FUNDAMENTALS OF GUIDED MISSILES

SR Mohan

Defence Research & Development Organisation
Ministry of Defence, India

Fundamentals of Guided Missiles

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Foreword

While writing the foreword of this book 'Fundamentals of Guided Missiles' authored by Rear Admiral SR Mohan, I am transported down memory lane to the 1970s, when a set of young scientists had joined Defence Research and Development Laboratory (DRDL) after graduating from the country's best institutions such as the IITs and IISc to take up the challenging task of carrying out Research and Development in Guided Missiles and build the counry's tactical missiles (SAMs, ATMs, etc.), as well as the strategic missiles (IRBM, etc.). All of us, without any exception, had no knowledge of Missile Systems, except for our basic knowledge of Mechanical Engineering, Aeronautical Engineering, Electronics Engineering, etc. Our senior colleagues in DRDL had the benefit of developing an Anti-tank Missile and a few of them had attended a course on Missile Systems at Cranfield, UK. The literature available on the subject was meagre and we had to resort to the process of development through reverse engineering and reading through Missile Design Handbook by Koelle; Propulsion by Sutton; and Control, Guidance and Navigation by Greensight, Chin, etc. Most of the available literature was of Second World War vintage. There was no single book that would cover Missile systems for beginners. It was a major handicap.

The then Director of DRDL, Air Commodore (later Air Marshal) AVS Narayanan, who then was leading a team to design the country's SAM and strategic missiles realised this knowledge gap and initiated dedicated training programmes at the Indian Institute of Science, Bangalore and Institute of Armament Technology (IAT), Pune. I was deputed to go through a course on Guided Weapons at IAT, Pune, after seven years of work in the development of Liquid Rocket Engines. During this course, I met for the first time, Rear Admiral (then Commander) SR Mohan, who was a member of Faculty at IAT. He delivered lectures on Missile Guidance and Control and as a Propulsion Engineer, it was my first exposure to these subjects. These lectures made an everlasting impact on me, leading to my developing an immense interest in these areas of missile system design. The personality of Adm Mohan as an excellent designer and teacher with outstanding understanding of the subject left an indelible impression on me.

I met Adm Mohan again in the early 1980s, when he was deputed to DRDL to lead a team of engineers to develop a short range surface-to-air missile, 'Trishul'. I had many opportunities to interact with him during the design and development of the 'Prithvi' Missile system of which I was an integral part. Later, when I was the Project Director of 'Prithvi', I approached him for designing the terminal guidance system for the ship-launched anti-ship version ot the Prithvi. He did an excellent job in designing a Homing Seeker in late 1980s, when DRDO had no experience in this complex field.

As a Project Director of Trishul, Adm Mohan also played the key role of a Chief Designer. His was the unique example of a Project Director controlling the design of all the major systems and subsystems of the Trishul weapon system. From the preliminary design of subsystems such as Propulsion, Radio Command Guidance, Control, Radio Altimeter, and Radio Proximity Fuze to the integration of Fire Control Radar and a Mobile Launcher on a tracked vehicle, and later replicating the same at a Naval shore establishment and conducting many flight trials of Trishul, he had a hand in every aspect, establishing himself as an outstanding tactical missile system designer.

In the early years of 2000, I was the Director of Research Centre Imarat (RCI), which was the centre for systems study and design of different types of guided missiles. While many scientists and engineers of the laboratory were experts, each in his chosen field of work, I felt that an integrated series of lectures covering the design aspects of different subsystems will be highly beneficial to their work. I wanted to ensure that we develop a large number of missile system designers like Adm Mohan to take up the development of many missiles in the country in parallel. I thought of the Admiral, who was then leading a retired life and asked him to give a series of lectures to the scientists covering the fundamentals of the different Guided Missile subsystems. He readily consented and the happy outcome was that he, along with Professor Mahapatra of the Indian Institute of Science, conceived and conducted a course, covering the different aspects of subsystems design. I am very happy to see that this has now resulted in a book, covering extensively the fundamentals of the widely different disciplines, which go to make up a guided missile system.

The most striking feature of the book, to my mind, is the simple manner in which complex topics like Missile Kinematics, Command Guidance systems, Inertial Navigation, Homing systems, Tracking Radar, Infrared methods, etc., have been covered. This makes the book ideally suitable as a text book, to any scientist or engineer, starting on a career in the missile field, who has not been exposed to a formal course on Missile Design. I am also happy to note that many of the lessons learnt the hard way by the author in the course of developing a tactical missile

system have been included which will be of inestimable use to the engineers working on similar systems in future.

