MIL-STD-188-140

3 April 1981

SUPERSEDING:
SEE FORWARD

MILITARY STANDARD

EQUIPMENT
TECHNICAL DESIGN STANDARDS
FOR COMMON LONG HAUL/TACTICAL
RADIO COMMUNICATIONS
IN THE LOW FREQUENCY BAND
AND LOWER FREQUENCY BANDS

FSC TCTS

DEPARTMENT OF DEFENSE

Washington, D. C. 20301

Equipment Technical Design Standards for
Common Long Haul/Tactical Radio Communications
in Low Frequency Band and Lower Frequency Bands

MIL-STD-188-140

1. This Military Standard is approved and mandatory for use by all Departments and Agencies of the Department of Defense in accordance with the OASD (CCCI) Memorandum, dated 10 May 1977 (see APPENDIX A).

2. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed: Commander, Naval Electronic Systems Command, ATTN: ELEX 5043, Washington, D.C. 20360, by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

FOREWORD

1. In the past three decades MIL-STD-188, covering Miliary Communications Systems Technical Standards, has evolved from one applicable to all military communications (MIL-STD-188, MIL-STD-188A and MIL-STD-188B) to one applicable to tactical communications only (MIL-STD-188C).

2. Future standards for all military communications are published as part of a MIL-STD-188 series of documents. Military Communications System Technical Standards are subdivided into Common Long Haul and Tactical Standards (MIL-STD-188-100 series), Tactical Standards (MIL-STD-188-200 series) and Long Haul Standards (MIL-STD-188-300 series).

3. This document provides minimum performance requirements in the form of standards and design objectives to ensure interoperability of future extremely low frequency (ELF), infra-low frequency (ILF), very low frequency (VLF), and low frequency (LF) comnnications equipment.

4. Certain provisions of this document are the subject of international (NATO) standardization agreements, for example, STANAG 5030, STANAG 5031 and STANAG 5035. When a change notice, revision, or cancellation of this document is proposed which will affect or violate the international aggreement concerned, the preparing activity shall take appropriate reconciliation action through international standardization channels, including departmental standardization offices, if required. See 2.2, 5.3.1, and 5.4.1.

5. This document supersedes subparagraphs 4.5.2 through 4.5.5 of MIL-STD-188C.

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1. SCOPE

1.1 Purpose. This standard establishes minimum performance requirements in the form of standards and design objectives (DO's) to ensure interoperability of future communications equipment in the Extremely Low Frequency (ELF), Infra Low Frequency (ILF), Very Low Frequency (VLF) and Low Frequency (LF) bands. The frequency ranges of military communications equipment have been established as a result of band characteristics which do not necessarily depend upon administrative or scientific frequency band definitions. For example, in the area above ELF and ILF the military band of communications interest lies between 14 kilohertz (kHz) and 200 kHz, which extends into both VLF and LF bands. Also, efficient use of the limited bandwidth available at these lower frequencies precludes most analog modulation techniques; thus, this standard applies only to radio communication systems involving transmission of digital information.

1.2 Application. These standards shall be used in the design and engineering of new communications facilities for both the long haul and tactical systems. In some cases, reference is made to other documents which provide standards for specific applications. It is not intended that existing systems be immediately converted to comply with the requirements of these standards. New systems, and those undergoing major modification or rehabilitation, shall conform to these standards, subject to current procurement regulations.

1.3 System standards and DO's. Mandatory equipment parameter values or requirements (see APPENDIX A) are specified by use of the word "shall". Non-mandatory DO's are indicated within parentheses after a standardized parameter value or by use of the word "should".

2. REFERENCED DOCUMENTS

2.1 Issues of documents. The following documents of the issue listed in the Department of Defense Index of Specifications and Standards (DoDISS) and its supplements, form a part of this document to the extent specified herein. The date of the applicable DoDISS and supplements thereto shall be as specified in the solicitation.

STANDARDS

FEDERAL

FED-STD-1037	Glossary of Telecommunications Terms

MILITARY

MIL-STD-188-100	Common Long Haul and Tactical Military Communications System Technical Standards
MIL-STD-188-114	Electrical Characteristics of Digital Interface Circuits
MIL-STD-188-124	Grounding, Bonding and Shielding for Common Long Haul/Tactical Communications Systems
MIL-STD-461	Electromagnetic Interference Characteristics, Requirements for Equipment

(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Other publications. The following forms a part of this document to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or requests for proposal shall apply.

North Atlantic Treaty Organization Standardization Agreements (STANAG's)

STANAG 5030	Single Channel VLF RATT On-Line Broadcast System
STANAG 5031	Introduction of Modern Radio Equipment for Naval HF-MF and LF Shore-to-Ship Broadcasts
STANAG 5035	Introduction of an Improved System for Maritime Air Communications on HF, LF and UHF

(Copies of STANAGs required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

INTERNATIONAL REGULATIONS

General Secretariat of the International Telecommunication Union, Geneva	Radio Regulations

(Available from the International Telecommunication Union, Place Des Nations, 1211 Geneva - 20, Switzerland.

3. DEFINITIONS

3.1 Definitions of terms. Definition of terms used in this standard shall comply with FED-STD-1037.

3.2 Abbreviations and acronyms. The abbreviations and acronyms used in this document are listed in APPENDIX B.

4. GENERAL REQUIREMENTS

4.1 Functional employment. The radio equipments are employed in long haul and tactical communication systems and subsystems. A delineation between long haul and tactical communication systems can be found in FED-STD-1037. These systems provide communication service in the functional areas of command and control, logistics, intelligence, weather and administration. Traffic may be in one or more of the following forms: graphics, teletypewriter and data which may be transmitted as quasi-analog or digital signals.

4.2 Frequency band allocation. Section 5 specifies standards and DO's for radio equipment according to frequency band allocation.

