1 Introduction

Radar was developed for military use leading up to and during World War II. The first direct application of the use of radio waves to detect objects was by the German inventor Christian Hülsmeyer in 1904. It wasn't until June 17, 1935, that radio detection and ranging were demonstrated in Britain by Robert Watson-Watt and Edward George Bowen, who are generally credited with the invention of what was later termed "radar." *Radar* is an acronym for RAdio Detection And Ranging (or sometimes RAdio Direction and Ranging) and was first used by the U.S. Navy in 1940 [1]. Since its inception, the applications of radar have grown and diversified in numerous ways, including applications in the military, geophysics, astronomy, manufacturing, meteorology, automobile navigation, and more. During World War II, it was first observed that weather was causing unwanted echoes on the radar display. This led to the beginning of meteorological applications, thanks to the abundance of radar systems that were made available after the war for civilian research and the study of precipitation. Weather radar has since evolved independently. The first weather radar networks during the 1960s and 1970s could only measure reflectivity (these are known as reflectivity radar or *noncoherent radar*), providing information on the position and intensity of precipitation.

In May 1973, for the first time, a Doppler radar was used to document the life cycle of a tornado in Oklahoma. The radar observations showed the appearance of a cyclonic circulation aloft before the tornado touched ground [2]. This offered a glimpse of the forecasting potential deriving from additional radial velocity observations using coherent radar systems, marking the inception of the first key technological innovation in the history of weather radar, the Doppler weather radar. By the late 1980s, networks of Doppler radars started to be deployed worldwide, allowing forecasters not only to see the position and intensity of precipitation but also to get an unprecedented picture of the storm's dynamics and detect possible rotation in supercell storms (mesocyclones) and tornadoes. Between 1980 and 2000, Doppler weather radar networks became an essential component of the meteorological observation infrastructure in North America, Europe, Japan, and other developed countries. During this time, the observations from these radars started to be intensively used by national weather services, research institutions, and television stations.

The second major key innovation in weather radar technology has its roots in the research initiated during the 1970s, but eventually fed into operational systems and national weather networks around the turn of the millennium. In addition to coherency to exploit phase measurements in Doppler radar systems, dual polarization weather radar added a completely new dimension to the radar observation's capability, introducing a change comparable to going from black-and-white to color pictures in photography. These new colors, the polarimetric variables are rigorously defined and discussed in Chapter 4. Dual polarization technology had been a research topic for many years before becoming mainstream for radar operations. Nowadays, products based on polarimetric observations are routinely used to improve fundamental radar applications, such as flood forecasting and hail detection.

A third wave of innovation that benefited this field is the concept of small radar networks. At the time of writing this book this wave is still in its early stages, but the fundamental deployment strategy of weather radars has been changed. Historically, the national radar networks were considered expensive and were part of the national infrastructure for weather and aviation. However, the lower-cost small radar networks spearheaded by the Collaborative Adaptive Sensing of the Atmosphere (CASA) program [3] have changed the strategy. Now, local and state governments, and even private entities, are deploying small and dense weather radar networks. Of course, all these waves of innovative developments in radar meteorology have been aided by rapid technological advances in signal processing, computing, and communications.

The continuous evolution of weather radar technology and science has led to the new discipline of radar meteorology, which is taught in many universities around the world. Radar meteorology is often part of atmospheric sciences programs, but it's not a pure atmospheric discipline like most other course topics in these programs. The concept of weather radar is, rather, a combination of four disciplines: microphysics, dynamics, signals, and electromagnetics. Therefore, radar meteorology is fundamentally a multidisciplinary topic simultaneously housed in programs of atmospheric sciences, physics, and electrical engineering. The radar meteorology field has therefore enjoyed immense innovation afforded by the varied cross-disciplinary thinking over the decades of growth. A person taking a course taught from this book should be able to develop a basic understanding for practice in radar meteorology, as well as conduct research and operations with dual polarized weather radar. This book provides the necessary foundation for students to interpret dual polarized weather radar observations for both research and operational purposes. This book is intended for students who have completed basic college-level math and science prerequisites, such as physics, algebra, and calculus. Upon completion of the course, the student should be able to do the following:

- Understand the basic principles of a dual polarization weather radar system and be able to identify the radar system elements.
- Have the basic precipitation physics background needed to understand and interpret dual polarization radar observations.
- Be able to understand the principles of electromagnetic scattering from precipitation particles, including scattering of dual polarized electromagnetic waves.

