Chapter 1

Introduction and Overview

This book is a broad introduction to the theory and practice of modern remote sensing radars. Radars are one of the earliest engineering systems developed yet one that is relevant today, as new technologies enable the application of fundamental principles to modern needs. We begin with a little historical background that provides an interesting example of improvised, creative design, as well as an illustrative example of two fundamental modes of radar operation.

The well-known acronym stands for RAdio Detection And Ranging, derived from its original purpose, which was to sense the presence of remote or obscure objects and to simultaneously estimate the distance to those objects. The source of the term appears to be the U.S. Navy, which first coined it in the early years of World War II, an intense era of radar development, but the U.S. Army and the British also claim it. While maintaining its original technical meaning, today the term 'radar' is used in common speech to describe a range of subjective inferences as well. Today, in addition to its technical 'systems' aspect, the word has become an ordinary noun in common speech where it refers to a physiological state of awareness,. In many ways, though, the two uses are very similar as the original radar referred to a means of 'seeing' with radio waves while subjective 'sensing' refers to use of human intelligence and learning beyond vision.

In popular conception, radar devices operate by emitting a 'searching,' beamed, burst of electromagnetic energy into space and then 'listening-out' for an echo. When an echo is received a 'target' is said to be 'detected.' Simultaneously, the position of the target is determined from the combination of the direction of the beam and the time required for the pulse to reach the target and the echo to return, which allows calculation of the distance, or 'range,' to the target.[1] Most radars operate somewhat in this fashion. Further, there are many subtleties not revealed by the simple picture just described. As one example, targets are typically in motion with respect to the radar, and relative motion of the target has a important impact on optimal design of radar systems. Beyond such subtleties, an increasing number of important systems rely on configurations that are very different from a simple 'listen for the echo' system.

Our goal in this work is to set forth the underlying principles governing the performance of all radars, with an emphasis on those of importance of broad interest for civil, geophysical, and environmental applications of remote sensing. At the same time we hope to convey some of the practical lore of radar that current and future radar users, designers, analysts, and managers of radar systems will find helpful in understanding and addressing broad aspects of radar design related to remote sensing. Radar grew from an amalgam of skills drawn from several fields, including such esoteric areas as electromagnetic wave propagation and scattering, optics, antennas, and theories of information, signal detection, and games, to name some of the more prominent ones. Currently, work on modern radar systems continues both to depend on and motivate these fields. For this reason it is necessary to draw on sometimes disparate sources in order to construct a reasonably complete picture of how radar systems work and the manner in which various components of radar systems are optimized to best address a particular design problem.

Successful application of radar to scientific studies and exploration requires a thorough understanding of the subject of investigation as well as the intended application area. This is the *sine qua non* of the scientific use of radar. As an example, one who knows radar cannot become an oceanographer solely by studying the characteristics of radar echoes from the sea. But individuals or teams of individuals possessing detailed knowledge of physical oceanography *and* radar have produced marvelous systems for remotely sensing, *e.g.*, from ships or satellites, properties of the sea based on observations of radar signals reflected by ocean waves. Among the several skills needed, successful ventures of this type inherently require an understanding of the interaction of electromagnetic waves with the rough surface of the sea. Consequently, in this work we seek to provide an understanding how radar echoes are formed. Stated differently and more generally, we address the interactions of radar wave interactions with objects and surfaces inherent in remote sensing of the environment, which is more specifically known as

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[1] Readers will note that much of the jargon associated with radar systems arises from historical military roots, which drove early development. These terms remain today as they describe specific traits even if they are no longer used in their original context.

'scattering.'

1.1 Concepts and Origins

The fundamental properties of electromagnetic waves necessary for functioning of a radar, including their reflection by metallic and dielectric objects, were demonstrated in 1886 by Heinrich Hertz who carried out a series of laboratory experiments and demonstrations of wave generation and reflection phenomena at a wavelength of only 0.66 m. Subsequently, the earliest system developments required half a century to emerge. The earliest practical demonstration of reflections of radio waves for detection of remote objects followed at the turn of the century, as documented by patents for a land-based system awarded in 1904 to Christian Hülsmeyer on the basis of a *detection* of ships at ranges up to 3 km.[2] Marconi, who founded and built a thriving business on long-wave radio communications, suggested in 1922 the use of self-contained electromagnetic detection systems for use onboard ships. The first known demonstration of a practical U.S. ship detection system in the U.S. also occurred in 1922 when Taylor & Young at the U.S. Naval Research Laboratory used a 5-m wavelength, continuous-wave interference system to detect a wooden ship steaming on the Potomac River near Washington, DC. Three years later, in 1925, Breit & Tuve of the Carnegie Institution of Washington used a pulsed system to determine the height of the ionosphere, thereby providing an example of a time-domain implemention of a ranging system operating at a roughly 75 km range. By then the fact of remote sensing of objects by electromagnetic systems was well established, although it would be several more years before a compact system with collocated transmitter and receiver and improved precision was achieved, and fifteen more before the acronym RADAR was created. Progress in the 1930s was extremely rapid following these early steps, with many of the earliest and continuing developments in the U.S. at the Naval Research Laboratory carried out in secrecy. Similar development work was in progress in England and Germany, with the British making critical contributions to efforts in the U.S.