I wish to congratulate RAdm Mohan on the effort he has put in and the result thereof. Though, obviously written as a text book for the budding Guided Missile scientists and engineers of the Indian Defence Laboratories, I feel that it is likely to be highly useful to other students of Aerospace as well. I have no hesitation in recommending this book to anybody working in the field of Guided Missiles or Aerospace, who is desirous of obtaining a comprehensive knowledge of the system.

Dr VK Saraswat
FNAE, FAeSI, FASI, FIE, FPAS
12 April 2014 Fr SA to RM, Secretary, DoD, R&D and DG, DRDO

Preface

Some years ago, at the instance of the present Scientific Advisor to Raksha Mantri, Dr VK Saraswat, who was then the Director of Research Centre Imarat, Hyderabad, I delivered some lectures on the fundamentals of Guided Missile Systems to the scientific officers of that laboratory. I repeated the course in 2008. Many different disciplines of science and engineering are encountered in the study of a Guided Missile system. For example, knowledge of Control Engineering is essential for the design of a Flight Control system. Aerodynamics decides the shape of a missile. Radar and infrared systems are extensively used in the guidance of tactical missiles. During the lectures, I found that many of the engineers were interested in subjects, not directly connected to their areas of specialisation. For example, a specialist in radar was interested in missile propulsion and a structural specialist, working on the missile airframe was keen to know about gyros and accelerometers. During the course of my lectures, several of them suggested, that I should write a book on the lines of my lectures, covering different aspects of guided missiles. This book is the result of that suggestion. It has taken me over three years and, needless to say, has continuously undergone several revisions during this period.

In this book, I have tried to cover the different subjects to a 'greater than superficial' level. My knowledge on the subject is derived from many excellent books on the diverse subjects and therefore, the information contained in this book is nothing original, except possibly in the manner of presenting it. Over the years, I have been fortunate to have had the time to read many different books. My tenure, as an instructor in the Faculty of Guided Missiles, at the Institute of Armament Technology, Pune (now the Defence Institute of Armament Technology) with its extensive library, enabled me to read widely and cogitate on what I had read. In particular, I owe whatever I know about Missile Kinematics to the brilliant lectures of Professor PC Rath of that institute. I also learnt about blast warheads, fragmentation warheads including Gurney's formula and Hesh warheads from the then Wing Cdr Rathuri, who used to teach air armament. But, most of the topics

contained in this book will be found, discussed to a far greater depth, in many of the standard books on the different subjects. Anyone wanting to know more about Radar should study Skolnik's or Barton's definitive books on Radar, and if one is interested in Infrared Engineering, Hudson's book on the subject. 'Guided Missile Control System' by Garnell is a must-read for anyone wanting to learn this aspect of the subject. There are similar wonderful books on every one of the different subjects. I have included a list of references at the end of each chapter. The material contained in a chapter is based almost entirely on material in the reference books listed. Tha articles in Wikipedia and Google on the internet are excellent sources of information and I have included some references from these sources. I have written this book mostly from memory and it is possible that I have missed out some authors and sources in the references. If so, it is unintentional and my humble apologies to those missed out.

Unfortunately, most people, who already are specialists in any one field and who want to learn about other guided missile subsystems have neither the time nor the patience to go through many books covering the individual subjects. This book is meant for them. In that sense, this book can probably be called the 'Guided Missiles for the Non-man'. One may say that it contains aerodynamics for the non-aerodynamicist, control engineering for the non-control engineer, radar for the non-radar man, and so on. This being the case, every specialist is bound to feel that his own subject is inadequately covered. But it is my sincere hope that the different subjects are covered adequately enough to enable a person interested in Guided Missile systems to participate in any discussion on the subject meaningfully.

In addition, this book also contains some knowledge, learned through hard experience and which cannot be found in books. These are mostly included as notes at appropriate places. The recommendation for a separate earth line for the arming mechanism for the rocket motor is the result of experience. So is the one about changing the soft metal washer in a pressurised air bottle, every time it is charged and discharged. Some notes are also likely suggestions to overcome problems, which one may come across, while working in the development of missiles. These are not always proven and are either the result of my own thinking about the subject or ideas evolved during discussions with persons working in the field. I discussed and learnt a lot about systems from the senior members of the laboratory, in particular Shri Ranga Rao and Late Shri Krishnan, who were doyens in the field, as well as my friend Shri AK Kapoor, who was the head of the solid propulsion in those days. Occassionally, in this book, the presentation may be different from what is found in standard books. The method of deriving the Dynamic Error Compensation terms in Appendix 16, is one such example and is different (as far as my knowledge goes), from any I have come across. Thanks to

the articles in Wikipedia and Google, which have also contributed enormously to my knowledge.