- Understand the basic theory of weather radar signals.
- Develop a good understanding of the signal-processing system associated with a modern dual polarized weather radar.
- Understand the basic principles and applications of hydrometeor classification used with all modern operational and research dual polarized weather radar systems.
- Understand and apply rainfall estimation from weather radars.
- In addition to all these, the chapter on data quality provides a scientific basis for data quality and provides an understanding of limitations on interpretations. In the modern era of data science, the data quality chapter prepares the student to develop confidence in the dual polarization radar data set.
- Once a student has mastered all the essential fundamentals and applications, this book also prepares the student for the future of the field. The student will not only be able to analyze and interpret the individual radar observations but also to design an appropriate network and redefine network operations.

1.1 Radar in Meteorology

Earth's atmosphere has a layered structure that is based on how the temperature changes with height above the surface (Fig. 1.1). The troposphere is the lowest layer of the atmosphere, extending from the ground level up to about a global average of 13 km in altitude (locally, the height of the troposphere varies between 9 km over the polar regions and 17 km above the equatorial regions). The temperature decreases upward in the troposphere, reaching an average lowest value of -57°C on the top, and then starts to rise in the adjacent layer above, the stratosphere. The upper boundary of the troposphere is marked by the tropopause, a relatively thin layer (typically a few hundred meters deep) where the temperature inversion keeps the humid air of the troposphere separated from the dry stratosphere.

The troposphere is the portion of the atmosphere where weather occurs because it contains 99 percent of all the water vapor, the fundamental constituent of clouds. When an air mass in the troposphere becomes saturated with water vapor (reaching 100 percent relative humidity), condensation produces clouds, which may then form precipitation as soon as cloud particles (either liquid droplets or ice crystals) attain a size large enough to fall as a result of gravity. Precipitation has been measured historically by means of rain gauges, which provide the amounts of accumulated water at given locations over a time interval. Clouds and precipitation can also be remotely observed by exploiting the electromagnetic waves in a range of frequencies that goes from the visible portion of the spectrum to the radio wave, using airborne, spaceborne, and ground-based instruments. Active remote sensors like radar and lidar (*lidar* is an acronym for Laser Imaging, Detection, And Ranging) emit their own source of energy to illuminate a target (a cloud) and then analyze the returned signal. Conversely, passive sensors require some energy to be naturally available, either reflected (e.g., the

