U.S. Signal Corps and Mr. Edmund Morris, Curator of the Signal Corps Museum; *Scientific American*; the Administrator of the National Park Service, Carlsbad Caverns, New Mexico; Federal Aviation Agency, U.S. Army Air Defense Center, Ft. Bliss; CSF Thompson Co.; Western Electric Co.; Radatron Co.; Boston Technical Publishers; Bell Telephone Labs; Hewlett Packard Co.; *Aviation Week* and *Space Digest*; RCA Corp.; Varian Tube Division; McGraw-Hill Co.; Hughes Aircraft Co.; SFD Laboratories; Bendix Avionics; Dalmo Victor Co.; White Sands Missile Range; Raytheon Co.; SELENIA (Industrie Elettroniche Associate SpA); Narco Electronics; Collins Radio Co.; National Space Agency; Teledyne-Ryan; U.S. Navy; International Telephone and Telegraph Arctic Services; NORAD Air Defense Command; Lockheed Aircraft Co.; U.S. Army Satellite Communications Agency; and all those persons with whom I've discussed this project and who have given of their time and knowledge.

As science advances, we all learn more about the proper way of doing things, and we are able—through the use of high-speed and accurate computers—to solve equations which we previously just had to look at and wonder how many many years it would take to find solutions for them. We are now able to examine mathematical models of various concepts and equipment in such a way that we can optimize the developments and equipment based on such equations.

We are able to realize through the solution of mathematical equations what errors have existed in the handling of various waves and electrons and thus are able to correct them. Computers have made the rapid growth of science and technology a reality, as they play a very large part in the finalization of new equipment.

The computation module or block is a vital necessity nowadays in every radar system. What it does depends on the designed operation of that particular radar and the purpose for which it was created. We will consider computational blocks, but we will not go deeply in computational methodology here.

So we begin a reading journey through the pages of this text. I hope that you will be my constant companion as we try to learn from what is *old* and apply that knowledge to an understanding of the why's and wherefore's of that which is *new*. As one person of considerable mental stature observed, "You don't have to know history to live in this modern world, but a good understanding of it helps you to survive!"

Edward L. Safford Jr.

FIRST PRINTING

SECOND EDITION

Printed in the United States of America

Library of Congress Cataloging in Publication Data

Safford, Edward L.
Modern radar, theory, operation & maintenance.

Includes bibliographies and index.
1. Radar. I. Title.
TK6575.S3 1980 621.3848 80-20678
ISBN 0-8306-9918-X
ISBN 0-8306-1155-X

Contents

Chapter 1
Beginning & Evolution

Where was the beginning? To answer that question we must go back to the creation of the bat, the mouse-like mammal who sleeps during the daytime and is active during the hours between sunset and sunrise. Although restricted to this nocturnal time span, he is not unprepared for this kind of assignment because he is endowed with *radar*, or as most of our modern day scientists now prefer to call it, an *echolocation* system. This was the first—the true beginning—of radar and, although man was not aware of it until some time later in history, all of our conventional radar systems are based on the principles used by the bat.

The bat has been thought to live on the blood of other living things, and there is one kind of a bat—the vampire—found in South America which feasts on the blood of cattle and as of the 1980's they feed on humans who live near the bat locations. But the majority of bats are not "blood suckers." Most emerge at night from caves (Fig. 1-1) and other dark places, where they stay during the daytime *to feed upon the billions of insects* which, like them, come out of their hiding places at night. The ability of this little mammal to fly at extremely fast speeds in total darkness, to avoid obstacles, to find its friends, and mate, and to locate tiny insects in order to capture them, is possible only because of its natural radar device. How does this radar work?

When the bat leaves its upside-down roosting position, its long ears (like those of a German shepherd) are pitched forward

Fig. 1-1. Thousands of bats emerge from the entrance of the Carlsbad Cavern Cave in New Mexico at dusk.

and form the receiving end of a highly directional sound system. Its ears are tuned to frequencies far above those which we humans can hear—around 40 kHz. As the bat starts its flight, it emits sharp, piercing sounds which are of very short duration. These sounds travel through the air and are reflected by any object they encounter. The echo is heard by the bat—almost instantaneously—before it has moved very far in its natural flight.

Two phenomena are present: time and direction sensing. *The bat can determine how close it is to a reflecting object (or obstacle) by the time required for reflected sounds to reach its ears. And because of the directional characteristics of its ears, it can determine exactly in which direction the obstacle is located.* Keep these two criterial in mind. They are the bases of radar! The bat also knows if the obstacle is stationary, like a wall or a tree, or whether it is a moving object, such as another bat or an insect. It is a source of wonder to many that the bat's transmitter (its supersonic voice) is capable of emitting a **frequency modulated** sound as well as a "pulse" at a constant frequency. Scientists spent many years in development before they reached the frequency modulated radar concept as a practical technical device.

