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Introduction

1.1 Aim and Significance of Radar Data Processing

Generally, a modern radar system consists of two important components: a signal processor and a data processor. The signal processor is used for target detection (i.e., the suppression of undesirable signals produced by ground or sea surface clutter, meteorological factors, radio frequency interference, noise sources, and man-made interference) [1–3]. When the video output signal, after signal processing and constant false alarm rate (CFAR) detection fusion, exceeds a certain detection threshold, it can be determined that a target has been discovered. Then, the discovered target signal will be transmitted to the data recording device, where the space position, amplitude value, radial velocity, and other characteristic parameters of the target are recorded, usually by computers. The measurement output from the data recording device needs to be processed in the data processor, which associates, tracks, filters, smooths, and predicts the obtained measurement data – such as the target position (radial distance, azimuth, and pitch angle) and the motion parameters [4–6] – for the effective suppression of random errors occurring during the measurement, estimation of the trajectory and related motion parameters (velocity and acceleration, etc.) of the target in the control area, prediction of the target's position at the next moment, and formation of a steady target track, so that highly accurate real-time tracking is realized [7–9].

In terms of the level at which radar echo signals are processed, radar signal processing is usually viewed as the primary processing of the information detected by the radar unit. It is done at each radar station, with information obtained from the same radar and the same scanning period and distance unit, with the aim of extracting useful target information from clutter, noise, and various active and passive jamming backgrounds. Radar data processing is usually viewed as secondary processing of the radar information [10–13]. Making use of information from the same radar, but with different scanning periods and distance units, it can be done both at each independent radar station and at the information processing center or system command center of the radar network. Data fusion of multiple radars can be viewed as a third or tertiary processing of the radar information, which is usually done at the information processing center. Specifically, the information the processing

center receives is the measurement from the primary processing or the track from the secondary processing (usually called the local track) by multiple radars, and the track after fusion (called the global track or system track). The function of the secondary processing of radar information, based on the primary processing, is to filter and track several targets, and estimate the targets' motion parameters and characteristic parameters. Secondary processing is done strictly after primary processing, while there is no strict time limit between secondary and tertiary processing. The third level of processing is the expansion and extension of secondary processing, which is mainly reflected in space and dimension.

1.2 Basic Concepts in Radar Data Processing

The input to the radar data processing unit is the measurement from the front, which is the object of data processing, while the output is the track formed after data processing is conducted. Generally, functional modules of radar data processing include measurement pretreatment, track initiation and termination, and data association and tracking. A wave gate must be set up between the association and the tracking process, and their relationship is shown in the block diagram in Figure 1.1. The content and related concepts of the functional modules of radar data processing are briefly discussed as follows.

1.2.1 Measurements

Measurements, also called observations, refer to noise-corrupted observations related to the state of a target [14]. The measurements are not usually raw data points, but the output from the data recording device after signal processing. Measurements can be divided, according to whether they are associated with the known target track, into free measurements and correlated measurements. Free measurements are spots that are not correlated with the known target track, while correlated measurements are spots that are correlated with the known target track.

1.2.2 Measurement Preprocessing

Although modern radar adopts many signal processing technologies, there will always be a small proportion of clutter/interference signals left out. To relieve the computers doing the follow-up

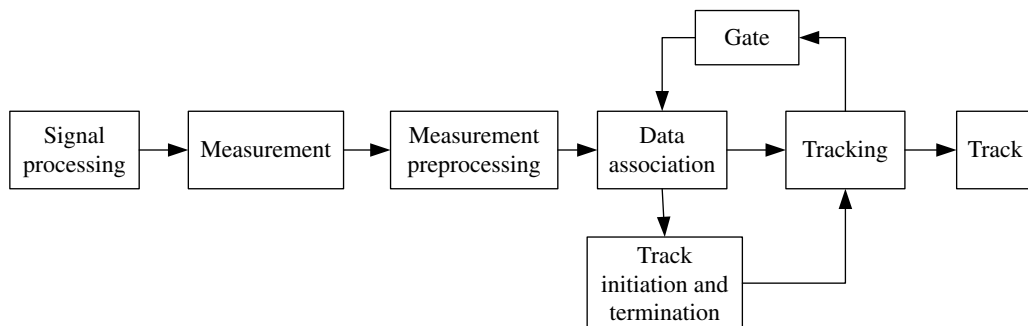


Figure 1.1 Radar data processing relation diagram

processing job from a heavy burden, prevent computers from saturation, and improve system performance, the measurement given by the primary processing needs to be preprocessed, which is called “measurement preprocessing”: the preprocessing of secondary processing of radar information. The preprocessing is a precondition of correct processing of radar data, since an effective measurement data processing method can actually help yield twice the result with half the effort, with the target tracking accuracy improved while the computational complexity of the target tracking is reduced. The measurement preprocessing technology mainly involves system error registration, time synchronization, space alignment, outlier rejection, and saturation prevention.

1.2.2.1 System Error Registration

The measurement data from radars contains two types of error. One is random error, resulting from the interior noise of the measurement system. Random error may vary with each measurement, and may be eliminated to some extent by increasing the frequency of measurement and minimizing its variance in the statistical sense by means of methods like filtering. The other is system error, resulting from measurement environments, antennas, servo systems, and such non-calibration factors in the data correction process as the position error of radar stations and the zero deviation of altimeters. System error is complex, slowly varying, and non-random, and can be viewed as an unknown variable in a relatively long period of time. As indicated by the findings in Ref. [15], when the ratio of system errors to random errors is greater than or equal to 1, the effect of distributed track fusion and centralized measurement fusion deteriorates markedly, and at this point system errors must be corrected.

1.2.2.2 Time Synchronization

Owing to the possible difference in each radar’s power-on time and sampling rate, the target measurement data recorded by data recording devices may be asynchronous. Therefore, these observation data must be synchronized in multiple-radar data processing. Usually, the sampling moment of a radar is set as the benchmark for the time of other radars.