It is my experience that, while most people are interested in the 'What' and 'How' of things, a few do want to know 'Why'. This book makes an attempt to cover the 'What', 'How' and 'Why' of the different subsystems that go into the making of a guided missile. Some 'Whys' can be satisfactorily answered only with mathematics and the appendices cover several aspects mathematically. It is possible that many of the derivations will not satisfy the mathematical purist, but I have tried to write the mathematics in a way that can be readily understood by most engineers. Also, I have avoided using terminology and concepts, which many engineers may find confusing. 'Spectral radiant emittance' and 'Radiant emittance' are two such terms.

Finally, I owe thanks to many, who encouraged me to write this book, especially my wife, Lalitha, who not only cheerfully put up with my preoccupation with this project for over three years, but also gave me encouragement, whenever my enthusiasm flagged.

Hyderabad SR Mohan

28 Nov 2012

Acknowledgements

As mentioned in the Preface, I owe whatever I know on the subject of guided missiles to the large number of excellent books on different subjects that I had the good fortune to come across in three different excellent libraries, in particular – Institute of Armament Technology (IAT), Pune; Defence Research and Development Laboratory (DRDL) and Research Centre Imarat (RCI), Hyderabad. I have cited as references in each chapter of those books, which are the source of my knowledge and to the authors and publishers to whom I owe an enormous gratitude. I recommend without hesitation that every student should read these references. In particular, since the subjects I used to lecture on were Guidance and Control, I should mention that I have read these books 'Introduction to Radar' by Merill I Skolnik, 'Infrared System Engineering' by Richard D Hudson and 'Guided Missile Control Systems' by P Garnell and D J East, many times and they have provided me exceptionally clear understanding of these subjects.

I am also deeply grateful to the many professors at IAT, Pune, who taught me the different aspects of the subject so thoroughly when I was undergoing the 'Special Weapons' course. In particular, I should mention the excellent lectures of Professor Rath on Missile Kinematics and those on Warheads by Wing Cdr IS Rathuri. Their notes form the basis of my knowledge on these subjects and that of the relevant chapters of this book. The Guided Weapons Handbook by Royal Military College, Shrivenham, has contributed enormously to my knowledge and the chapter on Warheads. Wing Cdr Madhava (later Air vice Marshal), who had studied 'Flight Control' at Cranfield, taught us the subject so well, that subsequently for many years, I used to teach the subject based on his notes, and the chapters on Flight Control and Autopilot in this book are mainly based on those. I also owe thanks to many scientists of DRDL and RCI, with whom I used to discuss various subjects leading to clarity of the subject in my mind. I would like to mention, with respect combined with gratitude, Shri AV Ranga Rao and the late Shri Krishnan, for the frequent technical discussions we had on the subject of Guided Missiles. I wish to acknowledge with thanks, the roles of Shri SK Ray and Shri P Venugopalan,

who were the directors of RCI and DRDL respectively, for their encouragement for publishing, what I had written only for inhouse consumption and recommending improvements. My heartfelt thanks are also due to Shri Anand Kumar Kapoor, who was the head of the Solid Propellant Division at DRDL, for a sizable part of my knowledge of propulsion.

My most sincere thanks are also due to Dr VK Saraswat, Former SA to RM, Secretary, Dept of Defence R&D and DG, DRDO (presently a member of NITI Ayog), himself a man with wide knowledge of the different subsystems, who as the then director of RCI, asked me to plan a syllabus and deliver lectures on Guided Missile systems to Scientific Officers of his laboratory. The lecture notes and the slides which I made for the lectures, form the skeleton of this book. But for these lectures and his encouragement, there would have been no book. I am also deeply thankful to him for consenting to write the 'Foreword' for the book.