Some years ago, the results of experiments conducted by Mr. Donald R. Griffin were published in **Scientific American** in an article entitled, "A Man-Made Obstacle Course for Bats." He proved that a bat could fly through a man-made obstacle course by means of its radar, and he made some determination as to the type of pulses produced by bats and the effectiveness with which the reflected sounds help them to avoid obstacles of various sizes (Fig. 1-2):

"Echo-location is still such a new discovery that we have not yet grasped all its refinements. The common impression is that it is merely a crude collision warning device. But the bat's use of its system to hunt insects shows that it must be very sharp and precise, and we have verified this by experiments in the laboratory. Small bats are put through their maneuvers in a room full of standardized arrays of rods or fine wires. Flying in a room with quarter-inch rods spaced about twice the wing span apart, the bats usually dodge the rods successfully, touching the rods only a small percentage of the time. As the diameter of the rods or wires is reduced, the percentage of success falls off. *When the thickness of the wire is considerably less than one tenth the wavelength of the bat's sounds, the animal's sonar becomes ineffective.* For example, the little brown bat (Myotis Lucifugus), whose shortest sound wavelength is about 3 millimeters, can detect a wire less than two

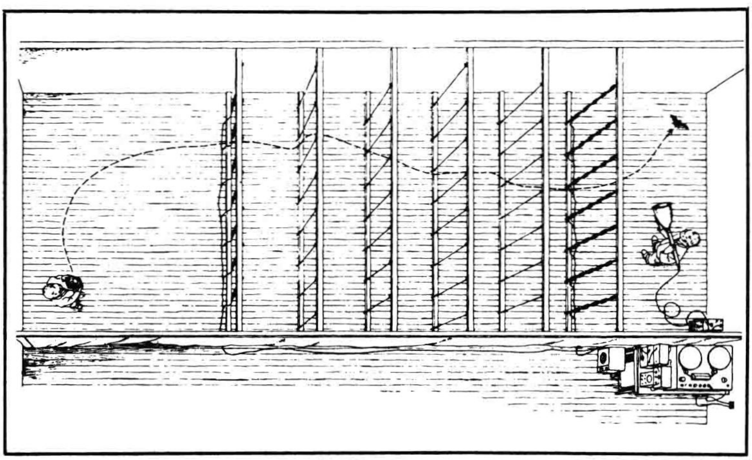

Fig. 1-2. Obstacles in the form of their vertical wires are avoided by a bat despite the presence of interfering noise from banks of loudspeakers to the left and right of the four sets of wires. The man at the right holds a microphone which picks up the bat's signals. (Reprinted with permission from Scientific American, July, 1958. All rights reserved.)

tenths of a millimeter in diameter, but its sonar system fails on wires less than one tenth of a millimeter in diameter."

This ability of the bat to avoid obstacles, and to do so in the midst of a confusion of noise, is a miracle which scientists are to this day trying to understand. The same scientists would also like to know exactly how a bat is able to identify its own cry and its own echoes amidst the hundreds of thousands of others which other bats are using for guidance. Glance again at Fig. 1-1 and imagine the terrible din if you were capable of hearing up to 40 kHz. How on earth can one bat detect its own cry and echo? What wouldn't modern missile-makers give to be able to produce missile guidance systems as immune to jamming as this, and at the same efficiency level!

INITIAL DEVELOPMENTS

It is interesting to look at some actual figures which compare man's early radar accomplishments with that of the bat's in terms of efficiency, power and frequency. First, however, let us examine how man learned about radar and how he developed it.

It is known by most people who have an interest in electronics and electrical engineering that it was Heinrich Hertz who discovered the radio wave. He is also the one who discovered the phenomena which makes our modern day radar possible. In 1886, in Karlsruhe, Germany, Heinrich Hertz found that radio waves of about 60 centimeters could be reflected from solid conducting objects, and that these waves could be bent through such insulating materials as paraffin wax. It is said that he also established the basic principle of the directional detection of radio waves by means of a loop antenna.

In 1903, Christian Huelsmeyer of Dusseldorf did some experimenting with radio waves reflected from ships. This was the result of a suggestion made by Marconi when he was informed of the discovery by Hertz. Marconi said the phenomena of reflection should be used to assist ship navigation. The importance of using the reflection principle to aid ships can be appreciated only when you realize the difficulty of steering at night or in dense fog. No wonder there was so much active interest in trying to adapt this principle to ship navigation and to the detection of objects in the dark. Naturally, some scientists began to wonder if storms at sea could be detected and their direction determined so ships might be steered to avoid them. Thunderstorms, of course, generate electro-magnetic signals in the form of lightning pulses.