1.2.2.3 Space Alignment

Space alignment is the process of unifying the coordinate origin, coordinate axis direction, etc. of the data from the radar stations in different places, so as to bring the measurement data from several radars into a unified reference framework, paving the way for the follow-up radar data processing.

1.2.2.4 Outlier Rejection

Outlier rejection is the process of removing the obviously abnormal values from radar measurement data.

1.2.2.5 Saturation Prevention

Saturation prevention mainly deals with saturation in the following two cases.

1. In the design of a data processing system, there is a limit to the number of target data. However, in a real system, saturation occurs when the data to be processed exceed the processing capacity.

2. The time used to process data is limited. Saturation occurs when the number of measurements, or batches of targets, reaches a certain extent. In this case, the processing of the data from one observation has to be interrupted before the processor starts to deal with the next batch of data.

1.2.3 Data Association

In the single-target, clutter-free environment, where there is only one measurement in the target-related wave gate, only tracking is involved. Under multi-target circumstances, where a single measurement falls in the intersection area of several wave gates or several measurements fall in the related wave gate of a single target, data association is involved. For instance, suppose two target tracks have been established before the radar's n th scanning, and two echoes are detected in the n th scanning, are the echoes from two new targets or from the two established tracks at that time? If they are from the two established tracks at that time, then in what way can the echoes resulting from the two scans and the two tracks be correctly paired? The answer involves data association, the establishment of the relationship between the radar measurements at a given moment and the measurements (or tracks) at other moments, to check whether these measurements originate from the processing of the same target (or to ensure a correct process of measurement-and-track pairing).

Data association, also called "data correlation" or "measurement correlation," is a crucial issue in radar data processing. False data association could pair the target with a false velocity, which could result in the collision of aircraft with air traffic control radars, or the loss of target interception with military radars. Data association is realized through related wave gates, which exclude the true measurements of other targets and the false measurements of noise and interference.

Generally, data association can be categorized, according to what is being associated with what, into the following classes [16]:

1. measurement-to-measurement (track initiation);
2. measurement-to-track (track maintenance or track updating);
3. track-to-track, also called track correlation (track fusion).

1.2.4 Wave Gate

In the process of target track initiation and tracking, a wave gate is often used to solve data association problems. What then is a wave gate? How many categories is it divided into? A brief discussion of these questions follows.

An initial wave gate is a domain centering on free measurements, used to determine the region where the target's observations may occur. At the track initiation stage, the initial wave gate is normally bigger for better target acquisition.

A correlation wave gate (or tracking wave gate, validation gate) is a domain centering on the predicted position of the tracked target, used to determine the region where the target's observations may occur [17].

The size of the wave gate is related to the magnitude of radar measurement error, the probability of correct echo reception, etc. That is to say, when deciding the wave gate's shape and size, one should make it highly probable that the true measurement falls in the wave gate, while making sure that there are not many unrelated measurements in the correlation wave gate. The echo falling in the correlation wave gate is called a candidate echo. The size of the tracking gate reflects the error in the predicted target position and velocity, which is related to the tracking method, radar measurement error, and required correct correlation rate. The size of the correlation wave gate is

not fixed in the tracking process, but adaptive adjustment should be made among small, medium, and large wave gates in accordance with the tracking conditions.

1. For a target in uniform rectilinear motion (e.g., a civil airliner flying smoothly at high altitude), a small wave gate should be set up, with its minimum size no less than three times the mean square root value of the measurement error.
2. When the target maneuver is relatively small (e.g., when the aircraft is taking off, landing, or making a slow turn), a medium wave gate should be set up, by adding one or two times the mean square root value of the measurement error to the small wave gate.
3. When the target maneuver is relatively big (e.g., when the aircraft is making a fast turn, or when the target is lost and recaptured), a large wave gate should be set up. Besides, at the track initiation stage, a large wave gate should be adopted to effectively capture the target's initial wave gate.

1.2.5 Track Initiation and Termination

Track initiation refers to the process from the entrance (and detection) of a target into the radar coverage area to the establishment of the target track. Target initiation is important in radar data processing. If the track initiation is incorrect, target tracking is impossible.

Since the target being tracked may escape the surveillance zone at any time, once it goes beyond the radar detection range, the tracker must make relevant decisions to eliminate the unwanted track files for track termination.

1.2.6 Tracking

Tracking is one of the two primary issues in radar data processing. It refers to the processing of the target's measurements for the constant estimation of the target's current state [16]. The multiple-radar and multi-target tracking system is a highly complex large-scale system, whose complexity is mainly due to the uncertainty in radar data processing.

1. From the perspective of measurement data, the received radar measurements form a random sequence, which may be obtained by non-equal interval sampling, and the observation noises are non-Gaussian. This should be considered in real measurement data processing.
2. From the perspective of multi-target tracking, the complexity of the tracking problem lies mainly in:
 - a. the uncertainty of measurement origin – since there are multiple targets and false alarms, many measurements may be produced in radar environments, which will lead to the uncertainty of the measurements used for filtering;
 - b. the uncertainty of the target model parameter – since targets could be on maneuvers at any time, the model parameter initially set could be incorrect. Therefore, adjustments must be made to the model parameter in accordance with the tracking conditions; hence maneuvering target tracking.
3. From the perspective of the system, the tracking system could be nonlinear, with a complex construction. On the one hand, the system tracking performance under complex circumstances depends chiefly on the filtering algorithm's capability to deal with the uncertainty of measurement origins and target model parameters, or its capability to effectively solve the problem of measurement correlation and adaptive target tracking. On the other hand, the nonlinear characteristics of the system itself should also be taken into consideration.

For the effective tracking of the target under these complex circumstances, the following two problems need to be solved.