4.3 Radio regulations. For subsystem and equipment design, the choice and performance of the equipment, as well as frequencies and emissions of any radio subsystem, shall comply with the applicable requirements of the current edition of the International Telecommunication Union (ITU) Radio Regulations. Adequate familiarity with these regulations is, therefore, required of designers and users of radio subsystems. Final approval of frequency bands, operating modes, and equipment characteristics rests within DoD with the Military Communications - Electronics Board (MCEB).

NOTE: Radio regulations information. The use of the frequency spectrum is regulated by international agreements embodied in the Radio Regulations, published by the General Secretariat of the ITU, Geneva, Switzerland, and modified periodically by a World Administrative Radio Conference (WARC). These radio regulations are further qualified at the national level through Federal Government agencies, such as the Department of Commerce, the Interdepartment Radio Advisory Committee (IRAC), and through military agencies, such as the Joint Chiefs of Staff (JCS) and the MCEB. Military frequency planning, including joint functional frequency allocation tables, is established as a joint action area under the MCEB.

4.4 Interface parameters.

4.4.1 Digital interface characteristics. All digital interfaces between equipments where the information being conveyed is in the form of binary signals at the direct current (DC) baseband level shall comply with the applicable requirements of the current edition of MIL-STD-188-114.

4.4.2 Modulation and data signaling rates. The modulation rates (expressed in bauds (Bd)) and the data signaling rates (expressed in bits per second (b/s)) at interface POINTs A of FIGURE 1 shall be those contained in the Modulation and Data Signaling Rates paragraph of MIL-STD-188-100 except that the modulation rates and data signaling rates above 9600 Bds or b/s shall not apply.

4.5 Electromagnetic interference (EMI) and electromagnetic compatibility (EMC) requirements. Equipments shall meet the applicable EMI and EMC requirements of MIL-STD-461 which shall be specified in the equipment specification.

4.6 Grounding, bonding and shielding. Grounding, bonding and shielding for VLF and LF bands shall conform to the applicable requirements of the current edition of MIL-STD-188-124.

5. DETAILED REQUIREMENTS

5.1 ELF band (below 300 hertz(Hz)). Under consideration.

5.2 ILF band (300 Hz to 3000 Hz). Under consideration.

5.3 VLF band (3 kilohertz(kHz) to 30 kHz). The VLF band is employed primarily for broadcast in the maritime and aeronautical mobile service and for limited long haul communications. Some military equipment in this field is designed to operate in both the VLF and the LF bands.

5.3.1 NATO interoperability requirements for single channel VLF. For interoperation with NATO member nations, single channel VLF on-line broadcast systems shall conform to the applicable requirements of the current edition of STANAG 5030.

5.3.2 Radio frequency characteristics.

5.3.2.1 Radio frequency tuning. VLF radio equipments shall be capable of being tuned and aligned, over the frequency range of the equipment, at integral multiples of ten Hz increments even though the carrier (or center) frequency may be assigned differently.

5.3.2.2 Radio frequency stability. The frequency stability of the VLF radio equipment, with respect to the initial frequency after calibration shall be at least within 1 part in 10^9 per day and 4 parts in 10^8 over the first 30 days. The stability shall not be degraded by more than 2 parts in 10^8 for each 30-day period thereafter.

5.3.2.3 Radio frequency accuracy. VLF radio equipment shall be capable (by calibration or alignment if necessary) of a frequency accuracy within 1 part in 10^{10} of any designated frequency within the frequency range of the equipment.

5.3.2.4 Phase jitter. The maximum phase jitter of individual VLF transmitting and receiving equipment averaged over a period equal to two times the reciprocal of the modulation rate shall not exceed 3 degrees for systems using coherent demodulation and 15 degrees for systems using non-coherent demodulation. Measurement shall be performed for at least 100 sample time periods.

NOTE: The maximum amount of phase jitter that can be tolerated in any given system is dependent upon the modulation technique used and may be less than the standard specified in 5.3.2.4.

5.3.2.5 Radio frequency harmonic distortion. The harmonic distortion of the RF output of VLF radio transmitting equipment shall comply with the applicable requirements of MIL-STD-461.

5.3.2.6 Radio frequency spurious emissions. The spurious RF emissions of VLF radio transmitting equipment shall comply with the applicable requirements of MIL-STD-461.

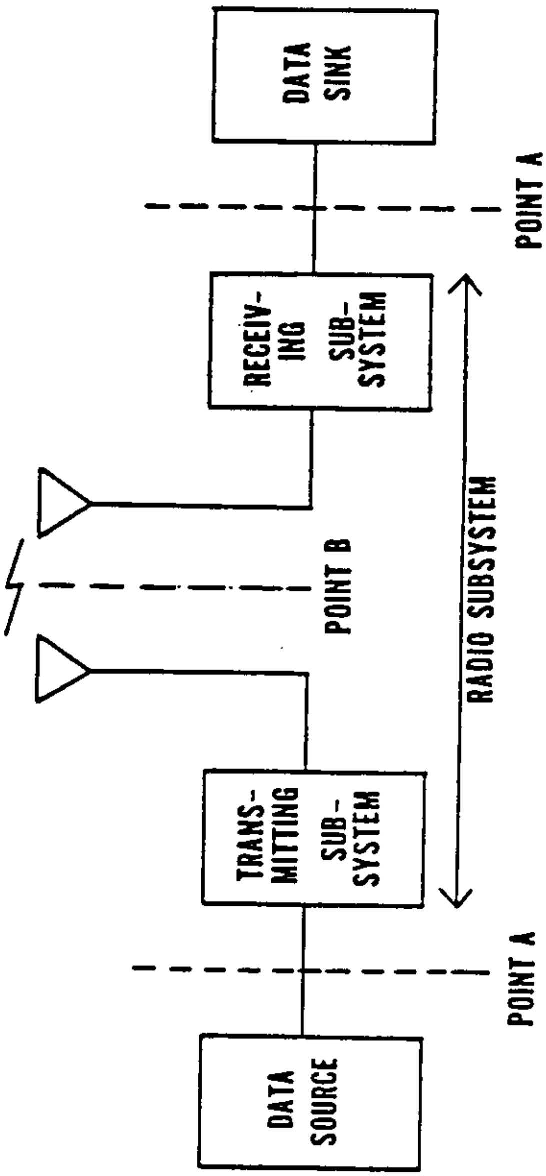

FIGURE 1. Radio subsystem interface points

5.3.2.7 Carrier noise level. The carrier noise level of VLF transmitting equipment shall be at least 50 decibels (dB) (DO: 60 dB) below the unmodulated or continuous wave (cw) carrier level within ±5 percent of the unmodulated or cw carrier frequency. This measurement shall be made at the RF output of the transmitter under operational or simulated operational conditions which must be specified in the equipment specification.