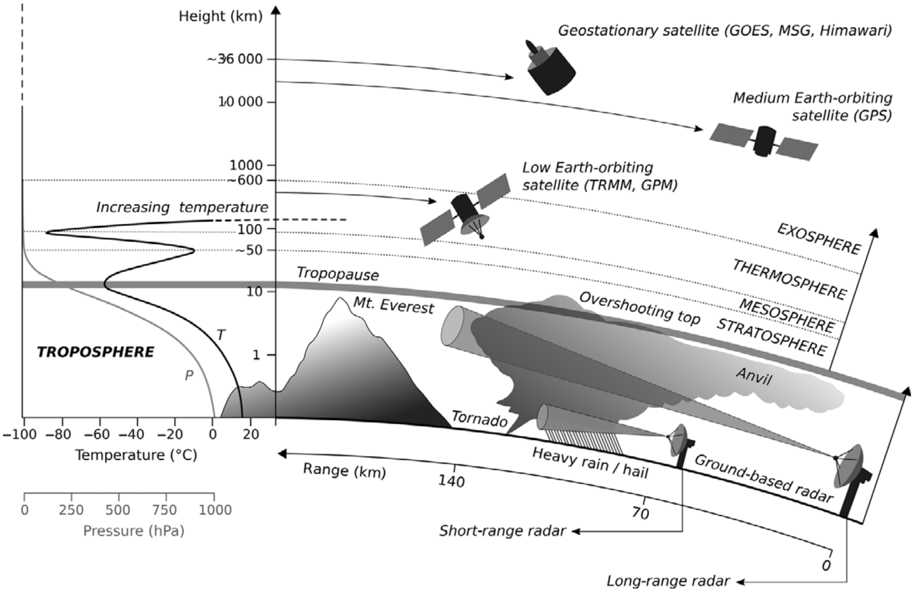

Figure 1.1 Vertical structure of the atmosphere, with height in logarithmic scale. On the left, the average profiles of pressure (gray line) and temperature (black line) drive the partition of the atmosphere in successive layers. The tropopause is the boundary between the troposphere and the stratosphere, located at an average height of 13 km. On the right, short-range and long-range ground-based radars are depicted as they observe a thunderstorm penetrating into the stratosphere (overshooting top). Weather systems can also be observed from space by low Earth-orbiting satellites, such as the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM) mission, and by geostationary satellites flying at altitudes of $\sim 36,000$ km, such as the European Meteosat Second Generation (MSG), the Geostationary Operational Environmental Satellite (GOES) operated by the United States, and Japan's Geostationary Meteorological Satellite "Himawari" (GMS).

sun's light reflected by clouds and detected in the visible channels of meteorological satellites) or thermally emitted (the infrared channels).

Ground-based weather radars have become an essential component of meteorological weather and aviation services around the world, with operational networks deployed in most countries and continuously providing updated observations every few minutes. Weather radar has evolved to the point that it plays a critical role in both developing our understanding of weather and also protecting people and property during severe weather events and supporting the transportation sector. The advent of dual polarization systems brought a paramount contribution to our understanding of precipitation microphysics. Since the early days of radar polarimetry during the 1970s, research focused primarily on rainfall, contributing to revealing the inner structure of precipitation down to the level of the individual raindrop's shape. During the last couple of decades, the ice phase of precipitation has received increasing interest as a result of the advances in modeling the electromagnetic response of complex ice-crystal shapes. Dual polarization observations have revealed a number of significant recurring signatures associated with different types of weather systems, from columns of differential reflectivity in convective storms to signatures of specific differential phase aloft in connection with enhanced snow growth (these and other characteristic signatures are discussed in Chapter 8).

Recent advances in radar technology include the development of lower-cost systems operating at shorter wavelengths. In fact, whereas operational weather radar networks have mainly been using the S band (10-cm wavelength, e.g., the WSR-88D network in the United States) or the C band (5-cm wavelength, e.g., in Europe and Japan), smaller networks of X-band radars (3-cm wavelength) are being deployed in many regions. The lower cost of shorter-wavelength systems directly derives from the smaller antenna size and shorter-range design, thus requiring lower-cost transmitters (Chapter 2), and allows for denser networks of short-range radars (as opposed to sparser networks of long-range systems), thus coping with the observation gap induced by the Earth's curvature (Chapter 10).

The radar observations are reported in a spherical coordinate system using azimuth, elevation, and range to spatially locate the observation volume, as shown in Figure 1.2. The observation volume (denoted by V) has a finite size in azimuth, elevation, and range, which are all determined by the radar's design and operating parameters. The azimuth follows the cardinal directions, where north is 0°, and the azimuth increases as the antenna rotates clockwise toward east (90°), south (180°), and west (270°). As the azimuth continues to increase, it "aliases" when crossing over north so that the azimuth is always from $0^\circ \leq$ azimuth $< 360^\circ$(where $0^\circ$and $360^\circ$are the same position). The radar's elevation is typically reported from 0° to 90°, with 0° pointing parallel to the surface at the radar's location (see Section 2.4.5 for beam-height discussion). At 90° elevation, the radar is pointing vertically (this is the mode of operation for vertical profilers).