First, the establishment of the target motion model and the observation model. Estimation theory, which provides a foundation for radar data processing, requires the establishment of a system model describing the dynamic characteristics of target and radar measurement processes. A valuable method of describing the system model, the state variable method, is based on the system state equation and the observation equation. According to this method, the state variable, system state equation, system observation equation, system noise and observation noise, system input and output (i.e., the estimated value of the state variable) are the five essential elements of the target tracking system modeling. The five elements above reflect the basic characteristics of a system, and can be viewed as a complete expression of a dynamic system. The introduction of the state variable is the core of creating an optimum control and estimation theory, because in the state space, the state variable defined should be a batch of variables with minimum dimensions that can fully reflect the system dynamic characteristics. The state variable at any given time is expressed as a function of the state variable prior to that time, and the input/output relationship of the system is described by the state transition model and the output observation model in the time domain. The state reflects the system's "interior condition." The input can be described by the state equation, which is composed of the decided time function and the random process representing the unpredictable variable or noise. The output is a function of the state vector, usually disturbed by the random observation error, and can be described by measurement equations. In the system modeling process, the use of the system state equation and the observation equation in the description of the dynamic characteristics of the target is therefore the most successful method in common use. The relation between the state equation and the measurement equation is shown in Figure 1.2.

Second, the tracking algorithm. The tracking filtering algorithm in the state space is actually a matter of optimum estimation based on state space. The following two points are of major concern.

1. Multiple maneuvering target tracking. Maneuvers are both the basic attribute of the target and the forms of motion commonly used in attacks or escapes. Therefore, maneuvering multi-target tracking is the focus of target tracking, dealing with the problem of a maneuvering target model, testing and tracking algorithm.
2. The optimality, robustness, and rapidity of tracking algorithms. That is to say, an overall consideration is needed of the tracking timeliness, tracking accuracy, and robustness of the algorithm.

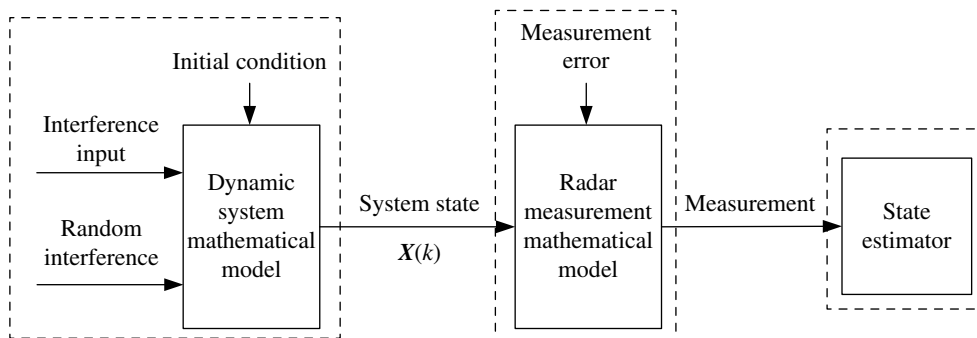


Figure 1.2 Filtering diagram

1.2.7 Track

A track is a trajectory which is formed with the states of a target estimated from a set of measurements of the same target (i.e., tracking trajectory). The radar, when conducting multi-target data processing, designates an identity (ID) for each tracking trajectory, namely the track ID, which serves as a point of reference for all the parameters related to a given track. The measurement of the track's reliability can be described by the track quality which, if properly controlled, can help both promptly and accurately initiate a track so that a new target file is set up, and cancel a track so that the redundant target files are cleared up. Tracks are the ultimate result of data processing, as shown in Figure 1.3.

The concepts related to tracks also include the following.

1. *Possible track*. The possible track is a track composed of a single measurement point.
2. *Tentative track*. Tentative tracks are tracks composed of two or more measurement points with low track quality. They could be target tracks, or random interference, namely false tracks. After initial correlation is complete, a possible track is turned into a tentative track or a canceled track. The tentative track is also called a temporary track.
3. *Confirmed track*. A confirmed track, also called a reliable track or a stable track, is a track with stable output or a track whose track quality exceeds a given value. It is the formal track set up by the data processor, and is generally considered as a true target track.
4. *Fixed track*. A fixed track is a track composed of clutter measurements, whose position does not change much with the scans of a radar set.

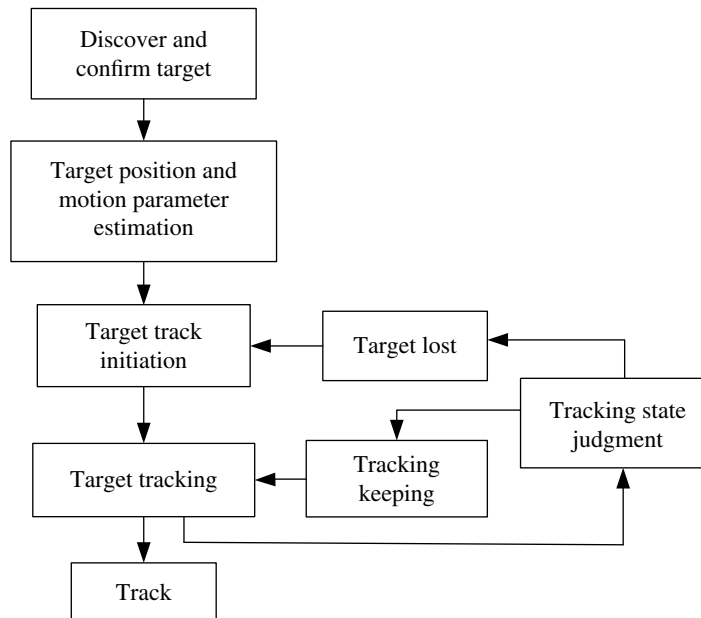


Figure 1.3 Data processing flowchart

The following sequence can be determined in the correlation process of measurements and tracks: fixed tracks first, then reliable tracks, and finally tentative tracks. That is to say, after a batch of observation measurements is obtained, the correlation of these measurements and the fixed track is done first. The measurements that can be correlated with the fixed track are deleted from the measurement file and are used to update the fixed track (i.e., to replace the old clutter points with the measurements that are correlated). If these measurements cannot be correlated with the fixed track, they should be correlated with the existing confirmed track. The successfully correlated measurements are used to update the confirmed track. The measurements that cannot be correlated with the confirmed track should be correlated with the tentative track, which finally either disappears or is turned into a confirmed track or a fixed track. The confirmed track has priority over the tentative track, which excludes the possibility that the tentative track obtains measurements from the reliable track.

