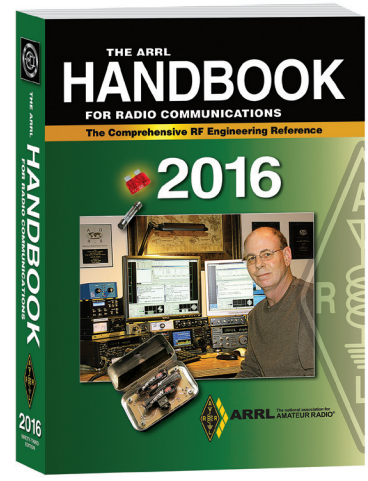
2016

The ARRL Handbook

For Radio Communications



About the Cover:
Top RTTY contest operator Don Hill, AA5AU operates with low power from his effective station. [Shay Hill, photo]

Ninety-Third Edition

Published by:
ARRL

the national association for Amateur Radio™
Newington, CT 06111 USA

Editor
H. Ward Silver, NØAX

Contributing Editors
Steven R. Ford, WB8IMY
Mark J. Wilson, K1RO

Editorial Assistant
Maty Weinberg, KB1EIB

Technical Consultants
Michael E. Gruber, W1MG
Edward F. Hare, Jr., W1RFI
Zachary H.J. Lau, W1VT

Cover Design
Sue Fagan, KB1OKW
Bob Inderbitzen, NQ1R

Production
Michelle Bloom, WB1ENT
Jodi Morin, KA1JPA
David F. Pingree, N1NAS

Additional Contributors to the 2016 Edition
Alan Appelgate, KØBG
John Burningham, W2XAB
Joe Eisenberg, KØNEB
Joel Hallas, W1ZR
Markus Hansen,VE7CA
Scott Honakker, N7SS
Anthony Langton, GM4HTU
Rick Lindquist, WW1ME
Carl Luetzelschwab, K9LA
Steve McDonald, VE7SL
Michael Sapp, WA3TTS
David Stockton, GM4ZNX
Michael Stott, VE3EBR
Jim Tonne, W4ENE
Paul Verhage, KD4STH

ISBN: 978-1-62595-041-3 Softcover

ISBN: 978-1-62595-042-0 Hardcover

Ninety-Third Edition

Contents

A more detailed Table of Contents is included at the beginning of each chapter.

Foreword

This *2016 ARRL Handbook* is the 93rd edition of this technical reference for Amateur Radio — thanks for choosing this book and welcome! You'll find that the book covers a lot of ground: the fundamentals of electronics and radio signals, construction practices, antennas and propagation, equipment and circuit design, and other useful reference information. This is typical of Amateur Radio, with 730,000 hams in the United States and millions more around the world.

The *ARRL Handbook* is written for hams in need of instruction and training as they fulfill our Basis and Purpose in pursuit of technical and communications excellence. Likewise, the *Handbook* is a value-packed reference for students and technical professionals in search of practical hands-on information.

The book is organized in several sections starting with the Fundamental Theory chapters which introduce basic ideas about electronics and circuits. They are followed by the Practical Design and Principles section with chapters that focus on the various circuits and equipment actually in use through an amateur station. What radio reference book would be without an Antenna Systems and Radio Propagation section? Finally, there are sections on Equipment Construction and Maintenance as well as Station Assembly and Management.

The book includes a CD-ROM with dozens of supplementary articles, projects, and references that go beyond what we can fit in print. Don't miss out — open that envelope inside the back cover and install the files on your PC! Here's what you'll find:

Complete Handbook content as a searchable PDF text

Space Communications — by Joe Taylor, K1JT, and Steve Ford, WB8IMY

Digital Communications — by Steve Ford, WB8IMY

Image Communications — by Tom O'Hara, W6ORG, and Dave Jones, KB4YZ

Annual Transceiver Review — by Joel Hallas, W1ZR

What else is on the CD-ROM? Look at the CD-ROM Content listing at the start of every chapter starting with Chapter 2 — Electrical Fundamentals. You'll find articles and projects and more reference information!

Once again, we are pleased to offer the latest collection of professional-quality design software from Jim Tonne, W4ENE, starting with his famous *ELSIE* filter design program. In a departure from years past, we are making the software available from the *Handbook*'s very own website: **www.arrl.org/arrl-handbook-reference**. This is where you'll find the Tonnesoft package along with other utilities and even more supplemental instruction and information.

