清华大学学术专著

雷达目标检测与恒虚警处理

Radar Target Detection and CFAR Processing

（第二版）

何 友　关 键　孟祥伟　等著

HE You　GUAN Jian　MENG Xiangwei

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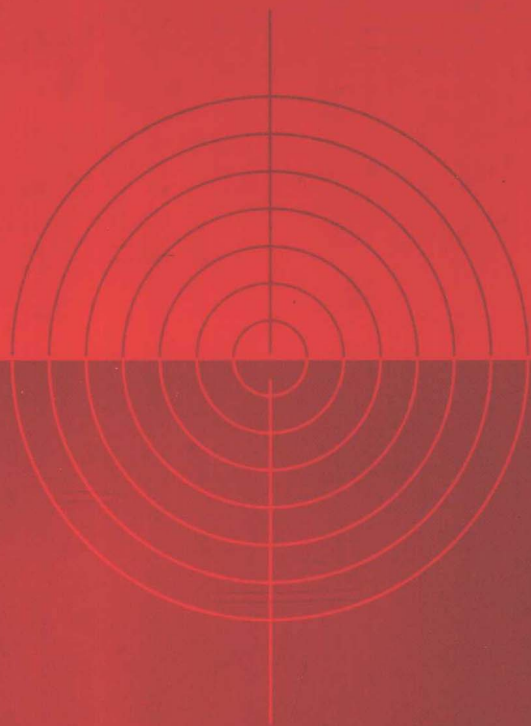
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内 容 简 介

本书是关于雷达目标检测和恒虚警(CFAR)处理理论与方法的一部专著。书中总结了三十多年来,在这一领域国际上的研究进展及大量研究成果。全书由 15 章组成,主要内容有经典的固定门限检测、均值类 CFAR 检测器、有序统计类 CFAR 检测器、采用自动筛选技术的广义有序统计类 CFAR 检测器、自适应 CFAR 检测器、韦布尔和对数正态杂波背景中的 CFAR 检测器、复合高斯分布杂波中的 CFAR 处理、非参量 CFAR 处理、杂波图 CFAR 处理、变换域 CFAR 处理、距离扩展目标检测、多传感器分布式 CFAR 处理以及其他 CFAR 处理方法,最后是本书的回顾、建议与展望。

本书可供从事雷达工程、声纳、电子工程、信号与信息处理等专业的科技人员阅读和参考,还可以作为上述专业的研究生教材。

Abstract

This book is a monograph about radar target detection and constant false alarm rate (CFAR) processing theory and technique. In this book, the international advances in this research field for more than thirty years and many fruits of authors' research are summarized. The book is composed of fifteen chapters. The main contents are classical detection with fixed threshold, mean-level type CFAR detectors, order-statistics type CFAR detectors, generalized order statistics CFAR detectors with automatic censoring technique, adaptive CFAR detectors, CFAR processing in Weibull and Lognormal clutter, CFAR processing in compound Gaussian clutter, nonparametric CFAR processing, clutter map CFAR processing, CFAR processing in transform domain, detection of range-spread target, distributed CFAR processing with multisensor and other CFAR methods. A brief review with suggestions and prospects is shown in the last chapter.

This book is targeted for scientist and researchers engaged in radar engineering, sonar technique, electronic engineering, signal and information processing etc. It can also serve as a textbook of graduate students majoring in the above areas.

第二版前言

　　雷达目标检测和跟踪中的虚警问题是每个雷达系统和设计人员不可回避的重要问题之一。三十多年来,雷达目标检测与 CFAR 处理技术逐渐发展成为国际雷达信号处理界的一大热门研究领域和关键性课题。CFAR 技术是雷达自动检测系统中控制虚警率的最重要手段,它在雷达目标自动检测过程中起着极其重要的作用。

　　《雷达自动检测与恒虚警处理》自从 1999 年出版第一版以来,受到广大读者的厚爱与关怀,作者对此表示衷心的感谢。雷达目标自动检测与恒虚警处理的理论、算法和应用的不断发展,使我们迫切感觉到要对本书进行全面的扩展、完善、修改和补充新的内容,以适应当前雷达目标检测领域发展的需要。

　　本书是在《雷达自动检测与恒虚警处理》的基础上进行系统地扩展、完善并加以修改和增订而成的。这次结合近十多年的最新研究成果对原书做了较大幅度的修订。主要做了如下工作:

　　① 将书名修订为《雷达目标检测与恒虚警处理》,因为在以前的雷达目标自动检测技术中强调"自动",而现在的雷达目标检测方法的"自动"功能是不言而喻的,因此还是强调目标检测,而不用"雷达自动检测",以区别于雷达的自动测试;