5.3.2.8 Necessary bandwidth. The necessary bandwidth of VLF radio equipment in hertz shall not exceed 2.4 times the modulation rate in bauds for a modulation index of 1.0 or shall not exceed 1.2 times the modulation rate in bauds for a modulation index of 0.5

5.3.3 Modulation. Modulation techniques for the VLF band are not standardized in this document.

NOTE: Modulation techniques should be selected carefully to meet all system interoperability requirements. Examples of current modulation techniques are given in APPENDIX C.

5.3.4 Amplitude frequency response. The maximum to minimum amplitude frequency response of VLF radio transmitting and receiving equipment, measured individually, over the necessary bandwidth for each, shall not exceed 1 dB.

5.3.5 Envelope delay distortion. The envelope delay distortion of VLF radio transmitting and receiving equipment, measured individually, shall not exceed 50 microseconds (μ sec) over the necessary bandwidth.

5.3.6 Interface parameters. See 4.4.

5.3.7 VLF modulation rates. The modulation rates for VLF radio equipment at the interface POINT B of FIGURE 1 shall be selected from the following, as applicable:

a. 5 Bd

b. 50×2^n Bd ($n = 0, 1,2,3...7$)

c. 75×2^n Bd ($n = 0, 1,2,3...7$)

5.3.8 Modulation frequency accuracy. Modulation frequency accuracies shall be as follows:

a. For VLF radio equipment using coherent demodulation, the modulation frequency accuracies shall correspond to the RF accuracy tolerances of 5.3.2.3.

b. For VLF radio equipment using non-coherent demodulation, the tolerance of the MARK or SPACE frequencies shall not exceed ±10 percent of the frequency shift.

5.3.9 Precision time/time interval (PTTI) system interface. Under consideration.

5.4 LF band (30 kHz to 300 kHz). The LF band is employed primarily for broadcast in the maritime and aeronautical mobile service and for limited long haul communications. Some military equipment in this field is designed to operate in both the VLF and the LF bands.

5.4.1 NATO interoperability requirements.

5.4.1.1 Shore-to-ship broadcast systems. For interoperation with NATO member nations, LF shore-to-ship broadcast systems shall comply with the applicable requirements of the current edition of STANAG 5031.

5.4.1.2 Maritime air communications sytems. For interoperations with NATO member nations, LF maritime air communication systems shall comply with the applicable requirements of the current edition of STANAG 5035.

5.4.2 Radio frequency characteristics.

5.4.2.1 Radio frequency tuning. LF radio equipment shall be capable of being tuned and aligned, over the frequency range of the equipment, at integral multiples of ten Hz increments even though the carrier (or center) frequency may be assigned differently.

5.4.2.2 Radio frequency stability. The frequency stability of the LF radio equipment, with respect to the initial frequency after calibration, shall be at least within 1 part in 10^9 per day and 4 parts in 10^8 over the first 30 days. The stability shall not be degraded by more than 2 parts in 10^8 for each 30-day period thereafter.

5.4.2.3 Radio frequency accuracy. LF radio equipment shall be capable (by calibration or alignment if necessary) of a frequency accuracy within 1 part in 10^{10} of any designated frequency within the frequency range of the equipment.

5.4.2.4 Phase jitter. The maximum phase jitter of individual LF radio transmitting and receiving equipment averaged over a period equal to two times the reciprocal of the modulation rate shall not exceed 3 degrees for systems using coherent demodulation and 15 degrees for systems using non-coherent demodulation. Measurement shall be performed for at least 100 sample time periods.

NOTE: The maximum amount of phase jitter that can be tolerated in any given system is dependent upon the modulation technique used and may be less than the above standard specified in 5.4.2.4.

5.4.2.5 Radio frequency harmonic distortion. The harmonic distortion of the RF output of LF radio transmitting equipment shall comply with the applicable requirements of MIL-STD-461.

5.4.2.6 Radio frequency spurious emissions. The spurious RF emissions of LF radio transmitting equipment shall comply with the applicable requirements of MIL-STD-461.

5.4.2.7 Carrier noise level. The carrier noise level of LF transmitting equipment shall be at least 50 dB (DO: 60 dB) below the unmodulated or cw carrier level within ± 5 percent of the unmodulated or cw carrier frequency. This measurement shall be made at the RF output of the transmitter under operational or simulated operational conditions which must be specified in the equipment specification.

5.4.2.8 Necessary bandwidth. The necessary bandwidth of LF radio equipment in hertz shall not exceed 2.4 times the modulation rate in bauds for a modulation index of 1.0 or shall not exceed 1.2 times the modulation rate in bauds for a modulation index of 0.5.

5.4.3 Modulation. Modulation techniques for the LF band are not standardized in this document.

NOTE: Modulation techniques should be selected carefully to meet all system interoperability requirements. Examples of current modulation techniques are given in APPENDIX C.

5.4.4 Amplitude frequency response. The maximum to minimum amplitude frequency response for LF radio transmitting and receiving equipment, measured individually, over the necessary bandwidth for each, shall not exceed 1.5 dB.