Research and development related to military radars provided the technical underpinnings and skills central to later developments in electronic computers as well as the machines of high-energy physics. For example, design and operation of the large particle accelerators rely on the availability of very high-power klystron microwave amplifiers developed for radar to

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[2] That is, Hülsmeyer's device could remotely sense the arrival or departure of a ship with the range of his apparatus, but could not accurately determine the position.

provide the energizing waves for the electron and positron beams. Picosecond resolution timing circuits employed originally in nuclear reaction analyzers and now routinely in semiconductor laboratories are the descendants of trigger circuits developed for switching early radars. At the same time, radar benefited from developments in electronic capabilities. For example, data modems and the earliest computer networks were created as links connecting multiple radar observation sites with a central data processing facility for the purpose of tracking aircraft.

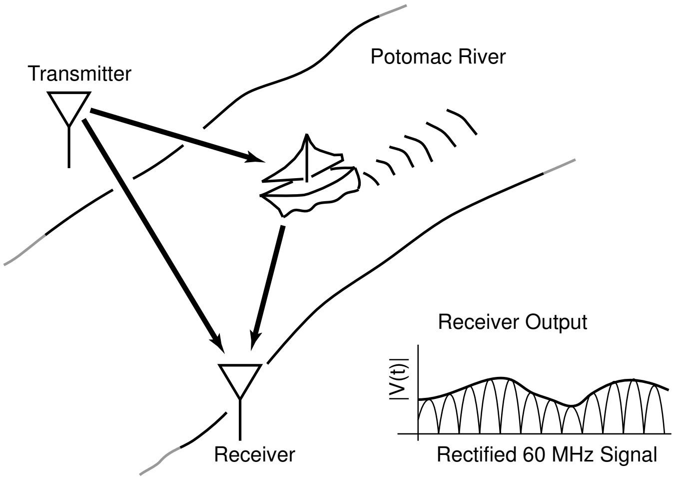

Figure 1.1: Geometry of Original Taylor & Young Interference Radar System, 1922. Signals reflected from boat on the river and those propagating directly from the transmitter 'interfere' at the receiver. Beats between direct and reflected signals are 'detected' by rectifying the receiver output.

Figure 1.1 illustrates the principle of the interference system employed by Taylor & Young in 1922 to detect the presence of vessels on the Potomac River. The experimenters placed a continuous wave, or 'CW,' transmitter and receiver on opposite shores. Signals radiated by the transmitter reached the receiver by the direct path between the two, and also by a reflection path from boats on the river. Both signals appear at the receiving antenna, where the output signal is the linear sum of the two inputs. The receiver was a simple amplifier with a rectifier serving as the 'detector' for which the receiver output was the signal envelop, *i.e.*, a voltage proportional to the magnitude of the summed input signal. The phase and amplitude differences between the direct and reflected signals depended on the difference in the two path lengths and on the 'disturbance' of the illuminating wave, which in turn depended on the electromagnetic wave *scattering*, properties of the boat. As a result of the boat's motion the characteristics of the reflected signal, in particular its *time delay* with respect to the signal received directly from the transmitter, varied at the receiver. Each change of 2π in the phase difference between the two signals indicated a change in the path difference of one wavelength, which was apparent at the output of the detector. Through this mechanism the motion of the boat resulted in a regular pattern of variations in the receiver output, thus revealing the boat's presence and some information about its progress on the river (*v.* inset, Fig. 1.1). This experiment is widely accepted as the first demonstration of a radar system, although Hülmeyer's patent precedes it, while others reject it as incomplete.