　　② 综合近十几年雷达目标检测技术的发展,对雷达目标检测的研究现状给予了更全面的阐述;

　　③ 充实了雷达目标自动检测所需的基础理论,对第一版第 1 章雷达目标自动检测原理和第 2 章均值类 CFAR 检测器的内容进行了完善和扩充,特别是补充了多脉冲和相干脉冲条件下雷达目标检测的原理和方法,并将"雷达自动检测原理"更名为"经典的固定门限检测";

　　④ 充实了有序统计类 CFAR 检测器的研究内容,增加了一些理论分析和新的检测方法;

　　⑤ 增加了采用自动筛选技术的 MTM-、TMGO-和 TMSO-CFAR 检测器的研究内容,使得这部分的内容更加系统和完善;

　　⑥ 对自适应 CFAR 处理一章进行了修改,主要包括 E-CFAR 检测器、VTM-CFAR 检测器以及 Himonas 的一系列 CFAR 检测器,主要以文字和框图的形式对这些检测器进行了简要阐述,并补充了一些新的自适应 CFAR 检测器,归纳总结了"自适应类"CFAR 检测器的基本方法;

　　⑦ 将韦布尔和对数正态杂波背景中的 CFAR 技术以及两参数 CFAR 技术原书中两章内容合并为一章,首先研究了在韦布尔和对数正态杂波中能提供 CFAR 检测的经典 Log-t 检测器,再按照非高斯背景中单参数和双参数检测方法的次序对原有内容进行了重新组织和改写;

　　⑧ 将"K 分布和莱斯分布杂波中的 CFAR 处理"更名为"复合高斯分布杂波中的 CFAR 处理",并删掉原书中"莱斯分布杂波中的 CFAR 处理"这一部分内容。从"复合高斯分布"出发,将 K 分布模型作为特例,重点介绍 K 分布杂波中的 CFAR 处理,并补充了近年来意

大利 Gini 等人关于复合高斯杂波中 CFAR 检测的研究成果；

⑨ 基于非参量检测和变换域 CFAR 处理最新的理论研究成果和工程实际中的应用状况，对原书中第 9 章、第 10 章的内容进行了大幅度的更替；扩展了时频域 CFAR 处理的最新研究成果，补充了其他变换域 CFAR 处理的内容；

⑩ 增加了杂波图 CFAR 处理章节，主要内容包括 Nitzberg 杂波图处理、杂波图处理的点技术和面技术，以及空域和时域混合处理的 CM/L-CFAR 检测器和相应内容的性能分析；

⑪ 新增了距离扩展目标检测技术，重点讨论了复合高斯杂波、复合高斯杂波加热噪声及 SαS 分布杂波背景中距离扩展目标的检测问题；

⑫ 新增了多传感器分布式 CFAR 处理，重点讨论了两类多传感器分布式 CFAR 检测器，具体包括分布式 CA-CFAR 检测器，分布式 OS-CFAR 检测器以及基于 R 类、S 类和 P 类局部检测统计量的分布式 CFAR 检测器；

⑬ 全面修改了"回顾、建议和展望"一章，结合雷达目标自动检测技术的新发展，系统地总结了全书的内容，并为今后继续开展该领域的工作给予了指导性意见。此外，根据最近十多年来国内外的研究成果，本书增加了必要的参考文献，并对一些文字叙述不正确之处进行了修正，旨在进一步增加本书的可读性。

在本书第二版出版之际，本书作者在此衷心感谢德国汉堡大学 H. Rohling 教授、清华大学陆大绁教授、彭应宁教授，以及国内著名雷达专家保铮院士、王越院士、郭桂蓉院士、刘永坦院士、毛二可院士、王小谟院士、张光义院士、贲德院士、张锡祥院士、黄培康院士、吴一戎院士、吴曼青院士等多年来对我们的科学研究工作所给予的指导、关心和帮助。同时，感谢清华大学出版社，特别是王一玲编辑对本书按期高质量出版的大力支持。

本书由何友教授，关键教授，孟祥伟教授，黄勇博士，简涛博士，曲付勇博士生执笔，并由何友教授对全书进行了统稿。在成书过程中，刘宁波博士生，陈小龙博士生，刘光明博士生，张晓利博士生，徐从安硕士生等参加了本书的校对工作。

我们希望本书的出版，不仅给广大从事雷达目标检测和 CFAR 处理的科技人员提供一本可读性较好的参考书，也给学习雷达目标检测和 CFAR 处理的研究生提供一本内容比较全面的教材。

恳请广大学者能一如既往地关心本书，并提出宝贵的意见和建议。

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何友　关键　孟祥伟

2011 年 8 月

于烟台海军航空工程学院

Foreword of the Second Edition

The false alarm problem of radar target detection and tracking is one of the important issues which can not be avoided by each radar system and designer. The radar target detection and CFAR processing technology have gradually developed into a popular research area and key issues in the international radar signal processing community over the past three decades. CFAR technology is the most important tool in the control of false alarm rate in automatic radar target detection system, which plays an important role in the process of automatic radar detection.