5. *Canceled track*. When its quality is lower than a given value or is composed of isolated random interference points, the track is called a canceled track, and the process is called track cancellation or track termination. Track cancellation is the process of erasing the track when it does not conform to a certain rule, which means the track is not a track of a true target, or that the corresponding target has moved out of the radar coverage range. Specifically, when a certain track cannot be correlated with any measurement in a certain scan, an extrapolation should be done according to the latest velocity. Any track that does not receive a measurement in a certain number of successive scans should be canceled. The primary task of track cancellation is to promptly cancel a false track with the true one being retained.

There are three possible instances of track cancellation.

- i. Possible tracks (with only track heads) to be canceled as long as there is no measurement in the first scanning period that follows them.
 - ii. Tentative tracks (such as a newly initiated track) to be erased from the database as long as there is no measurement in the three successive scanning periods that follow them.
 - iii. Confirmed tracks, whose cancellation should be done with caution. If no measurement falls in the relevant wave gates in four to six successive scanning periods, cancellation of the track can be considered. It is worth noting that extrapolation must be used several times to expand the wave gates to recapture the lost target. Of course, track quality management can also be used to cancel a track.
6. *Redundant tracks*. Two or more tracks being allocated to the same true target is called track redundancy. The unnecessary track is called a redundant track.
 7. *Track interruption*. If a certain track is allocated to a true target at time t , but no track is allocated to the target at time $t + m$, then track interruption happens at time t , where m is a parameter set by the tester, usually $m = 1$.
 8. *Track switch*. If a certain track is allocated to a true target at time t , while another track is allocated to the target at time $t + m$, then track switch happens at time t , where m is a parameter set by the tester, usually $m = 1$.
 9. *Track life* (the length of a track; the times the track is successively correlated). Based on whether the terminated track is false or true, it can be divided into [18, 19]:
 - a. *False track life*. The average times of radar scanning from the initiation of a false track to its deletion is called false track life. False track can sometimes last for a long time when false measurements are highly dense.

- b. *True track life*. The average times of radar scanning of a true track mistaken for a false one and deleted after it is initiated.

True track maintenance time is restricted by two factors:

1. The measurement track correlation error (the true measurement is measured but is correlated with other tracks, which commonly occurs in dense target environments or crossed target environments) could lower the quality of a true track, or even result in the deletion of a true track mistaken for a false one.
2. The times that measurements are successively lost reach a given threshold, so the track is deleted as a lost target, which commonly happens when the signal-to-noise ratio is low or there is strong interference.

1.3 Design Requirements and Main Technical Indexes of Radar Data Processors

1.3.1 Basic Tasks of Data Processors

As can be seen from the discussion and elaboration of the relevant basic concepts in radar data processing, the basic tasks of data processors include:

- a. measurement pretreatment;
- b. determination of the correlation area and correlation principle, and the distinction between true and false measurements;
- c. the establishment of new tracks;
- d. the correlation of measurements and existing tracks, track maintenance;
- e. the correlation between and fusion of tracks;
- f. track termination and track management, including quality grade determination and track quality management;
- g. situation display, including the display of tracks and measurements.

1.3.2 The Engineering Design of Data Processors

The engineering design of data processors is a comprehensive design. Generally, the following three issues need to be considered.

First, the balanced relationship between tracking accuracy, robustness, and real-time performance. Target tracking algorithms are mostly obtained when the probability distribution function of the system noise and measurement noise is subject to certain assumptions, and usually the assumed system noise and observation noise are both Gaussian white noise. However, in real systems it is hardly possible to find a matrix that accords completely with Gaussian distribution because the mutation of the electromagnetic environment, the immaturity and failure of the observation equipment, etc. can result in the deviation of observations from the Gaussian distribution. When the system's actual noise distribution deviates from the assumed noise distribution, tracking algorithms can effectively exclude the interference of the uncertainty factors and abnormal values in the system, and consequently ensure that there is not much change in the estimation effect and the estimation accuracy. Simply put, the tracking algorithms can ensure the robustness of estimation algorithms in this case, so that the system can operate normally. This is

robust tracking (estimation). In other words, a relatively “loose” assumption of the noise distribution mode is allowed, which may not be the optimum one for a certain specific distribution mode, but can exclude the interference of the abnormal values and help improve the anti-interference ability of the system.

Basically, research on the robust estimation theory aims to find estimation algorithms that can both exclude or resist the influence of the abnormal value (cases) and basically possess the good characteristics of traditional estimation algorithms (i.e., algorithms that incorporate considerations of optimality and robustness of estimation in a balanced manner). What optimality emphasizes is an algorithm that makes the system index function reach its minimum (or maximum), while what robustness focuses on is an algorithm that sacrifices some indices of the system to improve its anti-interference performance. Therefore, an optimal balance between robustness and optimality is what needs to be taken into consideration in the whole process of robust tracking system design. Some efficiency has to be sacrificed to robustness [10].

Common problems in the balance between tracking accuracy, robustness, and real-time performance are:

1. Excessive emphasis is put on the tracking accuracy index, while the robustness index is neglected. As a result, the accuracy of the target tracking result is high at the simulation stage, but declines markedly at the actual engineering test stage, which reduces the algorithm’s engineering value.
2. Too idealized an index design results in complexity of the algorithm structure, which badly affects its real-time performance.

As for engineering algorithms, the index of robustness is the first priority, followed by the tracking accuracy and the real-time index. However, in an engineered index design, the three indexes mentioned above are the basic technical indexes on which compromises must be made.

The second issue is one of reliability. An algorithm that is simple in structure, highly reliable, easy to realize, and mature in engineering should be used in the engineering design of radar data processing. Otherwise, the system cannot operate normally and continuously. Meanwhile, the design of the software system data processor needs to be modularized, visible, and revisable.