A little thought and some simple calculations will show that the rate of signal variation can be related to the combination of the position and velocity of the boat relative to the transmitter and receiver. On the other hand, the strength of the modulation is related to the size, shape, orientation, and position of the boat in that these affect the strength and phase of the scattering. So we immediately see that the performance of the radar depends on the combination of the hardware system, the geometry, and the electric wave scattering characteristics of the 'target.' The geometry and arrangment of the Taylor & Young experiment is referred to as a *bistatic* configuration, denoting the well-separated transmitter and receiver, as well as aspects of the system design that depend on the separation. Users of WiFi and cellular systems will recognize the parallels between the phenomena described above and the multipath communication problem in which interference between directly propagating and reflected digital signals can have deleterious effects on the performance of the data link. The underlying interference phenomenon is physically the same as that observed directly by Taylor & Young, with the primary difference being use of an unmodulated waveform to detect the boat.

Figure 1.1 illustrates a second type of system fielded by Breit & Tuve in 1925, just three years later. In this instance the experimenters for the first time employed a *pulsed* radar to measure the time required for an electromagnetic wave to travel to and from the radar located on the ground and Earth's ionosphere, which is the shell of ionized, conducting gas found in Earth's outer atmosphere. Breit & Tuve found it necessary to place the transmitter and receiver on opposite sides of a small hill in order to prevent the transmitted signal from overloading the receiver amplifier. Signals emitted by the transmitter reached the receiver along an near vertical, transmitter-ionosphere-receiver path $\overline{abc}$. In addition, there was considerable leakage between the transmitter and receiver by diffraction, scattering, and ground wave propagation via the over-the-hill path $\overline{ac}$. Because the shortest pulses that could be generated with the

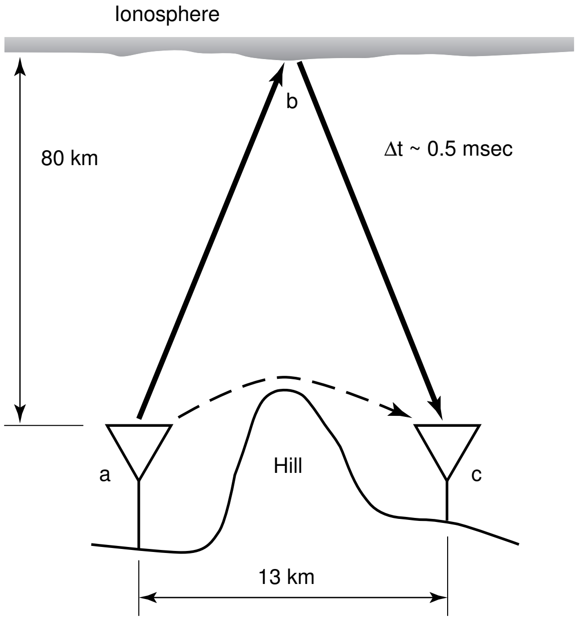

Figure 1.2: Breit & Tuve Setup for Ionospheric Height Measurement. Height of the ionosphere was first measured by Breit & Tuve using a pulsed-signal reflection system. Folklore has it that the hill in this experiment was Capitol Hill in Washington, D.C., although we have not been able to firmly validate this claim.

technology of the period were of the order of millisecs in duration, signals traveling to the receiver along the two paths overlapped somewhat in time (*v.* Fig. 1.1). In the absence of the hill acting as a screen, the ionospheric echo would have been undetectable in the presence of the strong pulse from the nearby transmitter.

The arrangement of Breit & Tuve's measurement is fundamentally different from that of Taylor & Young's in that the transmitter and receiver are geometrically close to each other as viewed from the reflection point in the ionosphere. Except for the need to use the hill to improve the dynamic range of the system, the transmitter and receiver could shared a common location. A configuration in which the transmitter and receiver are collocated is referred to as *monostatic*, implying that only *backscattered* echoes are observed.

Early British work was closely related to that in the U.S. and led the field in important ways. By the beginning of 1940 a number of radar stations operating at 25 MHz ($\lambda = 12$ m) were in place along the eastern and southern shores of England and Scotland for detection of enemy aircraft approaching the coast from mainland Europe. This system was known by the code name "Chain Home." Chain Home could operate in either a cooperative interference mode

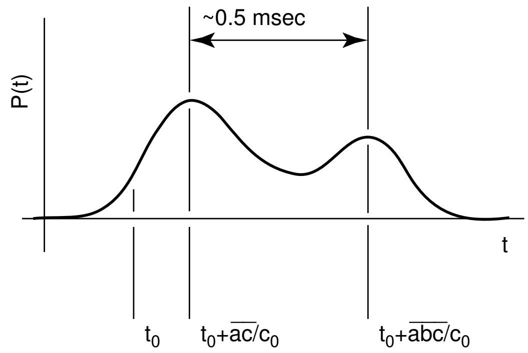

Figure 1.3: Breit & Tuve Ionospheric Echo: Direct and echo signals received by Breit & Tuve overlapped as a result of length of transmitter pulse. Transmission time is t_0, speed of light is c_0.

employing two or more stations, similar to the Taylor & Young experiment on the Potomac, or in a single station mode with the same site transmitting and receiving, similar to the original Breit & Tuve configuration albeit with the use of antennas directed toward the horizon. Thus, the Chain Home system could operate in either a monostatic or bistatic mode. These radars provided data on the location and speed of approaching aircraft that were critical to the efficient use of the numerically weaker British fighter force.