And how can I thank Dr APJ Abdul Kalam adequately for making me the project director of Trishul? The problems faced were invaluable in making me study, discuss with the different specialists about possible solutions and understand the complexities of the various subsystems. Attending the many presentations and discussions was likewise an eye opener. Unfortunately, since that great man, who was the mentor to many, is no more with us, I can only bow my head to the memory of Dr Kalam now. I,very humbly, dedicate this book to the memory of Dr Kalam, a wonderful man and a great soul.

Finally, I thank Shri Gopal Bhushan, Director, DESIDOC, for not only accepting to print this book, but also readily extending every support that the monographs division needed to bring out this book. My thanks to his staff of the monograph division, who must have worked so long and hard to bring a book of this length with so many diagrams into print. My special thanks are due to Smt Anitha Saravanan, Head, Monographs division, who constantly interacted with me every step of the way and solved the many problems encountered, considering that this document covers science and technology in so many different areas of specialisation.

SR Mohan

List of Acronyms

AAM or AAW	Air-to-Air Missile
ACLOS	Automatic Command to Line-of-Sight
AGC	Automatic Gain Control
AM	Amplitude Modulation
AMTI	Airborne MTI
APN	Augmented Proportional Navigation
ASM or ASW	Air-to-Surface Missile
ATM	Anti-tank Missile
AUM or AUW	Air-to-Underwater Missile
CCW	Counter Clock Wise
CDB	Cast Double Base
CE	Characteristic Equation
CEP	Circular Error Probable
CG	Centre of Gravity
CKP	Cumulative Kill Probability
Coho	Coherent Oscillator
CLOS	Command to Line-of-Sight System
COLOS	Command to Off the Line-of-Sight
Cosro	Conical Scan on Receive Only
CP	Centre of Pressure
CTPB	Carboxyl Terminated Poly-Butadiene
CW	Clock Wise
CW	Continuous Wave
DA	Direct Action
DEC	Dynamic Error Compensation
DISMAC	Digital Scene Area Matching and Correlation
EBW	Exploding Bridge Wire
ECM	Electronic Countermeasures
EDB	Extruded Double Base

EED	Electro-Explosive Device
EGT	Exhaust Gas Temperature
EHF	Extremely High Frequency
EMCDB	Elastomer Modified CDB
ERA	Explosive Reaction Armour
ESG	Electrostatic Gyro
FAE	Fuel-Air Explosive
FLIR	Forward Looking Infrared
FM	Frequency Modulation
FMCW	Frequency Modulated Continuous Wave
FOG	Fibre Optic Laser Gyro
FOV	Field-of-View
FRP	Fibre Re-inforced Plastic
FSK	Frequency Shift Keying
GPS	Global Positioning System
HE	High Explosive
HESH	High Explosive Squash Head
HF	High Frequency
HTPB	Hydroxyl Terminated Poly-Butadiene
ICBM	Inter Continental Ballistic Missiles
ICW	Interrupted Continuous Wave
IF	Intermediate Frequency
IFF	Interrogation of Friend or Foe
IIR	Imaging Infrared Systems
INS	Inertial Navigation System
IPN	Iso Propyl Nitrate
IR	Infra Red
IRBM	Intermediate Range Ballistic Missiles
IRCM	Infra Red Counter Measure
IRFNA	Inhibited RFNA
ITU	International Telecommunications Union
KE	Kinetic Energy
LF	Low Frequency
LOS	Line-of-Sight
MAW	Misalignment Wave

MCLOS	Manual Command to Line-of-Sight
MCT	Mercury Cadmium Telluride
MEMS	Micro Electro Mechanical System
MF	Medium Frequency
MGR	Missile Guidance Radar
MIRV	Multiple Independently Targetable Re-entry Vehicle
MOPA	Master Oscillator Power Amplifier
MRBM	Medium Range Ballistic Missiles
MTI	Moving Target Indicator
MTR	Missile Tracking Radar
NCNG	Nitrocellulose and Nitroglycerine
Nd YAG	Neodymium Yttrium Aluminium Garnet
OBC	Onboard Computer
PE	Potential Energy
PETN	Penta Erythritol Tetranitrate
PN	Proportional Navigation
PPI	Plan Position Indicator
PPN	Pure Proportional Navigation
PPS	Pulse Per Second
PRF	Pulse Repitition Frequency
RCS	Radar Cross-Section
RCW	Reference Cosine Wave
RF	Radio Frequency
RFNA	Red Fuming Nitric Acid
RIG	Rate Integrating Gyros
RLG	Ring Laser Gyro
RSL	Rotation of Sight Line
RSS	Root Sum of Square
RSW	Reference Sine Wave
SACLOS	Semi-Automatic Command to Line-of-Sight
SAM	Safety and Arming Mechanism
SAM or SAW	Surface-to-Air Missile
SAR	Synthetic Aperture Radar
SAU	Safety and Arming Unit
SAW	Surface Acoustic Wave