5.4.5 Envelope delay distortion. The envelope delay distortion of LF radio transmitting and receiving equipment, measured individually, shall not exceed 50 μ secs over the necessary bandwidth.

5.4.6 Interface parameters. See 4.4.

5.4.7 LF modulation rates. The modulation rates for LF radio equipment at the interface POINT B of FIGURE 1 shall be selected from the following, as applicable:

a. 5 Bd

b. 50×2^n Bd (n = 0, 1, 2, 3...7)

c. 75×2^n Bd (n = 0, 1, 2, 3...7)

5.4.8 Modulation frequency accuracy.

a. For LF radio equipment using coherent demodulation, the modulation frequency accuracies shall correspond to the RF accuracy tolerances of 5.4.2.3.

b. For LF radio equipment using non-coherent demodulation the tolerance of the MARK or SPACE frequencies shall not exceed ± 10 percent of the frequency shift.

5.4.9 PTTI system interface. Under consideration.

Custodians:
Army - CR
Navy - EC
Air Force - 17

Review activities:
Army - SC

User activities:
Army -
Navy - AS, MC
Air Force -

Preparing activity:
NAVY-EC
(Project TCTS 1400)

APPENDIX A

MEMORANDUM FROM THE ASSISTANT SECRETARY OF DEFENSE FOR COMMUNICATIONS, COMMAND, CONTROL AND INTELLIGENCE, 10 MAY 1977, SUBJECT: MANDATORY USE OF MILITARY STANDARDS IN THE 188 SERIES.

This Appendix contains information related to MIL-STD-188-140. APPENDIX A is a mandatory part of this standard.

ASSISTANT SECRETARY OF DEFENSE
WASHINGTON, D. C. 20301

10 MAY 1977

COMMUNICATIONS, COMMAND,
CONTROL, AND INTELLIGENCE

MEMORANDUM FOR Assistant Secretary of the Army (I&L)
Assistant Secretary of the Navy (I&L)
Assistant Secretary of the Air Force (I&L)
Commandant of the Marine Corps
Director, Defense Communications Agency
Director, National Security Agency

SUBJECT: Mandatory use of military standards in the 188 Series

On January 3, 1972, the Assistant Secretary of Defense (I&L) found it necessary to make a significant change in the DoD Standardization Manual 4120.3M because of recurring misapplications of military standards in general. The essence of the change is that military standards as a general rule are now cited as "approved for use" rather than "mandatory for use" in the Department of Defense.

This deference to the judgment of the designing and procuring agencies is clearly appropriate to standards dealing with process, component ruggedness and reliability, paint finishes, and the like. It is clearly not appropriate to standards such as those in the MILSTD 188 series which address telecommunication design parameters. These influence the functional integrity of telecommunication systems and their ability to efficiently interoperate with other functionally similar Government and commercial systems. Therefore, relevant military standards in the 188 series will continue to be mandatory for use within the Department of Defense.

To minimize the probability of misapplication of these standards, it is incumbent upon the developers of the MILSTD 188 series to insure that each standard is not only essential but of uniformly high quality, clear and concise as to application, and wherever possible compatible with existing or proposed national, international and Federal telecommunication standards. It is also incumbent upon the users of these standards to cite in their procurement specifications only those standards which are clearly necessary to the proper functioning of the device or systems over its projected lifetime.

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This direction is in consonance with the recommendations made by the Director, Defense Materiel Specifications and Standards Office, in his letter of March 4, 1977, which was addressed to the U.S. Army Electronics Command.

Gerald P. Dinneen

cc:
OASD(MRA&L), DMSSO
Co-Chairman, JSC, ECOM (DRSEL-CE-CS)
Co-Chairman, JSC, DCEC (R110)
OJCS (J-3), Telecom Div

APPENDIX B

ACRONYMS AND ABBREVIATIONS

10. SCOPE

10.1 Purpose. This Appendix provides explanations of acronyms and abbreviations used in this standard. The acronyms and abbreviations are in accordance with FED-STD-1037.

AM	Amplitude Modulation
ASCII	American Standard Code for Information Interchange (also known as USASCII)
Bd	Baud
b/s	Bits per Second
CSK	Compatible Shift Keying
CTFS	Central Time and Frequency System
CWFSK	Continuous Wave Frequency Shift Keying
DO	Design Objective
ELF	Extremely Low Frequency (below 300 Hz)
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
FDM	Frequency Division Multiplex
FSK	Frequency Shift Keying
ICW	Interrupted Continuous Wave
ILF	Infra Low Frequency (300 Hz to 3 kHz)
IRAC	Interdepartment Radio Advisory Committee
ITU	International Telecommunication Union
JCS	Joint Chiefs of Staff
LF	Low Frequency (30 kHz to 300 kHz)
MCEB	Military Communications Electronics Board
MF	Medium Frequency (0.3 MHz to 3.0 MHz)
MSK	Minimum Shift Keying
NATO	North Atlantic Treaty Organization
NAVOBSY	U.S. Naval Observatory
PSK	Phase Shift Keying
PTTI	Precise Time and Time Interval
RATT	Radio Teletype
SLHC	DoD Standardization Area Code for Long-Haul Communications
SNR	Signal to Noise Ratio
SSB	Single Sideband
STANAG	NATO Standardization Agreement
TCTS	DoD Standardization Area Code for Tactical Communications Technical Standards
TWX	Teletypewriter Exchange Service
VLF	Very Low Frequency (3 kHz to 30 kHz)
WARC	World Administrative Radio Conference

APPENDIX C

TUTORIAL INFORMATION

10. Modulation characteristics for the VLF and LF bands. This appendix contains tutorial information and is not a mandatory part of MIL-STD-188-140.

10.1 Scope. This appendix presents the salient characteristics of modulation techniques used in the VLF and LF bands which are unique from those used in higher frequency bands.