Since 1999, the first edition of *Automatic Radar Detection and CFAR Processing* has been winning the readers' love and care. The authors would like to express our sincere gratitude. With the development of the theories, algorithms and applications of automatic radar target detection and CFAR processing, we urgently feel it is necessary to expand, improve, modify and add new content to meet the current needs of developments in the field of radar target detection.

The content of this book has been expanded systematically, improved and then revised and enlarged based on our book *Automatic Radar Detection and CFAR Processing* written in 1999. We have revised the first edition extensively with the latest research over the past ten years. The revisions are as follows: (1) The book is renamed as *Radar Target Detection and CFAR Processing*. This is because the past automatic radar target detection stresses the word "automatic", while the "automatic" function of present radar target detection methods is self-evident. Thus, we emphasize the radar detection instead of "automatic radar detection" in order to differ from automatic radar test. (2) Combing with the development of radar target detection algorithms over the past ten years, more comprehensive elaboration has been made on the present study of automatic radar detection algorithms. (3) The necessary basic theories of automatic radar target detection are enlarged. The principles of automatic radar target detection in Chapter 1 and the mean-level type CFAR detectors in Chapter 2 are improved and enlarged. Especially, the theories and methods of radar target detection with multiple pulses and coherent pulses are supplemented and as well "principles of automatic radar detection" is renamed as "classic fixed threshold detection". (4) The content of "order statistics type CFAR detectors" are extended with some theoretical analysis and new methods. (5) The MTM-, TMGO- and TMSO-CFAR detectors of automatic censoring technique are added so as to make the content more systematical and substantial. (6) The chapter named as adaptive CFAR detectors is revised and the E-CFAR detector, VTM-CFAR detector and a series of Himonas CFAR detectors are scaled back with brief descriptions in the form of text and

diagram. Some novel adaptive CFAR detectors are added and the fundamental algorithms of adaptive CFAR detectors are summarized. (7) The chapter named as CFAR technique in Weibull and log-normal clutter background and the chapter named as biparametric CFAR techniques are combined into one chapter. Firstly, the classical Log-t CFAR detector in Weibull and log-normal clutter is researched and then the original content are reorganized and rewritten according to the order of single parametric detection and biparametric detection. (8) "CFAR processing in K distribution and Rice distribution clutter" is renamed as "CFAR processing in compound Gaussian distribution clutter", and the "Rice distribution clutter" is canceled. Beginning with the "compound Gaussian distribution", CFAR detection in K distribution clutter is emphasized with regarding the K distribution model as the special case. Also the recent research results of the Italian professor Gini about the CFAR detection in compound Gaussian clutter are added. (9) Based on the recent theories and research results of nonparametric CFAR processing and transform domains CFAR and theirs engineering applications, the content of chapter 9 and 10 in the original book are revised extensively, the recent research results about the CFAR processing in time-frequency domain and the CFAR processing technology in other transform domains are added. (10) Clutter map CFAR processing technology is added, and the main content includes Nitzberg's clutter map technique, clutter map point/plane-detection technique, spatial and temporal hybrid CM/L-CFAR clutter map detection technique as well as corresponding performance analysis. (11) Detection technology of range-spread target is added, and the range-spread target detection issues in compound Gaussian clutter, compound Gaussian clutter plus thermal noise as well as SαS clutter are mainly discussed. (12) Multisensor distributed CFAR processing is added and two kinds of detectors are mainly discussed, and the main content includes the distributed CA-CFAR detector, the distributed OS-CFAR detector and the distributed CFAR detectors based on kinds of R, S, and P local test statistic. (13) The chapter named as "review, suggestion and prospect" is revised entirely. The overall content of this book is summarized systematically with the new development of automatic radar detection technologies, which provides guidance for the future work in this area. In addition, according to the domestic and foreign research results over the past ten years, necessary references are added in the book and some mistakes on word description are revised. All of these aim at increasing the readability of this book.