Scramjets	Supersonic Combustion Ramjets
SHF	Super High Frequency
SHM	Simple Harmonic Motion
S/N ratio	Signal-to-Noise Ratio
SRBM	Short Range Ballistic Missiles
SSKP	Single Shot Kill Probability
SSM	Surface-to-Surface Missile
Stalo	Stable Local Oscillator
SUM or SUW	Surface-to-Underwater Missile
TBM	Theatre Ballistic Missiles
TE Cooler	Thermo-Electric Cooler
TERCOM	Terrain Comparison
TF	Transfer Function
TIR	Target Illumination Radar
TM	Time Mechanical
TNT	TriNitroToluene
TPN	True Proportional Navigation
TSFC	Thurst Specific Fuel Consumption
TTR	Target Tracking Radar
TVC	Thrust Vector Control
TVM	Track Via Missile
TWS	Tracle While Scan
UAM or UAW	Underwater-to-Air Missile
UDMH	Unsymmetrical Di-methyl Hydrazine
UHF	Ultra High Frequency
UUM or UUW	Underwater-to-Underwater Missile
VCO	Voltage Controlled Oscillator
VHF	Very High Frequency
VLF	Very Low Frequency
VT	Variable Time

CHAPTER 1

Guided Missile Systems

1.1 INTRODUCTION

Guided missiles form the cutting edge of all weapons of war today. The difference between the conventional weapons of yesteryear and the guided weapons is that, while the conventional weapon has to be launched in the correct direction with a lead angle to intercept the target at some future position, the guided weapon can be controlled in flight till interception to achieve destruction of the target. While guided missiles have become more and more sophisticated and smart, the fundamentals of missiles remain unchanged. A host of different disciplines of science and engineering go into the making of a guided weapon system. This chapter gives a bird's eye view of the different types of guided missile systems, and the subsystems, which go to make up a guided missile system.

Depending on the environment from which the missile is launched and the environment in which the target is to be found, the guided missile (or weapon) systems are classified as follows:

- Surface-to-Surface Missile (SSM or SSW)
- Surface-to-Air Missile (SAM or SAW)
- Surface-to-Underwater Missile (SUM or SUW)
- Air-to-Surface Missile (ASM or ASW)
- Air-to-Air Missile (AAM or AAW)
- Air-to-Underwater Missile (AUM or AUW)
- Underwater-to-Surface Missile (USM or USW)
- Underwater-to-Air Missile (UAM or UAW)
- Underwater-to-Underwater Missile (UUM or UUW)

All these varieties do not necessarily exist. For example, UAMs are not practical propositions, and UUMs are really torpedoes. Any missile system whose

target is a submarine like the SUM, will be a composite system, where the terminal underwater component is likely to be a homing torpedo.

Guided missiles may also be classified as strategic or tactical, with further subdivisions depending on the role. Strategic missiles are large missiles, often with nuclear warheads and very long ranges, meant to destroy the enemy's ability to wage war. Tactical missiles, on the other hand, are meant for battlefield use for the limited purpose of winning the battle or encounter. These can be of different kinds, depending on their roles.

1.2 STRATEGIC MISSILES

The target for strategic missiles will be a fixed position on earth, such as a city, troop forming up posistion, etc., whose coordinates are known a priori and the missile has to be programmed to fly to this geographical position. The guidance reduces to one of navigation to the target, which requires the missile to know continuously, its own position on the earth. The favoured method is 'Inertial Navigation', wherein the missile navigates to the target using inertial instruments like gyros and accelerometers. Celestial navigation – using stars for navigation – was an alternative to inertial navigation. It was used in some early missiles, but with navigation satellites in position, it is obsolete and currently, Global Positioning System (GPS), using navigation satellites becomes a possible alternative.