20. VLF and LF modulation characteristics. VLF and LF shore based communications transmitting systems are characterized by narrow RF bandwidths (less than conventional voice channels) and high power transmitters. Narrow bandwidths are the result of the fact that the antennas used at these frequencies are electrically very short even though they are often physically large. The antenna size versus wavelength results in a highly reactive antenna impedance with a low resistance (High Q) and consequently limited bandwidth and long charge/discharge time constant. High power radio transmitters are used because of the low radiation efficiency of the antenna, the need for long-range radio communications, and significant sea water attenuation for communications with submerged submarines. Both the necessity to operate to the limits of the bandwidth normally available and the high transmitting power involved place stringent requirements on the modulation techniques used.

20.1 Analog modulation techniques. Conventional analog amplitude modulation (AM) and frequency modulation (FM) are not widely used at VLF or LF because of their inefficient use of the available limited RF bandwidth.

20.2 Digital modulation techniques. Modulation techniques for VLF and LF are presently restricted to digital means because of limited system bandwidth. Additionally, the bandwidth restriction is such that the digital technique selected should be the most efficient in its use of bandwidth if a usable level of traffic throughput is to be attained. The principal digital modulation techniques are described in the following, with greater emphasis and detail on those in current use which yield the best operational capabilities.

20.2.1 Interrupted continuous wave (ICW). ICW or on-off keying (usually associated with international Morse Code) can be used with VLF and LF systems, but is presently used only as a back-up. In the case of fixed shore base installations, ICW data rates are severely limited by the time constant of the antenna circuit. Airborne transmitters, which have greater RF bandwidths because of their long trailing wire antennas, are still restricted from ICW use because of the resulting power supply surges which cannot be accommodated by aircraft generating systems operating near power supply limits and having little power supply inertial energy storage.

20.2.2 Continuous wave frequency shift keying (CWFSK). CWFSK is used as a back-up in airborne systems to take the place of ICW for transmitting Morse Code. CWFSK avoids power supply surges by transmitting a second tone to represent the off periods. It is a special case of FSK in which the SPACE frequency is separated from the MARK frequency by a large frequency separation (normally 200 Hz). This separation allows the receiver to filter out the SPACE frequency to receive only the MARK frequency, resulting in ICW reception. CWFSK can be coherently detected with a resulting substantial increase in signal-to-noise ratio (SNR).

20.3 Phase shift keying (PSK). PSK provides the most efficient use of RF bandwidth but is not presently used at VLF/LF because of the transients caused by phase discontinuities. If the conventional phase-reversal PSK is used (see FIGURE 2), these transients, which will be generated at the MARK/SPACE and SPACE/MARK transitions, can result in damage to the high power transmitter final amplifiers or cause a transmitter outage (kickdown).

20.4 Frequency shift keying (FSK). Except for the back-up use of ICW and CWFSK, FSK and modulation techniques which result in an FSK type of spectrum are the only ones used at VLF and LF. The phase discontinuity restrictions described in 20.3 apply as well to FSK and special techniques are employed to bring them within limits.