The *ARRL Handbook* is also full of projects that hams can use to construct a functional and effective home, mobile, or portable station. Projects range from simple accessories and small power supplies to legal-limit amplifiers and high-gain antennas.

We are continually looking for new projects and updated sections to add value in the shack and in the *Handbook*. Here are just some of the new faces in the Class of 2016:

- A comprehensive new connector identification chart courtesy of Pasternak
- Beacon transmitters for VHF/UHF by Michael Sapp, WA3TTS
- How does the ARRL Lab test equipment? You can read the ARRL Lab Test Procedures Manual!
- Microwave operators will want to read "Noise Instrumentation and Measurement" by Paul Wade W1GHZ
- Breaking entirely new ground, a CD-ROM article on lightwave transmitting and receiving was contributed by Steve McDonald, VE7SL, and Markus Hansen, VE7CA
- An up-to-the-minute treatment of fractional-n frequency synthesizers by Dave Stockton, GM4ZNX
- A high-altitude APRS tracker is described by Paul Verhage, KD4STH
- DMR (Digital Mobile Radio) makes an appearance in the Repeaters chapter, covered by John Burningham, W2XAB, and its key characteristics have been added to the digital mode characteristics table maintained by Scott Honakker, N7SS.
- SDR owners will want to check out the SDR Knob Box by Michael Stott, VE3EBR

Closing in on the 100th edition, the reference hams simply refer to as "the *Handbook*" continues to keep pace with the fast-moving technology hams employ around the world. No matter how long you've been licensed — months, years, or decades — there is something in the *Handbook* to interest you or that you can use to make your station better.

David Sumner, K1ZZ
Chief Executive Officer
Newington, Connecticut
August 2015

The Amateur's Code

The Radio Amateur is:

CONSIDERATE…never knowingly operates in such a way as to lessen the pleasure of others.

LOYAL…offers loyalty, encouragement and support to other amateurs, local clubs, and the American Radio Relay League, through which Amateur Radio in the United States is represented nationally and internationally.

PROGRESSIVE…with knowledge abreast of science, a well-built and efficient station and operation above reproach.