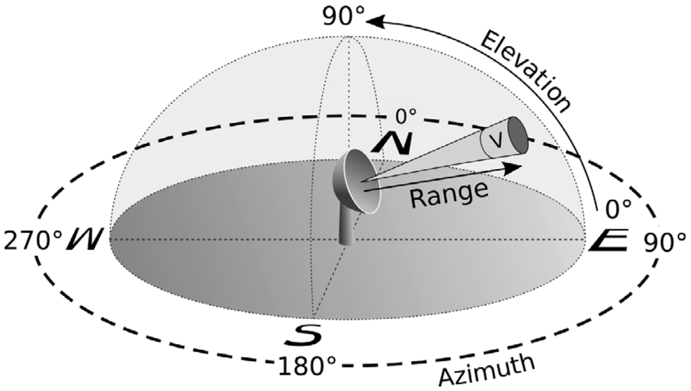

Figure 1.2 A diagram of the radar's spherical scanning volume whose coordinate system uses range, azimuth, and elevation. The radar measurements integrate a volume (V) defined by the antenna's beamwidths in the azimuth and elevation and pulses extent in the range (refer to Section 2.4.5 for a detailed discussion of the radar's geometry).

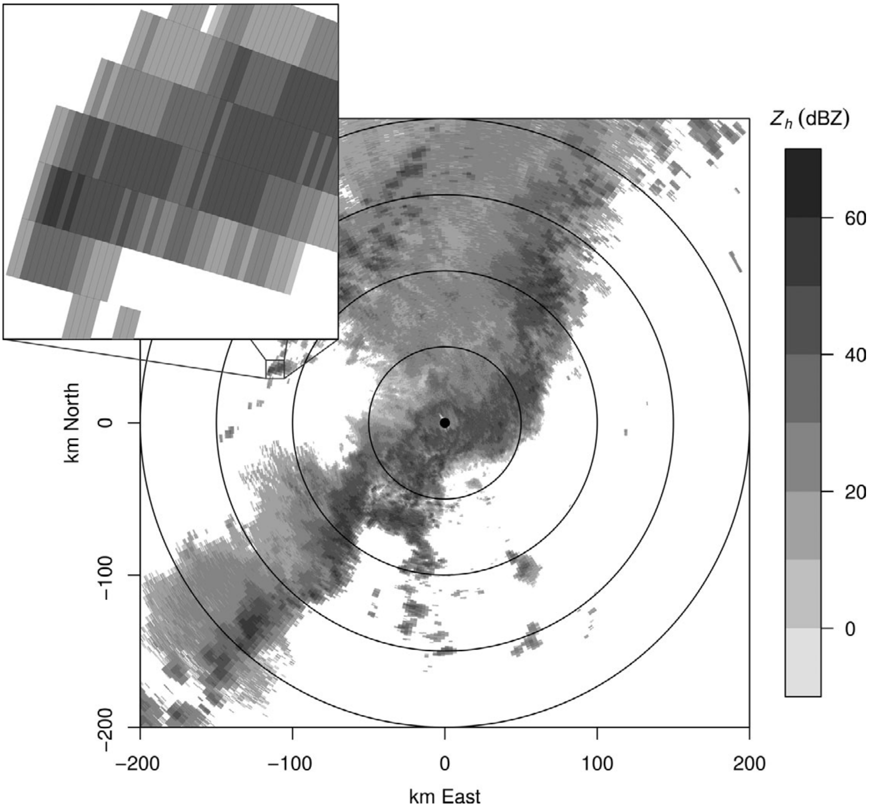

Figure 1.3 A PPI of the equivalent reflectivity factor for horizontal polarization at 1.5° elevation. The expanded view highlights the polar geometry of the radar volume, as well as the detail of the information (refer to Section 2.4.5 for discussion of the radar observation geometry).