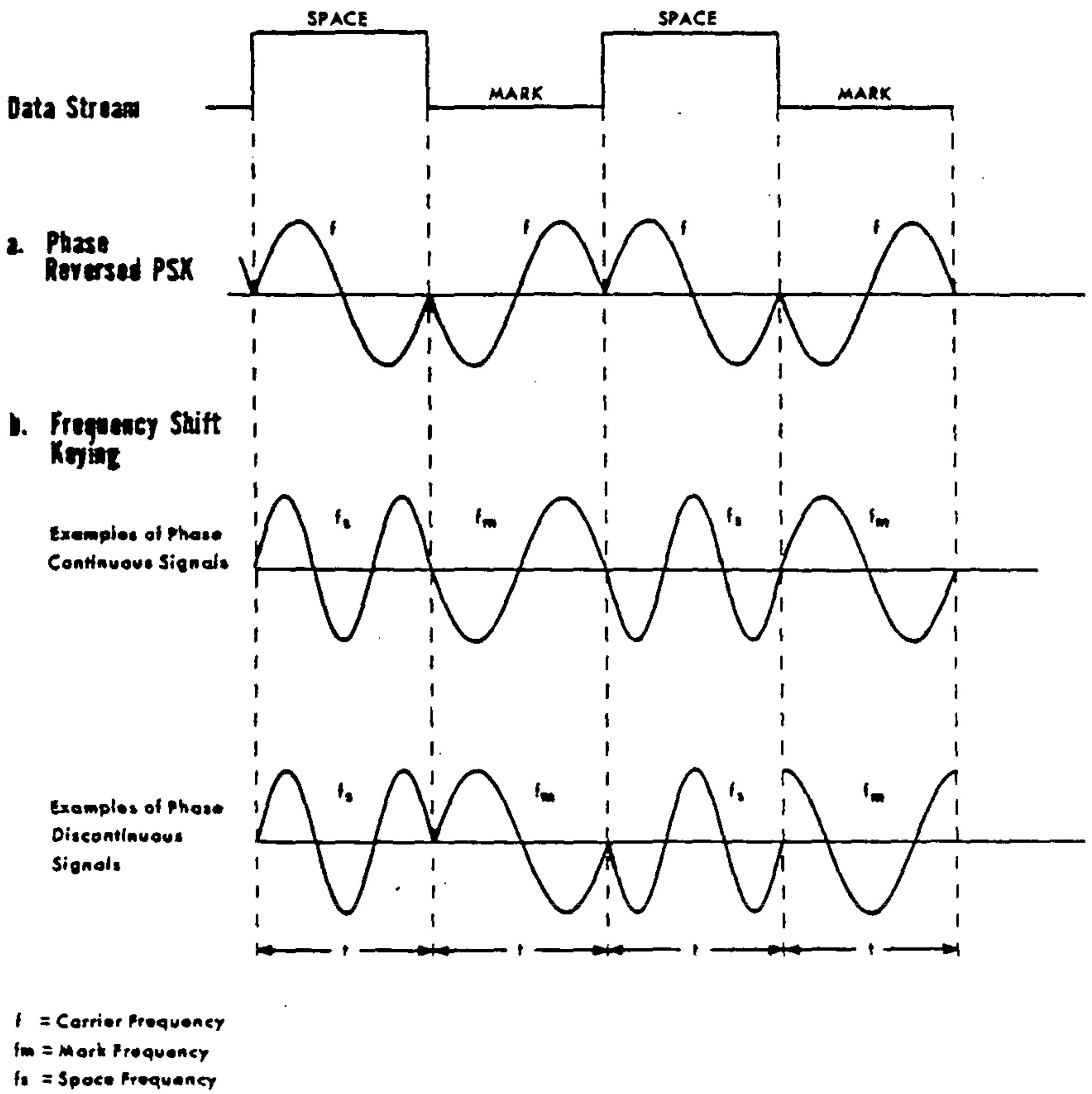


FIGURE 2. PSK and FSK transitions.

20.4.1 Phase continuity with FSK. The term phase continuity is used for the modulation process in lieu of phase coherency which is more often associated with the demodulation process.

In FSK there are distinct SPACE (f_s) and MARK (f_m) frequencies which can be generated separately or obtained from the sidebands of a tone modulated carrier. In neither case is the center frequency transmitted. The difference between the frequencies ($f_s - f_m$) is the total carrier shift. An FSK modulator must abruptly shift from SPACE to MARK frequencies (and vice versa) in accordance with the information code (data stream) and, in the present case, must accomplish this shift without an excessive discontinuity in phase. FIGURE 2 shows both a phase continuous and a phase discontinuous FSK transition.

FIGURE 3 further addresses the phase continuity/discontinuity phenomena in FSK.

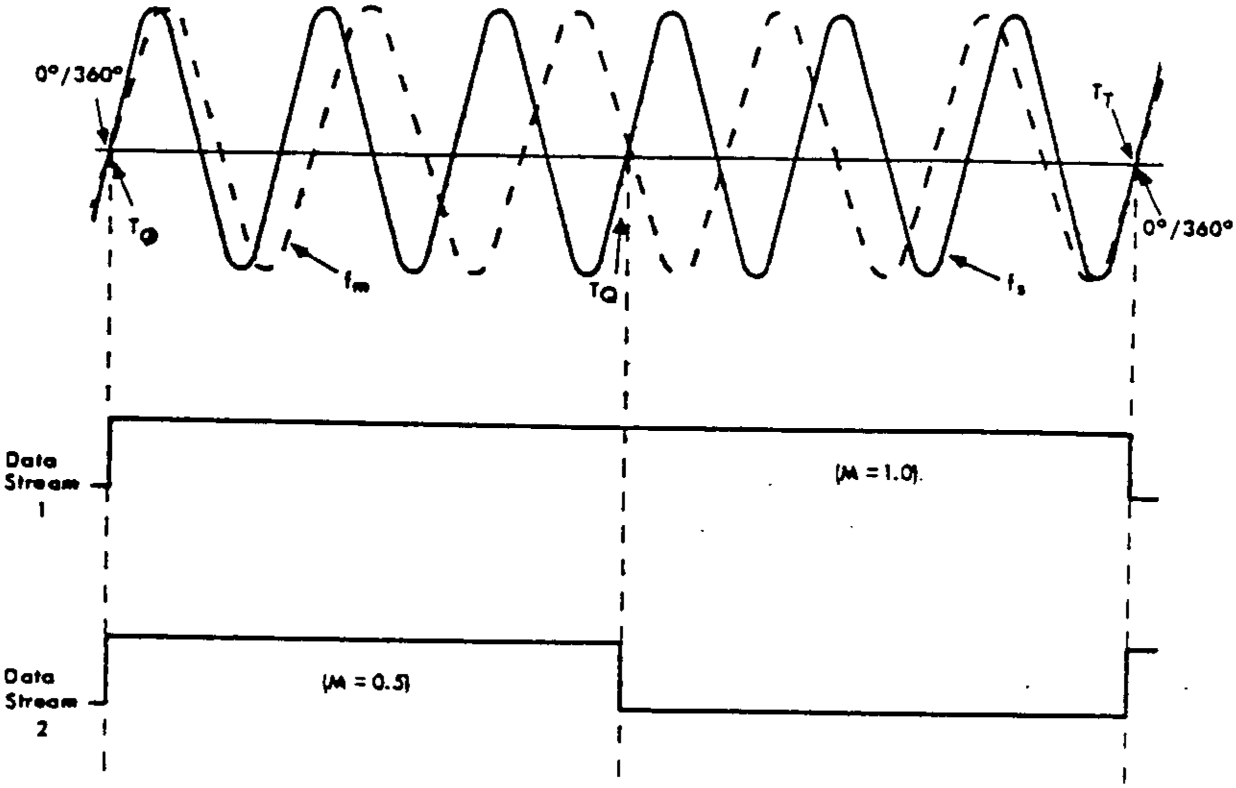
20.4.2 FSK modulation index. The modulation index (M) is defined as the carrier frequency shift ($f_s - f_m$) divided by the modulation rate (in bits per second (bit/sec)). It can be seen in FIGURE 3 that if the SPACE/MARK transitions are to be synchronized with the 0 degree to 360 degree crossings, the modulation rate (or transmitted signaling rate) must have a strict relationship to the total carrier frequency shift (or difference frequency). That is, for FSK with acceptable phase continuity: (a) The modulation index must be an integer; and (b) The relative phase of f_s and f_m must be the same at the instant of transition. The requirement to make the best possible use of bandwidth in VLF and LF results in the minimum modulation index of 1.0 being used for FSK in those bands.