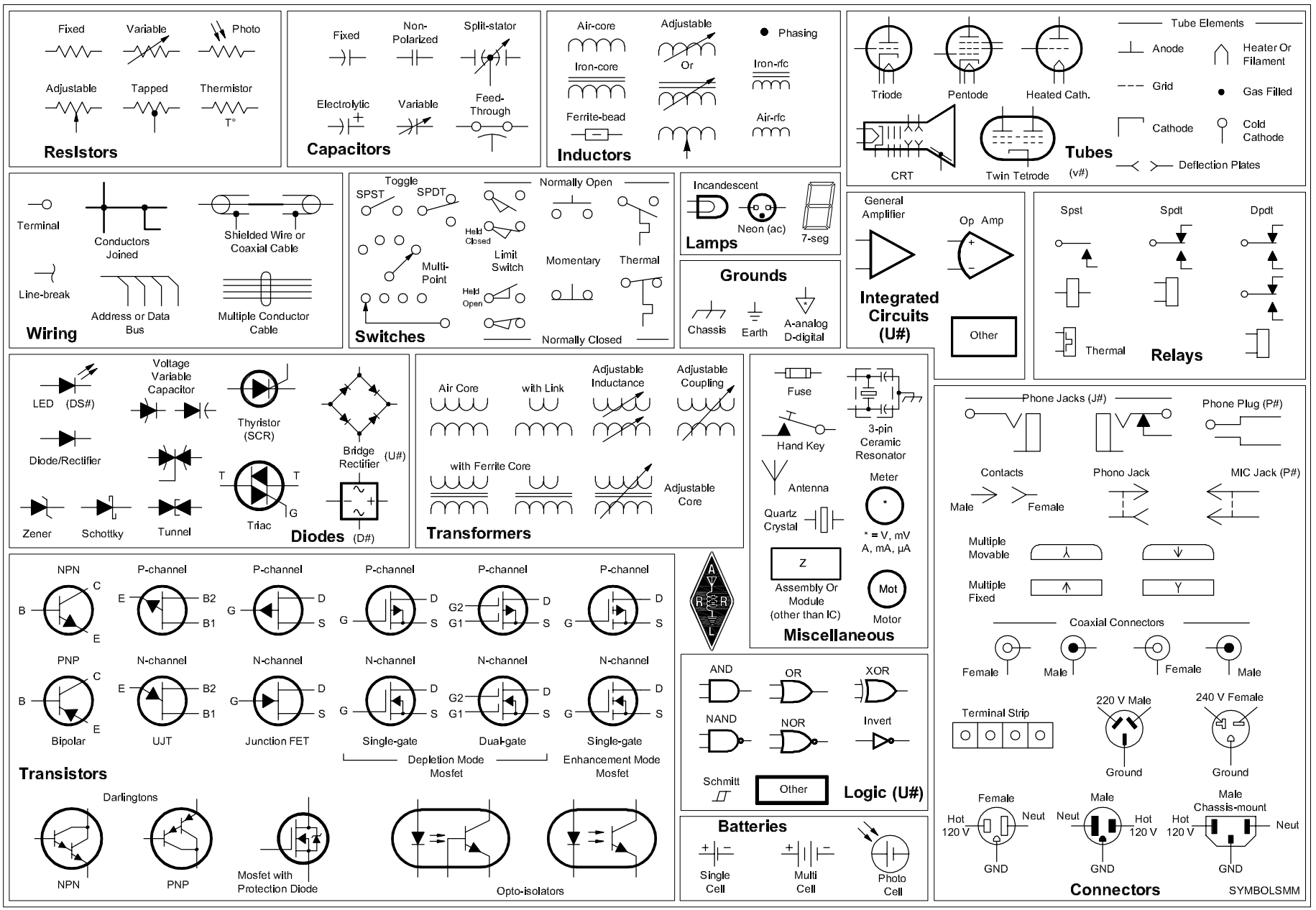
FRIENDLY…slow and patient operating when requested; friendly advice and counsel to the beginner; kindly assistance, cooperation and consideration for the interests of others. These are the hallmarks of the amateur spirit.

BALANCED…radio is an avocation, never interfering with duties owed to family, job, school or community.

PATRIOTIC…station and skill always ready for service to country and community.

—The original Amateur's Code was written by Paul M. Segal, W9EEA, in 1928.

Common Schematic Symbols Used in Circuit Diagrams



ARRL Member Services

Get Involved
www.arrl.org/get-involved

Join or Renew
www.arrl.org/join

Donate
www.arrl.org/donate

Shop
www.arrl.org/shop

Membership Benefits

Your ARRL membership includes ***QST*** magazine, plus dozens of other services and resources to help you **Get Started**, **Get Involved**, and **Get On the Air**. ARRL members enjoy Amateur Radio to the fullest!

Members-Only Web Services

Create an online ARRL Member Profile, and get access to ARRL members-only web services. Visit **www.arrl.org/myARRL** to register.

- ***QST* Digital Edition – www.arrl.org/qst**
  All members can access the enhanced digital edition of *QST* from a web browser. Apps are available for *iOS* and *Android* devices.
- ***QST* Archive and Periodicals Search – www.arrl.org/qst**
  Browse ARRL's extensive online *QST* archive. A searchable index for *QEX* and *NCJ* is also available.
- **Free E-Newsletters**
  Subscribe to a variety of ARRL e-newsletters and e-mail announcements: ham radio news, radio clubs, public service, contesting, and more!
- **Product Review Archive – www.arrl.org/qst**
  Download and view *QST* Product Reviews.
- **E-Mail Forwarding Service**
  E-mail sent to your **arrl.net** address will be forwarded to any e-mail account you specify.

ARRL Technical Information Service — www.arrl.org/tis

Call or e-mail our expert ARRL Technical Information Service specialists for answers to all your technical and operating questions. This service is FREE to ARRL members.

ARRL as an Advocate — www.arrl.org/regulatory-advocacy

ARRL supports legislation and regulatory measures that preserve and protect meaningful access to the radio spectrum. Our **ARRL Regulatory Information Branch** answers member questions concerning FCC rules and operating practices. ARRL's **Volunteer Counsel** and **Volunteer Consulting Engineer** programs open the door to assistance with antenna regulation and zoning issues.