At the moment of the publication of the second edition, the authors would like to express sincere thanks to Professor H. Rohling in University of Hamburg of Germany, Professor Lu Dajin, Peng Yingning in Tsinghua University, and other domestic well-known radar experts, Bao Zheng academician, Wang Yue academician, Guo Guirong academician, Liu Yongtan academician, Mao Erke academician, Wang Xiaomo academician, Zhang Guangyi academician, Ben De academician, Zhang Xixiang academician, Huang Peikang academician, Wu Yirong academician and Wu Manqing academician, et al. Thanks for their guidance, care and help to our scientific research over the years. Also, we would like to

give thanks to Tsinghua University Press, especially the great support of Editor Wang Yiling who guarantees the publication on schedule with high quality.

This book has been written by Professor He You, Professor Guan Jian, Professor Meng Xiangwei,Doctor Huang Yong, Doctor Jian Tao and Ph. D. Candidate Qu Fuyong. Professor He You has Compiled and revised the full book rigorously and Carefully. In the course of writing this book,Ph. D. Candidate Liu Ningbo,Ph. D. Candidate Chen Xiaolong, Ph. D. Candidate Liu Guangming Ph. D. Candidate Zhang Xiaoli,and Master Candidate Xu Cong'an et al. proof-readed this book.

We hope that the publication of this book will not only provide a readable reference book for the scientific workers engaged in the radar target detection and CFAR processing but also provide a comprehensive teaching material for the graduate students engaged in the radar target detection and CFAR processing.

Sincerely hope the majority of scholars continue to care about the book and make valuable comments and suggestions.

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He You,Guan Jian,Meng Xiangwei

August 2011

At Naval Aeronautical and Astronautical University,Yantai

第一版前言

在自然界中,无论在人造的机器或者生物体中,检测都是广泛存在的行为方式,它根据一定的准则做出事件是否存在的判决。由于环境的不稳定,准则的不精确,在此过程中事件并没有发生而被错误地判决为发生的概率,即虚警概率。

雷达是军事和民用领域中探测目标的主要工具。它的主要目的就是在存在干扰的背景中检测出有用目标,这些干扰包括接收机内部热噪声、地物、雨雪、海浪等杂波干扰和电子对抗措施(ECM)、人工有源和无源干扰以及与有用目标混杂在一起的邻近干扰目标和它的旁瓣等。在雷达自动检测系统中,通常是将自动检测和恒虚警(constant false alarm rate, CFAR)技术结合使用以保持在变化的杂波环境中获得可预测的检测性能和恒定虚警率。

雷达自动检测和跟踪中的虚警问题是每个雷达系统和设计人员不可回避的重要问题之一。二十多年来,雷达自动检测与 CFAR 处理技术逐渐发展成为国际雷达信号处理界的一大热门研究领域和关键性课题。CFAR 技术是雷达自动检测系统中控制虚警率的最重要手段,它在雷达自动检测过程中起着极其重要的作用。现在,CFAR 研究已经出现了多个研究方向。根据模拟杂波背景所使用的杂波分布模型分为:瑞利分布、韦布尔分布、对数正态分布、K 分布和莱斯分布模型中的 CFAR 研究;按照数据处理方式分为:参量和非参量 CFAR 技术;按处理所在的数域分为:时域和频域 CFAR 研究方法;根据数据的形式分为:标量和向量 CFAR 技术;根据信号的相关程度分为:相关和不相关信号及部分相关信号的 CFAR 方法。此外,还可分为单参数和多参数 CFAR 技术,单传感器和多传感器分布式 CFAR 技术,以及其他的一些研究方法。

对于涉足于该领域的雷达系统研究与设计人员,多年来一直渴望有一部全面、系统介绍自动检测重要准则和 CFAR 处理模型的专著。本书试图较全面、系统地向读者介绍当代雷达自动检测原理与 CFAR 处理技术的发展与最新研究成果,并重点介绍均值(ML)类 CFAR 检测器、有序统计量(OS)类 CFAR 检测器、具有自动筛选技术的广义有序统计量 CFAR 检测器、自适应 CFAR 检测器、韦布尔和对数正态杂波中的 CFAR 处理、两参数 CFAR 技术、莱斯和 K 分布杂波中的 CFAR 处理、非参量 CFAR 处理和频域中的 CFAR 处理方法等,同时研究它们在均匀杂波背景、多目标环境和杂波边缘环境这三种典型信号背景中的性能。在撰写过程中,我们尽可能地搜集了大量有关 CFAR 和自动检测理论的文献,并通过各章节的合理编排使读者对这些种类繁多的 CFAR 处理方法有一个比较清晰和系统的了解。