The third issue is that of intelligence information processing. Although the function modules contained in data processors are basically the same, different radars have different requirements for the data processor design. For example, the core of the skywave over-the-horizon radar is the ionosphere mathematical model. Specifically, the echo multipath resulting from the multipath structure of the ionosphere, and the severe attenuation of the echo signal resulting from the severe shortwave environment noise and ionosphere transmission characteristic can result in a higher probability of false alarms and missed alarms in radar measurements, leading to discontinuity of the track. However, the striking problem with the groundwave over-the-horizon radar is the rejection of false tracks and the maintenance of stable tracks. Therefore, in the design of data processors, an analysis of the data processor’s characteristics should be made first according to the system’s index requirements for data processors, including observation characteristics such as the measurements’ temporal and spatial distribution characteristics, noise distribution and statistical characteristics, the variation of the signal-to-noise ratio, the intensiveness of the targets, etc. Besides, the system’s resolution, probability of detector false alarms and discovery, accumulated time and coordinate system, etc. are also included in the analysis, to provide a basis for the assignment of data processor indexes and the emphasis of the design.

1.3.3 The Main Technical Indexes of Data Processors

The main technical indexes of data processors are as follows.

1. *Immediacy*. If the adopted tracking algorithm is too complex and takes too long a time to process the data, it is possible that the second batch of data will come before the processing of the first batch of data is complete, resulting in saturation of data processing. As a consequence, the processing effect and the immediacy of the situation display may be affected, so that the situation display cannot reflect the current target position information accurately.
2. *Tracking capacity*. The tracking capacity is the largest number of targets that the data processor can track simultaneously. The index becomes increasingly demanding with increasing intensiveness of targets, the complexity of the environment in which the sensors work, and the processing speed of the hardware system. Meanwhile, due to factors like undetected data, there could be discontinuous target tracks, so that one target track could be mistaken for several target tracks and assigned different target numbers, which increases the system tracking capacity.
3. *Probability of true target loss and false targets*. These are two mutually restricted crucial indexes. To ensure the initial probability of the true track, a large correlated wave gate must be built. This, on the one hand, makes it more probable that the true target will fall in the wave gate but, on the other hand, increases the number of other unrelated measurements falling in the wave gate, which is bad for the reduction in false track probability because the initiation of true targets is ensured at the expense of initiating a large number of false targets. Conversely, if the probability of false tracks is to be lowered, a small wave gate should be built; as a consequence, true targets may not fall in the wave gate, which could result in a loss of true targets. This requires a reasonable wave gate design, employing different principles according to the different emphases on the two indexes in engineering, or different detecting areas. In a specific system the test of this index is closely related to that of the detector index, requiring an overall consideration of the detector and data processor index [10].
4. *Tracking accuracy*. Tracking accuracy is a key index of the data processor. It depends mainly on the measurement accuracy of the detector, the data correlation, and the filtering algorithm adopted.

1.3.4 The Evaluation of Data Processors

The performance evaluation of the data processor mainly includes the following four aspects.

1. *Data association*. This is a comparatively complicated evaluation index. Data correlations are normally evaluated using the data under various circumstances – such as the existence of outliers, dense target environments, cross-target environments (see Chapter 17, Figure 17.1), target approaching and leaving (see Chapter 17, Figure 17.2), maneuvering multi-target environments, etc. – and by calculating indexes like the target's correct correlation probability, false correlation probability, missed correlation probability, etc.
2. *Tracking batches*. This reflects directly the tracking capacity and the processing capability of the system.
3. *The accuracy of the tracking filter*. The balance between indexes – including tracking accuracy, immediacy, and robustness (anti-interference ability) – should be considered comprehensively.
4. *Immediacy*. Actual measurement data should be used to test the processing speed of the data processor.

The evaluation of data processing is crucial to a radar system, because the test of many of its indexes – like coverage range, system resolution, tracking batches, tracking accuracy, target classification, and the estimation of threat – is ultimately determined by the evaluation of data processors. Related information will be discussed especially in Chapter 17.

1.4 History and Present Situation of Research in Radar Data Processing Technology

The earliest radar data processing method was the least-squares algorithm put forward by Gauss in 1795. Gauss used this method to predict Kamiya's orbit for the first time, and opened up the scientific field in which mathematical methods were used to process observation and experimental data. Despite its faults, such as neglect of the statistical characteristics of the observation data, the algorithm has its merits in that it is comparatively simple in calculation. Therefore, it is still a widely used estimation method, from which some forms suitable for real-time operation have developed through the generations. This method is used when accurate system dynamic errors and statistical characteristics of the observation data cannot be acquired.

The maximum likelihood method, proposed by R. A. Fisher in 1912, deals with the estimation problem from the perspective of probability density, and has made an important contribution to estimation theory. The estimation of a random process was not developed until the 1930s, while modern filtering theory was based on probability theory and random process theory. In 1940, American scholar N. Wiener, one of the originators of control theory, put forward a method to design statistical filters in frequency domains according to the requirement for fire control – the famous Wiener filtering. Since its proposal, the method has been used in the fields of communication, radar, and control, with great success. During the same period, former Soviet Union scholar Kolmogorov proposed and for the first time solved the problem of the prediction and extrapolation of the discrete stationary random sequence. The Wiener filtering, together with the Kolmogorov filtering method, opened up a new field in which the statistical method was used to deal with the random control problem, and established a foothold for the research and development of modern filter theories.

The Wiener filter, which adopts the frequency domain design method, is difficult in analysis and solution and complicated in operation [20]. What's more, the batch processing method it adopts demands large storage space. Consequently, its application is quite limited and it is only applicable to one-dimensional stationary random signal filtering. This defect in the Wiener filter forced people to seek other optimal filter design methods. An important contribution was made in this field by American scholar R. E. Kalman, who proposed the discrete-time system Kalman filter in 1960. In 1961, he worked with S. S. Bucy in extending this filtering theory to continuous-time systems [21], and formulated a complete theory of Kalman filter estimation.