Strategic missiles may be launched from land (or a surface ship), a submarine, or an aircraft. Ground-launched missiles have to be protected against pre-emptive attacks or retaliatory attacks by the enemy. They may be launched, either from a hardened underground silo or from a mobile vehicle, whose position keeps changing all the time. Both trucks with cross-country capability and railway flatbeds can be used for this purpose. Ship, submarine and air launched missiles are obviously safer from this perspective. The range of strategic missiles is very large and they follow either a ballistic trajectory or a low altitude aerodynamic trajectory (also called the supported trajectory) as shown in Fig. 1.1.

(a) Ballistic trajectory **(b) Aerodynamic trajectory**

Figure 1.1. Trajectory of strategic missiles.

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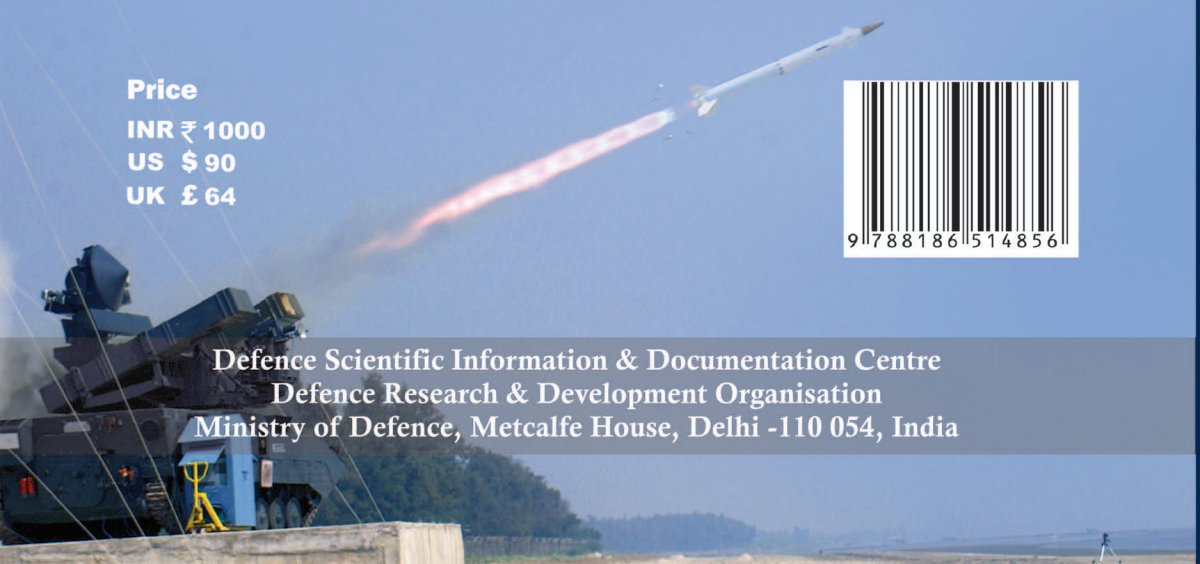
About the Book

The subject of Guided Missiles encompasses many disciplines and sciences. This publication is intended to provide an understanding on the different parts and how they interact in making up the whole to anyone working in this area. The publication includes within its covers, a detailed description on various topics, which go to make up the subject. It has been written primarily as a text book for scientists and engineers of DRDO, who come from diverse engineering backgrounds who desire to work in the field of Guided Missiles. The chapters cover widely different subjects like Aerodynamics, Control Engineering, Propulsion, Flight Control, Missile Kinematics, Radar, Infrared, Guidance, and Warheads starting from basics to a reasonable depth, so that the engineers/scientists can take part in meaningful technical discussions on Guided Missile systems. Though it is written with that prime purpose, it will probably be found useful by other students of Aerospace engineering, as well.

About the Author

Rear Admiral S R Mohan is a post graduate in Physics from the Madras University, Chennai. He was commissioned in the Indian Navy in 1955. He has undergone 'Long G course (specialist Naval Gunnery)' and the 'Special Weapons course' at the Institute of Armament Technology (IAT), Pune. He was posted to the faculty of Guided Missiles at IAT and rose to the position of Head of the faculty at Defence Research and Development Laboratory (DRDL). He was appointed as the Project Director of the Short Range Surface-to-Air Missile 'Trishul' at DRDL, which post, he held till his retirement in 1990. Dr Kalam, in his book, *Wings of Fire*, stated, 'this sailor-teacher-scientist, can outwit any expert in the country in the field of Command Guidance'.

Radm Mohan has been the recipient of 'Visisht Seva Medal' from the President of India, and the 'Dr Biren Roy Award' from the Aeronautical Society of India.



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