ARRL Group Benefit Programs* — www.arrl.org/benefits

- **ARRL Ham Radio Equipment Insurance Plan**
  Insurance is available to protect you from loss or damage to your station, antennas, and mobile equipment by lightning, theft, accident, fire, flood, tornado, and other natural disasters.
- **The ARRL Visa Signature® Card**
  Every purchase supports ARRL programs and services.
- **Liberty Mutual Auto and Home Insurance**
  ARRL members may qualify for special group discounts on home and auto insurance. Get a free quote.

* ARRL Group Benefit Programs are offered by third parties through contractual arrangements with ARRL. The programs and coverage are available in the US only. Other restrictions may apply.

Programs

Public Service — www.arrl.org/public-service

Amateur Radio Emergency Service® – **www.arrl.org/ares**
Emergency Communications Training – **www.arrl.org/emcomm-training**

Radiosport

Awards – **www.arrl.org/awards**
Contests – **www.arrl.org/contests**
QSL Service – **www.arrl.org/qsl**
Logbook of The World – **www.arrl.org/lotw**

Community

Radio Clubs (ARRL-affiliated clubs) – **www.arrl.org/clubs**
Hamfests and Conventions – **www.arrl.org/hamfests**
ARRL Field Organization – **www.arrl.org/field-organization**

Licensing, Education, and Training

Find a License Exam Session – **www.arrl.org/exam**
Find a Licensing Class – **www.arrl.org/class**
ARRL Continuing Education Program – **www.arrl.org/courses-training**
Books, Software, and Operating Resources – **www.arrl.org/shop**

Quick Links and Resources

QST – ARRL members' journal – **www.arrl.org/qst**
QEX – *A Forum for Communications Experimenters* – **www.arrl.org/qex**
NCJ – *National Contest Journal* – **www.arrl.org/ncj**
The ARRL Library – **www.arrl.org/library**
Support for Instructors – **www.arrl.org/instructors**
Support for Teachers – **www.arrl.org/teachers**
ARRL Volunteer Examiner Coordinator (ARRL VEC) – **www.arrl.org/vec**
Public and Media Relations – **www.arrl.org/media**
Forms and Media Warehouse – **www.arrl.org/forms**
FCC License Renewal – **www.arrl.org/fcc**
Foundation, Grants, and Scholarships – **www.arrl.org/arrl-foundation**
Advertising – **www.arrl.org/ads**

Interested in Becoming a New Ham?

www.arrl.org/newham • **newham@arrl.org** • 1-800-326-3942 (US)

Contact Us

ARRL, the national association for Amateur Radio®
225 Main Street, Newington, CT 06111-1494 USA
Tel 1-860-594-0200, Mon-Fri 8 AM to 5 PM ET (except holidays)
FAX 1-860-594-0259, e-mail **hqinfo@arrl.org**
Website – **www.arrl.org/contact-arrl**

Facebook
www.facebook.com/ARRL.org

Follow us on Twitter
twitter.com/arrl • twitter.com/w1aw • twitter.com/arrl_pr
twitter.com/arrl_youth • twitter.com/arrl_ares
twitter.com/arrl_dxcc

YouTube
www.youtube.com/ARRLHQ

The American Radio Relay League, Inc.

The American Radio Relay League, Inc. is a noncommercial association of radio amateurs, organized for the promotion of interest in Amateur Radio communication and experimentation, for the establishment of networks to provide communication in the event of disasters or other emergencies, for the advancement of the radio art and of the public welfare, for the representation of the radio amateur in legislative matters, and for the maintenance of fraternalism and a high standard of conduct.

ARRL is an incorporated association without capital stock chartered under the laws of the State of Connecticut, and is an exempt organization under Section 501(c)(3) of the Internal Revenue Code of 1986. Its affairs are governed by a Board of Directors, whose voting members are elected every three years by the general membership. The officers are elected or appointed by the directors. The League is noncommercial, and no one with a pervasive and continuing conflict of interest is eligible for membership on its Board.

"Of, by, and for the radio amateur," the ARRL numbers within its ranks the vast majority of active amateurs in the nation and has a proud history of achievement as the standard-bearer in amateur affairs.