20.4.3 Modulation with a modulation index of 0.5. As indicated in FIGURE 3, conventional FSK with a modulation index of 0.5 will result in a serious phase discontinuity every other transition period, which can result in transmitter outages (kickdowns). Modulation techniques have been developed which provide an FSK type waveform utilizing a modulation index of 0.5 with acceptable phase continuity and with half the RF bandwith of conventional FSK for the same modulation rate. Two such techniques are Compatible Shift Keying (CSK) and Minimum Shift Keying (MSK).

20.4.3.1 Compatible shift keying (CSK). CSK is characterized by a modulation technique having a modulation index of 0.5. FIGURE 4 illustrates how this is accomplished using SPACE and MARK frequencies and 180-degree phase shifted frequencies thereof. It must be understood that this example (and the one for MSK in 20.4.3.2) illustrates only one of several techniques to generate the same waveform. In the illustrated case of FIGURE 4 both the SPACE (f_s) and MARK (f_m) frequencies and those frequencies 180 degrees out of phase, that is, $f_s \angle -180°$ and $f_m \angle -180°$ are available and the proper frequencies are selected at the instant of transition so that the serious phase discontinuity is avoided.

20.4.3.2 Minimum shift keying (MSK). MSK is a modulation technique which results in an FSK type of waveform with a modulation index of 0.5 identical to that of CSK. Hence, CSK and MSK equipment can be compatible in some modes of operation.

20.4.3.2.1 MSK modulation. MSK modulation is achieved by phase modulation and amplitude shaping of two subcarrier frequencies that are then added together linearly to produce a frequency shifted carrier wave of constant amplitude and continuous phase. FIGURE 5 illustrates one implementation of the MSK modulation process. Two channels of synchronous data, X channel and Y channel, are applied to two amplitude modulators for multiplication by two time quadrature sine wave weighting functions; the X channel data is multiplied by a cos ($\omega_f t$) weighting function (where ω_f is the weighting function radian frequency) and the Y channel data is multiplied by a sin ($\omega_f t$) weighting function. The two amplitude weighted signals phase modulate X subchannel and Y subchannel subcarrier time quadrature signals of cos ($\omega_o t$) and sin ($\omega_o t$), respectively (where ω_o is the subcarrier radian frequency). The two phase modulated output frequencies are then combined (or linearly added) to produce a constant-amplitude phase-continuous MSK modulator output waveform with instantaneous frequency shifts which occur at times of subchannel bit transitions.



As shown above, DATA STREAM 1 properly matches the difference frequency (f_s - f_m) and thus is phase continuous at transitions T_ϕ and T_T(M = 1.0).

DATA STREAM 2 does not fully match the difference frequency (f_s - f_m) and is not phase continuous at transition T_Q.

Careful selection of the relationship of the difference frequency (f_s - f_m) and the bit rate (baud) of an FSK system will provide the desired phase continuity of an M = 1.0 system.

FIGURE 3. Phase continuity and discontinuity in FSK.

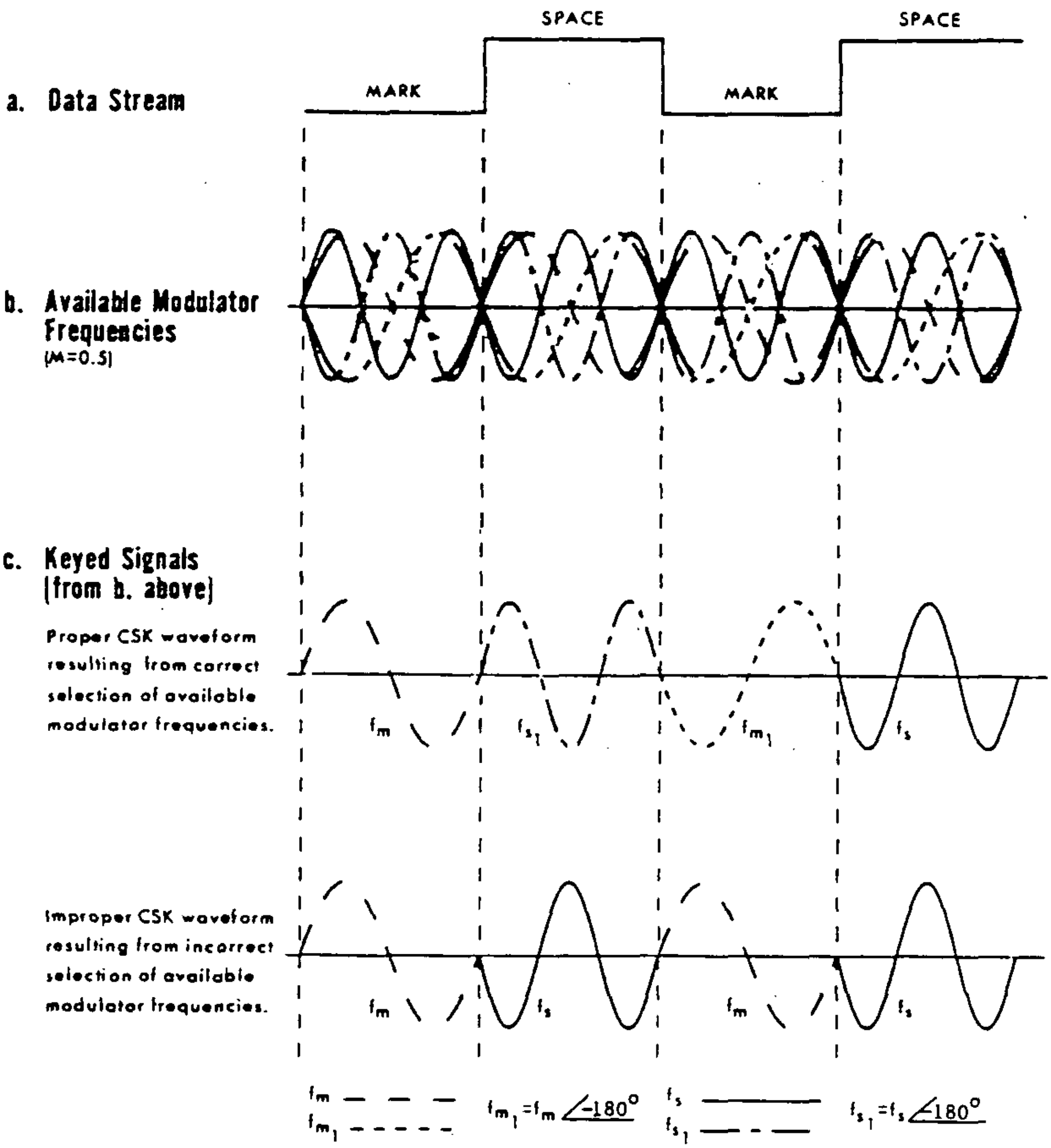


FIGURE 4. CSK transitions.