A British invention critical to the future course of radar design was made by Boot and Randall in 1940. The *magnetron* oscillator/amplifier was the first high-power microwave tube capable of producing very large pulse powers at frequencies above about 300 MHz, corresponding to wavelengths much shorter than 1 m. This development made possible the construction of pulsed transmitters capable of producing transmissions of only 1–10 μsec duration, or 100–1000 times shorter than those employed by Breit & Tuve. The result was a practical means of achieving high time-of-flight range resolution in combination with good angular accuracy with conveniently sized antennas. These charactersitics made possible efficient, compact designs suitable for use as detection and localization systems onboard aircraft and ships, as well as for early aircraft remote sensing systems. Subsequently, the vast majority of radars are refined extensions of early monostatic designs, although accumulated progress in transmitter, receiver, antenna, and signal processing technology renders a modern radar virtually unrecognizable at first glance as a successor to the earlier forms.

The systems employed in the two experiments by Taylor & Young and Breit & Tuve are the forerunners of all modern radar designs for which the four corners of the design space are i) monostatic and ii) bistatic geometries, iii) pulse-modulation, and iv) continuous-wave transmission. Modern radar systems provide examples of all four basic types, although bistatic systems and geometry relatively unusual. The primary conceptual extensions beyond the early stages are the broad development of modulation and signal processing techniques and the use of *multistatic geometries* in which the number of transmitters plus receivers is more that two, requiring the addition of a fifth vertex to our bounding box.

The literature of radar contains literally millions of entries, and no one can be familiar with the full breadth of this work. Further, an individual can devote an entire career to one of the subspecialities related to radar, such as transmitter or antenna development, signal processor and detector design, or analysis of radio wave scattering. But not to worry, the fundamentals or radar systemss are relatively few, and we introduce and explain the important concepts here.

The appendices contain a bibliography providing a selection of works and critical comments which the reader can use to guide further exploration of the field.

1.2 Modern Uses and Related Applications

What remained at the end of 1925, and is ongoing to the present, is the task of understanding fundamental constraints on the performance of radar systems and then in technological development, with the goal of finding refined implementations that approach known limits of optimum performance. While the frontiers of the last century were, for example, the limits of resolution, optimal design of waveforms, and digital realization of signal processing, current problems in remote sensing deal with issues such as optimal methods to distinguish between cultural and natural features of Earth's surface, estimation of the global biomass, the thickness of arctic permafrost, and the depth of the ice layer on Jupiter's moon Europa, detection of minute changes in the topography of Earth, and estimation of surface winds over the ocean. While the genesis and primary development of radar has its roots in military and navigation systems, the techniques and technology of radar have migrated to many other fields, as have the applications and the questions addressed.

Today, many radars are designed specifically for scientific and civil purposes, while others are adaptations of military radar systems to civilian ends. Consider that there are at least four broad categories of radar, as listed in Table 1.1.

While the concept of radar and the ideas discussed in this volume consider primarily electro-

Catagory	*Function*	*Subjects of Interest*
Astronomy	Scientific study	Planets, asteriods, comets, Sun
	Space exploration	Navigation, planetary sensing
Civil	Surveillance and control	Ships, aircraft, motor traffic
	Detection	Door openers, burgular alarms, collision avoidance
	Sports	Ball speed
	Weather	Rain tonight?
Defense	Surveillance & Detection	Vehicles, personnel
	Tracking, Guidance	Terrain avoidance, landing systems
Environmental	Scientific	Atmosphere, ocean, solid earth
	Geophysical	Earth's shape, continental drift
	Observation	Noctural birds and insects in flight
	Monitoring	Seismic shift, sea state, ice flows
	Policy & Management	Crop yields, forest health

Table 1.1: Some Major Categories of Radar Systems. Lists such as these are necessarily incomplete. Note the breadth of applications stretching across a wide range of cultural and economic segments of society.

magnetic systems, we note that there is also a number of systems based on use of mechanical, ratherthan electromagnetic waves. Indeed, the waves employed in radar-like systems need not be electromagnetic. Table 1.2 lists some examples of sensing techniques that are either near or direct analogs of radar. In these instances radar methods are adapted for use of acoustic or seismic waves, or electromagnetic waves are used in an unusual manner or in an unconventional setting. Predating these are are the evolved biological adaptations evident in nature, but which exhibit striking parallels to modern systems.