A *bona fide* interest in Amateur Radio is the only essential qualification of membership; an Amateur Radio license is not a prerequisite, although full voting membership is granted only to licensed amateurs in the US.

Membership inquiries and general correspondence should be addressed to the administrative headquarters: ARRL, 225 Main Street, Newington, Connecticut 06111-1494.

About the ARRL

The seed for Amateur Radio was planted in the 1890s, when Guglielmo Marconi began his experiments in wireless telegraphy. Soon he was joined by dozens, then hundreds, of others who were enthusiastic about sending and receiving messages through the air—some with a commercial interest, but others solely out of a love for this new communications medium. The United States government began licensing Amateur Radio operators in 1912.

By 1914, there were thousands of Amateur Radio operators—hams—in the United States. Hiram Percy Maxim, a leading Hartford, Connecticut inventor and industrialist, saw the need for an organization to band together this fledgling group of radio experimenters. In May 1914 he founded the American Radio Relay League (ARRL) to meet that need.

Today ARRL, with approximately 165,000 members, is the largest organization of radio amateurs in the United States. The ARRL is a not-for-profit organization that:

- promotes interest in Amateur Radio communications and experimentation
- represents US radio amateurs in legislative matters, and
- maintains fraternalism and a high standard of conduct among Amateur Radio operators.

At ARRL headquarters in the Hartford suburb of Newington, the staff helps serve the needs of members. ARRL is also International Secretariat for the International Amateur Radio Union, which is made up of similar societies in 150 countries around the world.

ARRL publishes the monthly journal *QST* and an interactive digital version of *QST*, as well as newsletters and many publications covering all aspects of Amateur Radio. Its headquarters station, W1AW, transmits bulletins of interest to radio amateurs and Morse code practice sessions. The ARRL also coordinates an extensive field organization, which includes volunteers who provide technical information and other support services for radio amateurs as well as communications for public-service activities. In addition, ARRL represents US amateurs with the Federal Communications Commission and other government agencies in the US and abroad.

Membership in ARRL means much more than receiving *QST* each month. In addition to the services already described, ARRL offers membership services on a personal level, such as the Technical Information Service—where members can get answers by phone, email or the ARRL website, to all their technical and operating questions.

Full ARRL membership (available only to licensed radio amateurs) gives you a voice in how the affairs of the organization are governed. ARRL policy is set by a Board of Directors (one from each of 15 Divisions). Each year, one-third of the ARRL Board of Directors stands for election by the full members they represent. The day-to-day operation of ARRL HQ is managed by an Executive Vice President and his staff.

No matter what aspect of Amateur Radio attracts you, ARRL membership is relevant and important. There would be no Amateur Radio as we know it today were it not for the ARRL. We would be happy to welcome you as a member! (An Amateur Radio license is not required for Associate Membership.) For more information about ARRL and answers to any questions you may have about Amateur Radio, write or call:

ARRL—the national association for Amateur Radio®
225 Main Street
Newington CT 06111-1494
Voice: 860-594-0200
Fax: 860-594-0259
E-mail: **hq@arrl.org**
Internet: **www.arrl.org**

Prospective new amateurs call (toll-free):
800-32-NEW HAM (800-326-3942)
You can also contact us via e-mail at **newham@arrl.org**
or check out the ARRL website at **www.arrl.org**

US Amateur Radio Bands

Effective Date
March 5, 2012

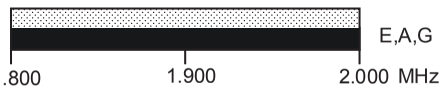
Published by:
ARRL The national association for AMATEUR RADIO®
www.arrl.org
225 Main Street, Newington, CT USA 06111-1494

US AMATEUR POWER LIMITS

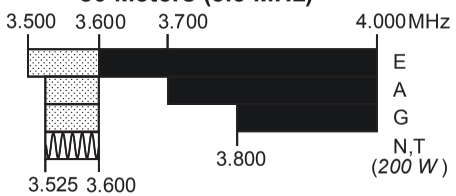
FCC 97.313 An amateur station must use the minimum transmitter power necessary to carry out the desired communications. (b) No station may transmit with a transmitter power exceeding 1.5 kW PEP.