应当指出,无论是雷达自动检测理论还是 CFAR 处理技术,当前仍处于迅速发展阶段,由于篇幅的限制,本书不可能对这些发展做出统览无余的介绍。为此,我们在每章的最后都进行了归纳和总结,指出一些重要的新发展,并罗列了相应的参考文献,供读者进一步阅览和研究参考。

本书第一作者在德国不伦瑞克工业大学进修期间,在 CFAR 领域得到了 H. Rohling 教授开拓性的指导,他对本书的出版给予了极大的鼓励和支持,在此表示最衷心的谢意。

著名雷达专家郦能敬教授和北京航空航天大学毛士艺教授对本书提出了一些宝贵意见。烟台海军航空工程学院刘永硕士参加了本书的出版工作,并为本书绘制了图形。在此一并表示感谢。

何友　关键　彭应宁　陆大绘

1998 年 10 月

于清华大学和烟台海军航空工程学院

Foreword of the First Edition

In whatever man-made machines or organisms all over the world, detection is a widespread behavior pattern. It is a judgment for the presence of an event, based on a given criterion. Due to the instability of the environment and the impreciseness of the criteria, the probability of not-happening events, which are judged to happen, is the false alarm probability.

Radar is the main tool of detecting targets in the martial and civilian applications. Its main purpose is to detect the interesting targets in the disturbances. These disturbances include internal thermal noise of receiver; clutter from ground, rain, snow, sea waves; electronic counter measures (ECM); active and passive interferences; neighboring useless targets and its side lobes. In radar systems, the automatic detection is usually combined with constant false alarm rate (CFAR) techniques to obtain the predictable detection performance, and at the same time, to keep the false alarm probability constant in changing clutter environment.

The false alarm problem in radar automatic detection and track is one of the important issues, which can not be avoided in the radar system design. In the past two decades, radar automatic detection and CFAR processing techniques gradually developed into popular research fields, and now is the key issues in the international radar signal processing community. More precisely, CFAR technique is the most important means to control the false alarm rate in radar system, and it plays an important role in the radar automatic detection process. Now, several research directions have appeared in the CFAR processing. According to the clutter distribution models, CFAR technique involves the Rayleigh, Weibull, lognormal, Rician and K distributions. According to the data processing methods, it includes parameters CFAR techniques and Non-parametric ones. According to the processing domains, it includes time domain CFAR methods and frequency domain ones. According to the data forms, it contains scalar CFAR techniques and vector ones. According to the signal correlation, it involves relevant, irrelevant and partly relevant signals. In addition, it also includes single-parameter and multi-parameter CFAR techniques, single-sensor and multi-sensor distributed CFAR techniques, as well as other methods.

For those who are engaged in the fields of radar system research and design, a comprehensive and systematic monograph introducing the important criteria for automatic detection and CFAR processing model is desirable for them. In this book, we attempt to

introduce the contemporary theories and the latest research results of radar CFAR processing techniques, comprehensively and systematically. It covers the mean lever (ML) CFAR detector, order statistics (OS) CFAR detector, CFAR detector based on generalized order statistics with automatic excision, adaptive CFAR detector, CFAR processing in Weibull and lognormal clutter, two-parameters CFAR technique, CFAR processing in Rician and K distributed clutter, non-parametric CFAR processing and frequency domain processing methods. Moreover, the performances for these CFAR detectors are investigated in homogeneous backgrounds, multiple target situations and clutter edge situations. In the writing process, we collected a wealth of literatures about automatic CFAR detection theory, and arranged each chapter appropriately so that the readers can understand various CFAR detectors clearly and systemically.

It should be noted that, both of radar automatic detection theory and CFAR processing techniques are still in rapid development. For the space limitations, we hardly give a fine-drawn description in this book. Hence, we provided the corresponding comparison and summary at the end of each chapter; and pointed out some new developments, while listing the corresponding references for readers' further reading and research.

The first author of this book was guided by Prof. H. Rohling, in the study period Technical University of Braunschweig in Germany. Herein we express our honestly appreciations to Prof. H. Rohling for his great encouragements and supports for the book publication.

The famous radar expert Prof. Li Nengjing, and Prof. Mao Shiyi of Beijing University of Aeronautics and Astronautics, gave lots of valuable suggestions for this book. Moreover, Liu Yong, master of Naval Aeronautical and Astronautical Engineering University, has worked for the book publication and has drawn figures for this book. Thank them together.

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He You, Guan Jian, Peng Yingning, Lu Dajin

October 1998

At Tsinghua University and Naval Aeronautical and Astronautical

Engineering University

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