The Kalman filter introduces the method for analysis of state variables to filtering theory, and obtains the time-domain solution of the minimum mean square error estimation problem. Moreover, the Kalman filter theory, which has broken through the limitations of the Wiener filter, can be used in non-stationary and multi-variable linear time-varying systems. With a recursive structure, the Kalman filter is more suitable for computer computation, requires lower computational complexity and smaller data memory, and has stronger real-time performance. It is because of its advantages over the other filtering methods mentioned above that the Kalman filter found practical engineering applications once proposed [22, 23]. The Apollo lunar landing program and the

design of the C-5A aircraft navigation system were the most successful examples of its early engineering applications. Because of the Kalman filter's wide application and simple design method, steady-state gain filtering was proposed on its basis to further lower the computational complexity [24, 25]. At present, the Kalman filter theory, as one of the most important optimum estimation theories, is widely used in various fields, such as target tracking, inertial guidance, GPS, air traffic control, fault diagnosis, etc. In the over 200-year history of filtering theory, Gauss, Wiener, and Kalman have made important contributions, laying theoretical foundations for radar data processing.

Since the filtering theory initiated by Kalman is only applicable to linear systems and requires that the observation equation should be linear, in the following 10 years Bucy, Sunahara, and coworkers were committed to research on the extension of the Kalman filtering theory to nonlinear systems and observations, and proposed a filtering method applicable to nonlinear systems – the extended Kalman filter [16, 25]. Then, successively, in the early 1970s Singer *et al.* proposed a series of maneuvering target tracking methods [26], and in the mid-1970s Pearson, Shibata, and coworkers successfully applied Kalman filtering technology to the airborne radar tracking system [27]. The traditional Kalman filtering theory is based on the precondition that the model is accurate and the statistical characteristics of random interference signals are known. However, in an actual system, sometimes the model is inaccurate, and/or the statistical characteristics of interference signals are not completely known, which could greatly lower the traditional Kalman filter's estimation accuracy and result in filtering divergence in severe cases. That is why some scholars introduced the idea of robust control to filtering theory, producing the robust filtering theory [28].

The increasingly complex application environment in recent years requires that radars be capable of tracking several targets simultaneously. The concept of multi-target tracking was advanced by Wax in an article published in *Applied Physics* in 1955 [29]. Then, in 1964, the article "The association of optimum data in monitoring theory," published by Sittler in *IEEE Transactions on Military Electronics*, became the pioneering work of multi-target tracking [30]. However, since the Kalman filter was not widely used at that time, he adopted the track splitting algorithm [16]. In the early 1970s, the Kalman filtering method began to be used systematically for multi-target processing in the case of false alarms [31]. The nearest-neighbor algorithm proposed by Singer in 1971 is the simplest method of solving data association problems [32], but this method has a low association rate in clutter environments. In this period, Y. Bar-Shalom played an important role, proposing in 1975 the probabilistic data association algorithm, which is especially applicable to single-target tracking in clutter environments [33]; on its basis, Fortmann, Bar-Shalom, and coworkers put forward the joint probabilistic data association algorithm (JPDA) to effectively solve the problem of multi-target tracking in clutter environments [34]. Based on Bar-Shalom's poly concept, in 1979, Reid proposed using the multiple hypothesis method to solve the problem of multi-target tracking [35].

With the development of science and technology in recent years, targets have to make maneuvers to avoid being tracked and attacked. Therefore, since 1970, Singer, Bar-Shalom, Birmiwal, and coworkers have successively proposed tracking maneuvering targets with the Singer algorithm, variable dimension filtering algorithm, interacting multiple model algorithm, etc. [32, 36–39]. In 1986, S. S. Blackman *et al.* started to do research on the group target tracking issue. In 1988, Carlson put forward the federated filter [40], aimed at providing a theoretical basis for the design of the fault tolerance combined navigation system [41]. In order to effectively solve the filter problem in nonlinear systems, Julier *et al.* put forward unscented KF (UKF) [42], which takes samples of the estimated vector's probability density function (PDF) so as to decide its mean value and covariance, and acquires an estimation accuracy which is better than the first-order EKF

algorithm and has the same magnitude as the second-order EKF algorithm. In Ref. [43] the particle filter (PF) algorithm is proposed, which is close to the UKF algorithm in performance except that it has a higher computational complexity. The PF has also been used in research tracking before detecting, etc. in recent years.

With further study being carried out on various aspects of the radar data processing technology, large numbers of treatises [5, 44–51], academic papers [52–56], and research reports [18, 23, 57] have emerged. Now data processing technology has been transformed from initial single-radar to multiple-radar, and from multiple-radar to multiple-sensor, with the emergence of a large number of treatises and papers on multiple-sensor information fusion [15, 58–64].

In the radar data processing field, many scholars and outstanding experts have made rewarding contributions, including Professor Bar-Shalom of the University of Connecticut, USA, who, since the end of the 1980s, has successively published many highly theoretical and systematical treatises on multi-target tracking with his students, originating many new theories and methods, especially in aspects of data association and multi-target/multi-sensor tracking data fusion. Their research features clear concepts, rigorous deduction, and strong theoretical dimensions. Another example is S. S. Blackman, an expert with Air America, whose research is characterized by its higher practicability, or stronger relevance, to actual engineering applications. Still another is Professor Farina of Naples University, one of the earliest scholars in radar data processing research.

1.5 Scope and Outline of the Book

Whether in modern defense or air and marine traffic control systems, multi-target tracking is an indispensable technology. Especially with developments in the “informatization” and networking of modern warfare, multi-target tracking technology is coming to the fore in all countries, as an active research field. For example, for air traffic control centers, the management of the aircraft in air and terminal areas, approach management, collision warning, and collision avoidance, etc. cannot be realized without a target tracking system, which requires the system to detect and track the aircraft, and accurately determine position, heading, and speed parameters, thus improving the safety of air traffic and the utilization of resources.

This book absorbs the latest developments in the field of radar data processing in recent years, aimed at providing people of the same profession with a foundation for further theoretical research and practical application. The main content and chapters are as follows.

Chapter 1: Introduction

This chapter discusses many basic concepts in radar data processing. Some of the practical issues addressed include engineering design requirements, principal technical indicators, and assessment of radar data processors.