Operational weather radars typically scan in a plan position indicator (PPI) mode, with the antenna completing a full rotation in the azimuth at a fixed elevation angle (Fig. 1.3). It is also common to find range-height indicator (RHI) scans, especially in research applications, where the antenna moves in elevation with a fixed azimuth angle. Some radar systems allow for the elevation to scan from 0° to 180°, which provides a "horizon-to-horizon" RHI scan, but strictly speaking, for describing the radar observation's position, the elevation is limited to 0° – 90°. Vertical pointing systems (also referred to as *zenith radar systems* or *vertical profilers*) are common in air motion, precipitation, and cloud observations. The scanning modes and the radar view geometry are discussed in Chapter 2 in greater detail.

Weather radar can also be carried by low-orbiting satellites, such as the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM), represented at an altitude of ~400 km in Figure 1.1. Although the operating principle of satellite-borne and ground-based radars is basically the same, the "art" of processing the collected observations requires specific expertise, which is essentially related to the different vantage points of the observing sensors.

1.2 Weather Radar Frequencies

The selection of the radar's operating frequency influences every aspect of the radar system design and performance, including physical size, system cost, and radar detection sensitivity. In addition, the coexistence of radar with other systems used by society, such as communication devices, also plays a role in the available choices. The various application groups, such as weather and climate, communication, and aviation, compete for access to a common resource: the frequency spectrum. The actual allocation of the frequency for the radars is managed by the frequency-allocation agencies of national and international regulations [4]. Using a higher operating frequency is one of the basic design decisions to achieve enhanced sensitivity at a lower cost. The radar's frequency selection is often an economic decision, and in many cases, the other "factors" that weigh on the radar performance also vary as the radar's frequency is varied. For certain applications, there are clear advantages to the use of some frequencies rather than others. In Chapter 4, we'll see that higher frequencies also attenuate more, which can reduce the sensitivity over long distances or in heavy rain. The scattering properties of hydrometeors are also frequency dependent. These frequency-dependent scattering characteristics can be informative, especially when comparing observations at two or more frequencies, allowing us to measure the microphysical characteristics of precipitation and clouds.

During World War II, radar frequency bands were referred to by letters for secrecy. Afterward, these designations were declassified, and the naming convention is still commonly followed, with a few accommodations. Previously, what is now divided into the Ku, K, and Ka bands was referred to as the K band. The subdivision was a result of the water-vapor absorption line at approximately 22 GHz, which hindered radar and communication system performance. This resulted in the Ku and Ka bands being identified as their own frequency bands (Ku being "K-under" and Ka being "K-above"). Other standards with different designations (or modified frequency ranges for the same letter designation) can be found. Here, we refer to the Institute of Electrical and Electronics Engineers (IEEE) standard, which was first issued in 1976. In 1984, the millimeter wave region was also revised to include letter designations, which are now the V and W bands. In Table 1.1, the 2002 revision [5] of the IEEE radar frequencies bands are listed. The sub-bands that may typically be used (but are not limited to) for weather radar applications are also shown.

As a reminder, f, the frequency (in hertz) and wavelength, λ, (in meters) are related through the speed of light, c, as $f = c/\lambda$. The speed of light in free space, $c = 299,792,458\,\mathrm{m\,s^{-1}}$, is typically used as a standard value for the speed of light in Earth's atmosphere.

Although radars operating at frequencies below the S band can detect precipitation, they are not typically used for such applications. Compared with the size and

Table 1.1 IEEE radar frequency band designations with typical weather radar frequency ranges.