As indicated above, the topic of radar draws from many disciplines. The melange of ideas and concepts underpinning the development of modern radar touches or incorporates a wide range of topics presently considered part of electrical engineering systems and principles, incompasing coding, information, detection, and game theory, signal processing, very high-speed switching, communications, computation, and data networking, all resting on basic physical

Probe Type	*Functions*	*Examples*
Acoustic Probes	Imaging	Medical diagnosis, non-distructive testing
	Material science	Determination of physical properties
	Acoustic microscope	Physical science experiments
Lidar	Remote sensing	Determination of effluent species
	Ranging	Surveying, Earth motions, space science
Seismology	Earth sensing	Imaging Earth's interior
	Exploration	Location & evaluation of minerals
Sonar	Oceanography	Mapping of ocean bottom, navigation
	Military	Underwater detection and communication
Biological	Prey detection	Bats, moths, porpoises
	Navigation	Dolphins, whales

Table 1.2: Radar-related technologies. With the exception of lidar, which is the optical analog of radar, the types and examples listed exploit the properties of mechanical, rather than electromagnetic, waves. Seismic probing can be based on the use of natural sources, as in the example of earthquakes, or intentional man-made sources such as controlled explosions. An understanding of the principles of radar can be applied directly to the mechanisms of many of these examples.

principles, including electromagnetics, wave propagation and scattering, and aspects of atmospheric science, oceanography, and geophysics, etc. Each of these topics, and many others, comes into play in some important aspect of the radar problem. Every system designer needs to be aware of these issues and, in the technical specialties, some designs require collective expertise in one or more areas.

In this volume we show how the several most significant of the topics above fit into or affect the performance of a radar system. To begin, Chapters 2 through 10 address fundamental issues of radar design and performance applicable to all radar systems, largely independent of intended application. The remaining chapters build on the fundamentals to develop a foundation for the study of advanced systems.

There are many histories of the early years of radar and its development, each interesting in its own right. We note that some of these work are replete with interesting examples of what was done and why, but also reveal the thinking behind *how* things *are* done. Two of the more popular are those by R.M. Page *Origins of Radar*, and A. Price, *Instruments of Darkness*, (*v.* Bibliography) which provide a comprehensive study of developments in the U.S. during WWII. A well-researched, recent history is *The Invention That Changed the World...*, by R. Buderi. Buderi's discussion nicely ties together the prominent American threads leading to important developments, primarily at MIT Radiation Laboratory, but also including the early British contributions.

Buderi's work is likely to become a standard reference for U.S. contributions in WWII through the height of the Cold War. A more personal account of early developments from a British point of view is given by E. G. Bowen in *Radar Days*, which describes contributions by the author to early research and development in radar, and his leadership of the development of airborne systems; the climate of the initial work in the field closely resembles that in the competitive startup environment of today, and is instructive reading. The work by H. von Kroge at GEMA is also a personal account reflecting the development of radar in Germany. Such works are valuable for their contribution to the history of our subject and its technology, and for the insights they give into the early applications, the ways in which technical innovation occurs, and the evolution of countermeasures that often drive military radar development. Some of the technical thrusts/reposts presages the tactics and strategies employed by modern computer manufacturers in jockeying for position in the modern marketplace.

In the rest of this work, as you will see, based on the large number of ways in which the basic physical phenomena can be exploited, we take a very broad view as to the definition of radar and include a wide range of configurations and unconventional systems of operation within the rubric. We endeavor to show that the basic principles of radar design, operation, and analysis have expanded to unanticipated applications in many topical fields. In one example, a modern manifestation of the Taylor & Young geometry, unmodulated signals transmitted by the Voyager and Cassini spacecraft and received on Earth have been used to study properties of the material making up the Rings of Saturn. 'Scattering' of the radio signals by particles within the rings can be detected on the ground at times when the spacecraft passes near or behind the ring system. In such instances as these and for the Taylor & Young experiments, we think in terms of a disturbance of the sensing wave rather than an 'echo' because the disturbed wave does not return to the source the way an 'echo' does. While these two experiments at first glance seem quite different, the analysis and interpretation of the data are nearly the same, albeit accomplished with with very different technologies. This is the trend of the future, in which developments in communication and signal processing make practical ideas and implementations that would astound the workers of ‘early days.’