Chapter 2: Parameter Estimation

Starting with the basic concept of time-constant parameter estimation, the chapter discusses some estimator properties like unbiasedness, variance of estimators, consistency and efficiency of estimators, etc. on the basis of the introduction of several frequently used time-constant parameter estimation techniques, such as maximum a posteriori (MAP), maximum likelihood (ML), minimum mean squared error (MMSE), and least squares (LS) estimators. Finally, the chapter analyzes the estimation of non-time-varying vectors, and discusses the LS, MMSE, and LMMSE estimators under vector circumstances.

Chapter 3: Linear Filtering Approaches

On the basis of the introduction of the measurement state and measurement equations for a Kalman filter, including the constant velocity model, constant acceleration model, and coordinate turn model, this chapter discusses the relevant filter models and the initiation of the Kalman filter. Finally, the chapter studies the steady-state Kalman filter, including a mathematical definition and judgment of stable filters, controllability and observability of random linear systems, etc.

Chapter 4: Nonlinear Filtering Approaches

This chapter discusses the nonlinear filtering approaches in radar data processing, including extended Kalman filter (EKF), unscented Kalman filter (UKF), and particle filter (PF), giving the filtering model of each approach. After a simulation analysis of two linear filter algorithms (Kalman filter and unbiased converted measurement Kalman filter), as well as two nonlinear filter algorithms (extended Kalman filter and unscented Kalman filter) in the same simulation environment on the condition that the posterior PDF of the system state is a Gauss hypothesis, a comparison of the tracking accuracy and computational complexity of these methods is made, and relevant conclusions drawn. The chapter also makes a simulation analysis using three nonlinear filter algorithms (extended Kalman filter, unscented Kalman filter, and particle filter), tracking the same target in the same simulation environment, compares the tracking accuracy and computational complexity of these approaches, and makes a comprehensive evaluation of the advantages and disadvantages of each approach.

Chapter 5: Measurement Preprocessing Techniques

This chapter deals with measurement processing. In a process where several sensors are used to track targets, in order to improve the tracking accuracy, it is necessary to fuse the information of several targets, while the primary problem to be solved in the fusion of multiple-sensor information is the synchronization of different sensors in time and space. The chapter first analyzes and discusses two issues: the time registration method; selection and transformation of the coordinate system. Since the selection of the coordinate system is closely related to practical application, and can directly influence the tracking effect of the whole system, the chapter starts with a discussion of some commonly used coordinate systems, and then studies some coordinate transformation techniques, to ensure that all the data information formats can be united in the same coordinate system. Finally, the chapter analyzes the problem of data compression to minimize the computational load and improve the track effect.

Chapter 6: Track Initiation in Multi-target Tracking

On the basis of the analysis of the shape, dimensions, and varieties of initial wave gates and correlation wave gates in track initiation, this chapter studies track initiation techniques in multi-target tracking, including target-oriented sequential processing techniques and batch processing techniques. Usually the sequential processing technique applies to target track initiation in clutter-free environments, and the target track initiates more quickly, while the batch processing technique is quite effective when applied to the initiation of the target track in strong clutter environments, which, however, is at the expense of increased computational complexity, and needs multiple scans to effectively initiate a track. Finally, a comparative analysis is made of the effects of several commonly used track initiation algorithms in the same simulation environment, including a logic-based method, modified logic-based method, Hough transformation method, and modified Hough transformation method, and relevant conclusions are drawn.

Chapter 7: Maximum Likelihood Class Multi-target Data Association Methods

This chapter mainly discusses the maximum likelihood class association methods, including the track splitting method, united maximum likelihood algorithm, 0–1 integer programming algorithm, and generalized correlation algorithm. The main feature of the maximum likelihood class filter algorithm is that it makes judgments on the basis of the likelihood ratio of the observation sequence, and does not create a probability that the sequence is correct. Specifically, the track splitting method makes use of likelihood functions to conduct pruning, excluding the measurement sequences that are unlikely to come from the target. The united maximum likelihood algorithm calculates the likelihood functions of different feasible partitions of all measurement sequences, and when the likelihood function reaches its maximum, the measurement sequence with feasible partition is considered the correct sequence from different targets. The principle of the 0–1 integer programming algorithm is similar to that of the united maximum likelihood algorithm, and it is further deduced from the united maximum likelihood algorithm. The generalized correlation algorithm defines a score function, which is used to initiate, confirm, and cancel tracks.

Chapter 8: Bayesian Multi-target Data Association Approach

This chapter mainly discusses the Bayesian association approach, which is concerned with studies on the latest determined measurement sets, including the nearest-neighbor algorithm, probabilistic data association algorithm (PDA), integrated probabilistic data association algorithm (IPDA), joint probabilistic data association algorithm (JPDA), etc. In the JPDA section of this chapter, a very simple and practical method of determining matrix separation is introduced, another merit of which is that errors are not likely to occur. Finally, the chapter compares and analyzes the track performance, consumed time, error tracking rate, etc. of various algorithms through simulation experiments.

Chapter 9: Tracking Maneuvering Targets

This chapter mainly discusses the tracking method of maneuvering targets. Generally, maneuvering target tracking methods can be divided into two classes: tracking algorithms with maneuvering detection capability (including the white noise model with adjustable level, variable dimension filtering algorithm, etc.) and adaptive tracking algorithms (including the modified input estimation algorithm, Singer model algorithm, the current model and its modified algorithm, Jerk model algorithm, multi-model algorithm, and interactive multi-model algorithm, etc.). The chapter discusses two typical maneuvering target tracking algorithms, makes a simulation analysis and comparison of the above two classes of methods through simulation examples, and draws conclusions.

Chapter 10: Group Target Tracking

This chapter mainly discusses the issue of group tracking. Because of problems typical of group tracking itself, the development and research in this area falls behind other techniques. The chapter starts with a discussion of the initiation of a group, and discusses several typical group initiation algorithms, including the definition, separation, and correlation of the group, and the estimation of the speed of the group. On this basis, it discusses refined track initiation of the targets in a group in a cluttered environment, proposes a group target refined track initiation algorithm based on the gray theory, and makes simulation verification and analysis. Besides, the chapter investigates centered group tracking, and analyzes and discusses such

aspects as the tracking updating, merging, and splitting of a group. In order to further solve the tracking problems of targets in a group, the chapter also studies the formation group tracking algorithm. Finally, an overall simulation analysis and summary is made of the group tracking algorithm.