IEEE Radar Band	IEEE Frequency Range	Typical Weather Radar Band
HF	3–30 MHz	
VHF	30–300 MHz	
UHF	300–1000 MHz	
L	1–2 GHz	
S	2–4 GHz	2.7–2.9 GHz
C	4–8 GHz	5.6–5.65 GHz (in the U.S.)
X	8–12 GHz	9.3–9.5 GHz
Ku	12–18 GHz	13.4–13.75 GHz
K	18–27 GHz	24.05–24.25 GHz
Ka	27–40 GHz	35.5–36.0 GHz
V	40–75 GHz	
W	75–110 GHz	94.0–94.1 GHz

performance possible with S-band and higher-frequency systems, radars in the VHF, UHF, and L bands are typically limited to characterizing winds, turbulence, and air motion. Vertically pointing wind profiles, operating at frequencies as low as 50 MHz, are used to measure air motion, but the vertical motion of precipitation is also measured. Vertical profilers for air motion (and precipitation) also include the 404-MHz National Oceanic and Atmospheric Administration (NOAA) profiler network and the 449-MHz and 915-MHz profilers as examples.

S-band weather radar systems are commonly used around the world in places where long operating ranges are needed. The WSR-88D (commonly known as NEXRAD) weather radar network is composed of S-band radars observing to ranges of 300 km and more. S band is ideal for observing precipitation, especially severe weather, because of the negligible attenuation in rain or ice. For all but the most severe weather (e.g., large hail), the scatterers are in the Rayleigh regime, and the S-band equivalent reflectivity factor closely matches the reflectivity factor (see Section 2.3.1). S-band weather radars are large systems (with 8.5-m-diameter antenna). The S-band frequency spectrum is crowded, and for radars located near populated areas, interference sources can degrade performance.

Like S band, C band is commonly used for operational weather radars around the world. C band has become more popular since the introduction of dual polarization, which can be used to mitigate the effects of attenuation due to precipitation (see Chapter 9), and the radars are lower cost compared with S band. In the United States, the terminal Doppler weather radars utilize the C band for monitoring weather around major metropolitan airports. For the same antenna beamwidth, a C-band antenna's diameter is approximately half that of an S-band antenna. The C-band radar is typically a more compact system, largely due to the reduced size of the antenna and pointing system. C-band weather radars experience low attenuation, except for the heaviest convection with the largest raindrops or hail, for which dual polarization methodology can mitigate the effects of attenuation. Because of the combination of higher sensitivity with frequency and lower system cost (a result of a smaller antenna), C-band radars have been extremely popular. As with the S band, the frequency spectrum at the C band is also crowded and subject to radio-frequency interference from communication infrastructure that can hamper radar operations.

X-band systems provide a relatively compact solution for mobile weather radars and networked short-range radar systems. One major advantage of X-band radar systems is that they are small and compact enough that they can be deployed on existing infrastructure, such as building rooftops, communication towers, and trailers. X-band radars are more adversely affected by attenuation in rain, and as a result, this can limit the X-band radar's effective range during extreme weather if the attenuation effect is not compensated by an increased transmitter power. To keep costs low, X-band radar systems are typically operated with observation ranges on the order of 50 km. As a result of the compact size and relatively low costs of short-range X-band radars, dense networks of overlapping systems are being deployed to provide higher spatial and temporal resolution. This solution has found rapid adoption in urban systems, where it may be cost prohibitive to find real estate to deploy large radar systems because their social footprint is fairly high. Because of the small size of X-band radars, they are easily deployed on trucks and used for mobile deployment to track severe storms or for temporary/seasonal deployments.