160 Meters (1.8 MHz)

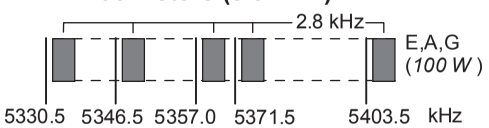
Avoid interference to radiolocation operations from 1.900 to 2.000 MHz



80 Meters (3.5 MHz)

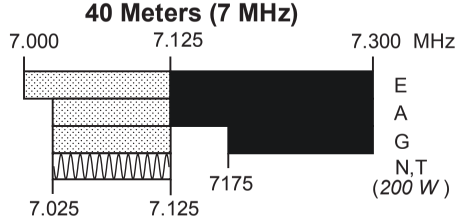


60 Meters (5.3 MHz)



General, Advanced, and Amateur Extra licensees may operate on these five channels on a secondary basis with a maximum effective radiated power (ERP) of 100 W PEP relative to a half-wave dipole. Permitted operating modes include upper sideband voice (USB), CW, RTTY, PSK31 and other digital modes such as PACTOR III as defined by the FCC Report and Order of November 18, 2011. USB is limited to 2.8 kHz centered on 5332, 5348, 5358.5, 5373 and 5405 kHz. CW and digital emissions must be centered 1.5 kHz above the channel frequencies indicated above. Only one signal at a time is permitted on any channel.

40 Meters (7 MHz)

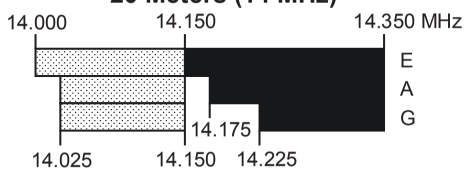


Phone and Image modes are permitted between 7.075 and 7.100 MHz for FCC licensed stations in ITU Regions 1 and 3 and by FCC licensed stations in ITU Region 2 West of 130 degrees West longitude or South of 20 degrees North latitude. See Sections 97.305(c) and 97.307(f)(11).
Novice and Technician licensees outside ITU Region 2 may use CW only between 7.025 and 7.075 MHz and between 7.100 and 7.125 MHz. 7.200 to 7.300 MHz is not available outside ITU Region 2. See Section 97.301(e). These exemptions do not apply to stations in the continental US.

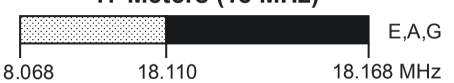
30 Meters (10.1 MHz)

Avoid interference to fixed services outside the US.

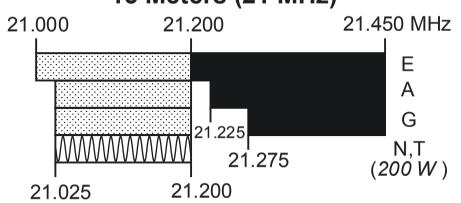
20 Meters (14 MHz)



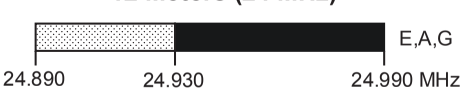
17 Meters (18 MHz)



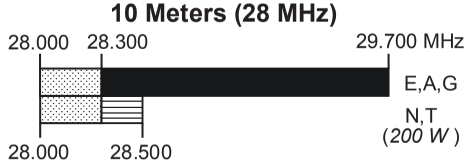
15 Meters (21 MHz)



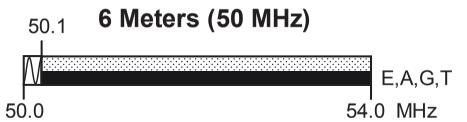
12 Meters (24 MHz)



10 Meters (28 MHz)

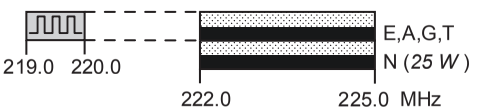


6 Meters (50 MHz)



2 Meters (144 MHz)

1.25 Meters (222 MHz)

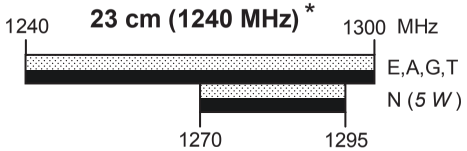


*Geographical and power restrictions may apply to all bands above 420 MHz. See *The ARRL Operating Manual* for information about your area.