Chapter 11: Multi-target Track Termination Theory and Track Management

This chapter starts with research on a multi-target tracking termination technique, discussing the relevant algorithms based on “nearest neighbor,” including the sequence probabilistic ratio test (SPRT) algorithm, tracking gate method, cost function method, Bayesian algorithm, and all-neighbors Bayesian algorithm, followed by a comparative analysis and relevant conclusions of the termination moment and false termination rate of the above-mentioned algorithms in the same simulation environment. The second part of the chapter relates to track ID management in the track management technique, including the management of single-track IDs, storage of track data, and management of double-track IDs. This part also discusses track quality management and track file management in information fusion systems, and analyzes the selection of initiation principles and the cancellation of tracks using track quality, as well as the management of track quality under single-station and multi-station circumstances.

Chapter 12: Passive Radar Data Processing

This chapter first discusses the space correlation of passive radar measurements, including passive location and tracking using the phase changing rate algorithm and Doppler shift changing rate multiple-model algorithm. The chapter also analyzes and discusses optimal deployment based on the area of the minimum concentration ellipse principle for passive sensors, as well as passive location using time difference of arrival, etc.

Chapter 13: Pulse Doppler Radar Data Processing

On the basis of the introduction of the basic characteristics of pulse Doppler (PD) radars, this chapter discusses the retrieval of radar data in single-target tracking and multi-target tracking systems. On this basis, a study is done on several typical tracking algorithms of PD radars, including optimal distance–velocity coupled tracking, radar target tracking with Doppler measurements, etc. The radar target tracking algorithm with Doppler measurements focuses on the unbiased sequential extended Kalman filter algorithm, unbiased sequential unscented Kalman filter algorithm, unscented Kalman filter algorithm with Doppler measurements, and unscented Kalman filter algorithm of maneuvering targets. A comparative analysis is made of several algorithms with Doppler measurements respectively in two simulation environments, and relevant conclusions are drawn.

Chapter 14: Phased Array Radar Data Processing

This chapter starts with an analysis and discussion of the phased array radar’s main indexes and features, and on this basis investigates the system structure and work process of phased radars, and provides relevant system structure block diagrams and phased radar flowcharts. In the phased radar data processing part, research is carried out on multi-target processing, variable sampling interval filtering, and resource scheduling strategies on the basis of the discussion of tracking filtering methods. With regard to variable sampling interval filtering, the chapter analyzes and discusses adaptive sampling with steady-state gain filters, adaptive sampling based on the interactive multiple model, adaptive sampling based on the forecast error covariance threshold,

and adaptive sampling with sampling intervals defined in advance. Finally, the chapter presents a simulation analysis and comparison of the performance of phased array radar track algorithms.

Chapter 15: Radar Network Error Registration Algorithm

This chapter starts with a discussion of the make-up of system errors and their influence, and in particular analyzes the influence of large range-finding system errors on tracks. Large range-finding system errors can result in the affine transformation of target tracks, as well as their shift and rotation, distorting the whole track, while azimuth-finding system errors can enlarge the target track shift only slightly, having a very small influence on the target track. On this basis, the chapter studies fixed radar error registration algorithms, including the RTQC error registration algorithm, LS error registration algorithm, GLS error registration algorithm, accurate maximum likelihood registration algorithm, and ECEF error registration algorithm. The chapter also deals with research into maneuvering radar error registration algorithms, particularly the maneuvering radar system modeling method, maneuvering radar registration algorithm with target locations known, MLRM algorithm, and ASR algorithm. The chapter ends with a simulation analysis and discussion of the performance of the above-mentioned algorithms.

Chapter 16: Radar Network Data Processing

On the basis of the introduction of performance evaluation indexes of radar networks, this chapter investigates data processing of a single-base radar, double-base radar, and multi-base radar network. Finally, the chapter studies the track correlation technique in radar network data processing, and focuses on the sequential track association algorithm in the case of multiple local nodes based on statistics.

Chapter 17: Evaluation of Radar Data Processing Performance

Radar data processing performance depends on various factors, which means that many factors are involved in the evaluation of radar data processing performance. This chapter mainly discusses the indexes of the evaluation of radar data processing performance in terms of average track initiation time, accumulative number of track interruptions, track ambiguity, accumulative number of track switches, track accuracy, maneuvering target tracking capability, false track ratio, divergence, track capacity, radar network detection probability, response time, etc. Finally, the chapter studies some evaluation methods of radar data processing performance, such as the Monte Carlo, semi-physical simulative evaluation, and testing methods.

Chapter 18: Radar Data Processing Simulation Technology

On the basis of the introduction of basic knowledge on system simulation, this chapter analyzes the methods of creating a uniform distribution, normal distribution, and arbitrarily distributed random numbers, as well as the simulation of the target motion model and the simulation of the observation process under different target motion circumstances. Finally, the chapter gives simulation examples of radar data processing algorithms, to help readers better understand the system simulation technology and radar data processing technology, and combine the two technologies in analyzing and solving practical problems in radar data processing.

Chapter 19: Practical Application of Radar Data Processing

This chapter discusses some typical uses of radar data processing technology in practical applications, including air traffic control systems, shipboard navigation radar, clutter suppression of shipboard radar, ground laser radar, marine surveillance systems, fleet aerial defense systems, airborne early warning radar, aircraft warning radar networks, phased array radar, etc. In practical

applications, the use of radar data processing technology to estimate the track of a target and predict its future location is not the ultimate purpose of a radar system. Users should make use of the information to make judgments and take actions which meet the specific requirements.

Chapter 20: Review, Suggestions, and Outlook

This chapter provides a review of the main theoretical research achievements in the book, and some suggestions on key problems in radar data processing technology. Finally, prospects are given for research directions and development trends of radar data processing technology.