Ku-band performance is similar to that of the X band. For the same beamwidth, the Ku-band radar has a slightly smaller antenna but also suffers from slightly more attenuation in rain. Ku-band weather radar systems are found on precipitation-observing satellites and are also used in atmospheric research. K-band radars are subject to enhanced attenuation as a result of increased water-vapor absorption around 22.24 GHz. Millimeter-wavelength radars (i.e., 30 GHz and above) used for precipitation observations primarily fall into the Ka and W bands. Because of their high attenuation rates in rain, these wavelengths focus on observing clouds, drizzle, and light rain at short ranges from the ground. Similarly, the differences in the scattering and attenuation at these frequencies make their observations important for characterizing the properties of the clouds and precipitation, especially when combined with observations at other frequencies. As a result of the short wavelength, these radars can be implemented in compact form factors while still achieving high sensitivities and fine spatial resolution.

1.3 Book Content

The book is organized as visually illustrated in Figure 1.4. Chapter 2 introduces the fundamental concepts of radar systems, including a description of the radar-centric observation geometry, the weather radar equation, and typical system configurations, along with a discussion of the main radar components. Then, the book presents three main themes:

- Essential background topics, namely, precipitation physics, are described in Chapter 3, whereas the necessary background electromagnetics are described in Chapter 4. These chapters provide essential background for the interpretation of

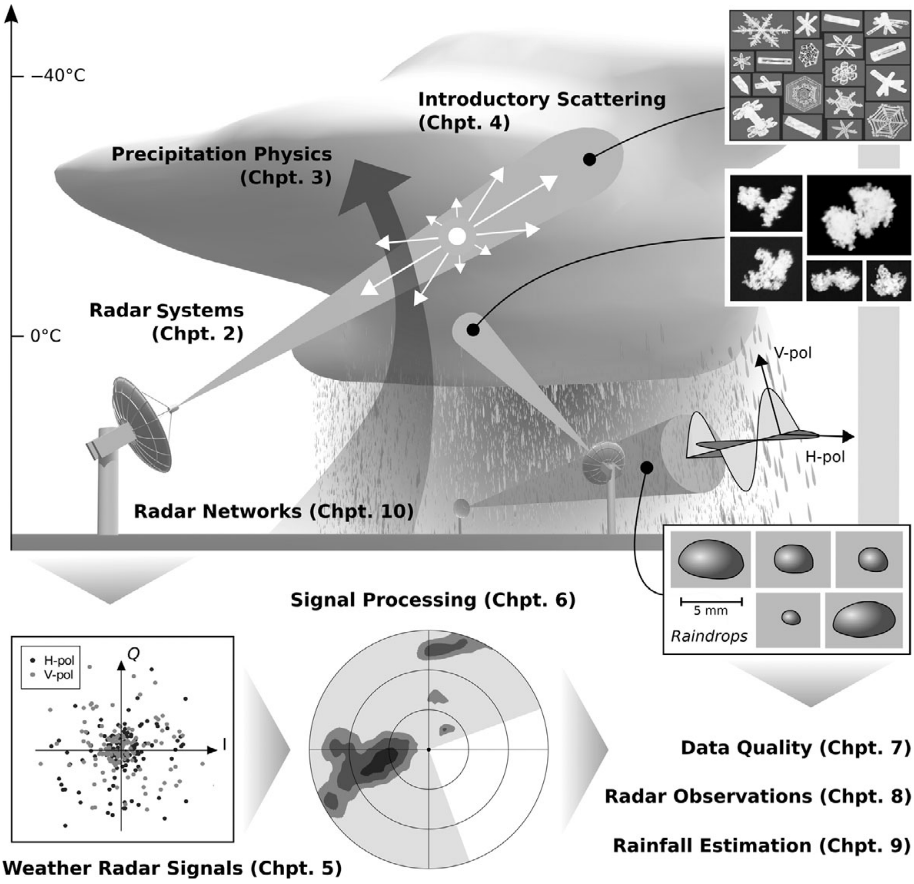

Figure 1.4 A network of three radars looking in different regions of the cloud provides a graphical overview of the book content. Crystal images in the top-right corner courtesy of SPEC$_{\text{inc}}$

the radar polarimetric observations, in terms of both the microphysical processes leading to precipitation in its various forms and the electromagnetic response of precipitation particles to the transmitted polarized wave.