70 cm (420 MHz)*

33 cm (902 MHz)*

23 cm (1240 MHz)*



All licensees except Novices are authorized all modes on the following frequencies:

2300-2310 MHz	10.0-10.5 GHz *	122.25-123.0 GHz
2390-2450 MHz	24.0-24.25 GHz	134-141 GHz
3300-3500 MHz	47.0-47.2 GHz	241-250 GHz
5650-5925 MHz	76.0-81.0 GHz	All above 275 GHz

* No pulse emissions

KEY

Note:
CW operation is permitted throughout all amateur bands.

MCW is authorized above 50.1 MHz, except for 144.0-144.1 and 219-220 MHz.

Test transmissions are authorized above 51 MHz, except for 219-220 MHz

- = RTTY and data
- = phone and image
- = CW *only*
- = SSB phone
- = USB phone, CW, RTTY, and data.
- = Fixed digital message forwarding systems *only*

E = Amateur Extra
A = Advanced
G = General
T = Technician
N = Novice

See *ARRLWeb at www.arrl.org* for detailed band plans.

ARRL
We're At Your Service

ARRL Headquarters:
860-594-0200 (Fax 860-594-0259)
email: hq@arrl.org

Publication Orders:
www.arrl.org/shop
Toll-Free 1-888-277-5289 (860-594-0355)
email: orders@arrl.org

Membership/Circulation Desk:
www.arrl.org/membership
Toll-Free 1-888-277-5289 (860-594-0338)
email: membership@arrl.org

Getting Started in Amateur Radio:
Toll-Free 1-800-326-3942 (860-594-0355)
email: newham@arrl.org

Exams: 860-594-0300 email: vec@arrl.org

 rev. 6/24/2015

ARRL Handbook CD-ROM Contents

On the CD-ROM included with this book you'll find this entire edition of the *Handbook*, including text, drawings, tables, illustrations and photographs. Using Adobe *Reader*, you can view, print or search the entire book. Also included is supplemental information and articles, PC board template packages, construction details for many projects, and companion software mentioned throughout. The CD-ROM is included in protective envelope attached inside the back cover of the book.

The *Handbook* has a supporting web page, as well — you'll find it at **www.arrl.org/arrl-handbook-reference**. This year, we are again providing you with the Companion Software listed below, but as downloadable files. This allows the author, Jim Tonne, W4ENE, to keep the latest versions of all files available to you at all times. Plus, additional files, articles, and notes that appear after the book was printed will be posted, as well.

Supplemental Files for Each Chapter

The CD-ROM provides supplemental information for most chapters of this book. This includes articles from *QST* and other sources, material from previous editions of the *ARRL Handbook*, tables and figures in support of the chapter material, and files that contain PC board layout and other design information to build and test the projects provided in the chapters. The supplemental information is arranged in folders for each chapter.

Companion Software

The following software is available from **www.arrl.org/arrl-handbook-reference:**
TubeCalculator, a *Windows* application by Bentley Chan and John Stanley, K4ERO, accompanies the tube type RF power amplifier discussion in the **RF Power Amplifiers** chapter.

The following *Windows* programs by Tonne Software **(www.tonnesoftware.com)** are provided by Jim Tonne, W4ENE.

ClassE — Designs single-ended Class E RF amplifiers.

Diplexer Designer — Designs both high-pass/low-pass and band-pass/band-stop types of diplexer circuits.

Helical Filter Designer — Designs and analyzes helical-resonator bandpass filters for the VHF and UHF frequency ranges.

JJSmith — A graphics-intensive transmission-line calculator based on the Smith chart.

Elsie — The free student edition of *Elsie,* a lumped-element filter design and analysis program.

Meter Basic — Designs and prints professional-quality analog meter scales on your printer. The full-featured version of *Meter* is available from Tonne Software.

OptLowpass Designer — Designs and analyzes very efficient transmitter output low-pass filters.

Pi-El — Designs and analyzes pi-L networks for transmitter output.

Quad Net — Designs and analyzes active quadrature ("90-degree") networks for use in SSB transmitters and receivers.

SVC Filter Designer — Standard-value component routine to design low-pass and high-pass filters and delivers exact-values as well as nearest-5% values.