- The next theme is the topic of radar signals, where the basics and origin of weather radar signal theory and properties are described in Chapter 5, and signal processing is explained in Chapter 6. In these two chapters, the theory of weather radar signals is described to provide the basis for the estimation of the radar variables from received signals. Some advanced signal-processing concepts, such as the pulse compression used in modern radars with solid-state transmitters, are also included in Chapter 6.
- The third theme is weather radar applications and includes chapters on data quality (Chapter 7), radar observations (Chapter 8), rainfall estimation (Chapter 9), and radar networks (Chapter 10). Data quality is discussed in Chapter 7 to provide guidance on the characterization of measurement accuracy and the interpretation

of radar measurements. Although example radar observations are provided throughout the book in support of the relevant topics being discussed, Chapter 8 is specifically devoted to the illustration of salient features of dual polarization observations in different meteorological contexts. Chapter 9 focuses on one of the important applications of weather radar, namely, for hydrological applications. Rainfall estimation and attenuation correction are discussed from the fundamental theoretical basis of rain microphysics and the capability of dual polarization measurements, leading to estimation algorithms. Finally, Chapter 10 is devoted to a discussion of radar networks, their design, the different types of networks, implications for the basic radar equation, and specific network-based applications, such as the retrieval of three-dimensional wind fields.

Students and researchers often take up the study of weather radar from either an atmospheric science, atmospheric physics, or engineering perspective, depending on their background or specific application needs. In this book, we made an effort to support learners of all disciplines in their efforts toward understanding this multidisciplinary field. A sequential reading of the book should give the reader a comprehensive picture of the multidisciplinary essence of radar meteorology (Fig. 1.4). However, knowing that some readers may be more interested in either the scientific or the technological side of weather radar, the book also offers possible alternative reading pathways, as illustrated in Figure 1.5. One pathway goes from Chapter 2 through the physics section to explore the processes taking place in the atmosphere (the formation and evolution of precipitation particles and their scattering response to the radar-transmitted wave). An alternative pathway goes from Chapter 2 directly into the signals section, following the path of a radar signal entering the radar systems on the left in Fig. 1.5 and then going into the signal processor to eventually produce the polarimetric moments we routinely see on radar displays. Finally, meteorological practitioners may use Chapters 3 – 6 as reference material and proceed from Chapter 2 directly to Chapter 7, where all pathways eventually reconnect.

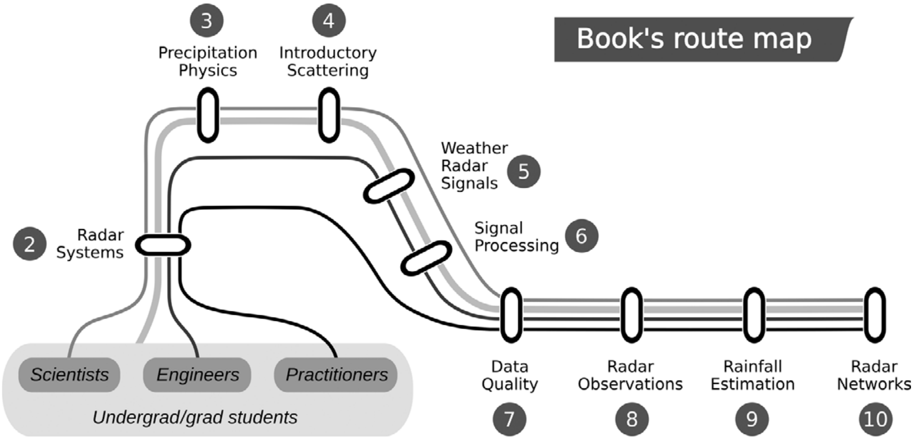

Figure 1.5 Alternative book's reading pathways.