20.4.3.2.2 MSK derivation. If D_x and D_y represent the digital data inputs from the X and Y channels, respectively, (the digital data from each channel will be a series of mark and space bits appearing in various sequence combinations) to the MSK modulator, the output from the modulator will assume one of four possible waveforms that conforms to the D_x and D_y input data. The inputs into the MSK summer at the MSK modulator output depicted in FIGURE 5 are:

$$D_x \cos(\omega_f t)\cos(\omega_o t) \quad \text{and}$$

$$D_y \sin(\omega_f t)\sin(\omega_o t)$$

Since

$$\cos(a)\cos(b) = \tfrac{1}{2}\left[\cos(a+b) + \cos(a-b)\right] \quad \text{and}$$

$$\sin(a)\sin(b) = \tfrac{1}{2}\left[\cos(a-b) - \cos(a+b)\right]$$

and if $a = \omega_o t$, $b = \omega_f t$

then $$D_x \cos(\omega_f t)\cos(\omega_o t) = \frac{D_x}{2}\left[\cos(\omega_o + \omega_f)t + \cos(\omega_o - \omega_f)t\right] \quad \text{and}$$

$$D_y \sin(\omega_f t)\cos(\omega_o t) = \frac{D_y}{2}\left[\cos(\omega_o - \omega_f)t - \cos(\omega_o + \omega_f)t\right]$$

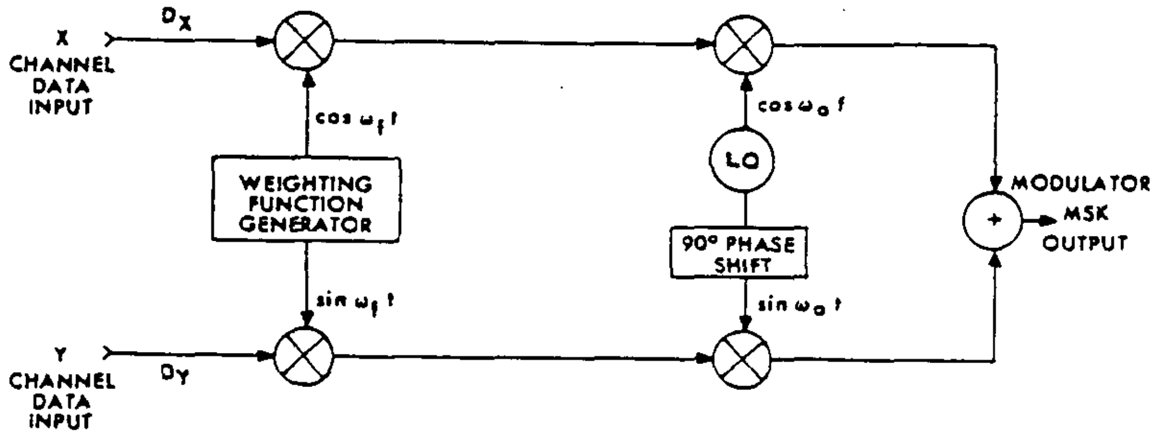


FIGURE 5. MSK modulator diagram.

The output from the MSK modulator is therefore:

$$\text{Output} = \underbrace{\frac{D_x}{2}\left[\cos(\omega_o + \omega_f)t + \cos(\omega_o - \omega_f)t\right]}_{\text{"X" Subchannel Data}} + \underbrace{\frac{D_y}{2}\left[\cos(\omega_o - \omega_f)t - \cos(\omega_o + \omega_f)t\right]}_{\text{"Y" Subchannel Data}}$$

If +1 represents a digital data mark input and -1 represents a digital data space input, the MSK modulator output waveform reduces to the four allowable waveforms indicated in TABLE I and shown in FIGURE 6.

TABLE I. Allowable MSK output waveforms.

Data Input		MSK Output Waveform
D_x	D_y	
+1(mark)	+1(mark)	$+\cos(\omega_o - \omega_f)t$
-1(space)	-1(space)	$-\cos(\omega_o - \omega_f)t$
-1(space)	+1(mark)	$-\cos(\omega_o + \omega_f)t$
+1(mark)	-1(space)	$+\cos(\omega_o + \omega_f)t$

Since the MSK output is determined by the X and Y channel digital data input to the X and Y subchannels, the MSK modulator output waveform will either change or remain the same every data bit period (T). Reference to TABLE I indicates that certain bit transitions (for example, the transitions from mark/mark to space/space and vice versa, the transitions from space/mark to mark/space and vice versa) cannot be allowed to occur if phase discontinuities in the MSK output waveform are to be prevented. The allowable transitions will be those in which only one of the subchannels is allowed to change at the end of a data bit period, T. By lengthening the bit period to 2T and inputting the X and Y channel data into the subchannels as indicated in FIGURE 7, only one of the subchannels can change during each time interval, T. In addition, the subchannel that is allowed to change during a time interval, T, is determined by whether the transition occurs at an even or odd multiple of T. The allowable transitions at even and at odd multiples of T as derived from FIGURE 7 are shown in TABLE II.

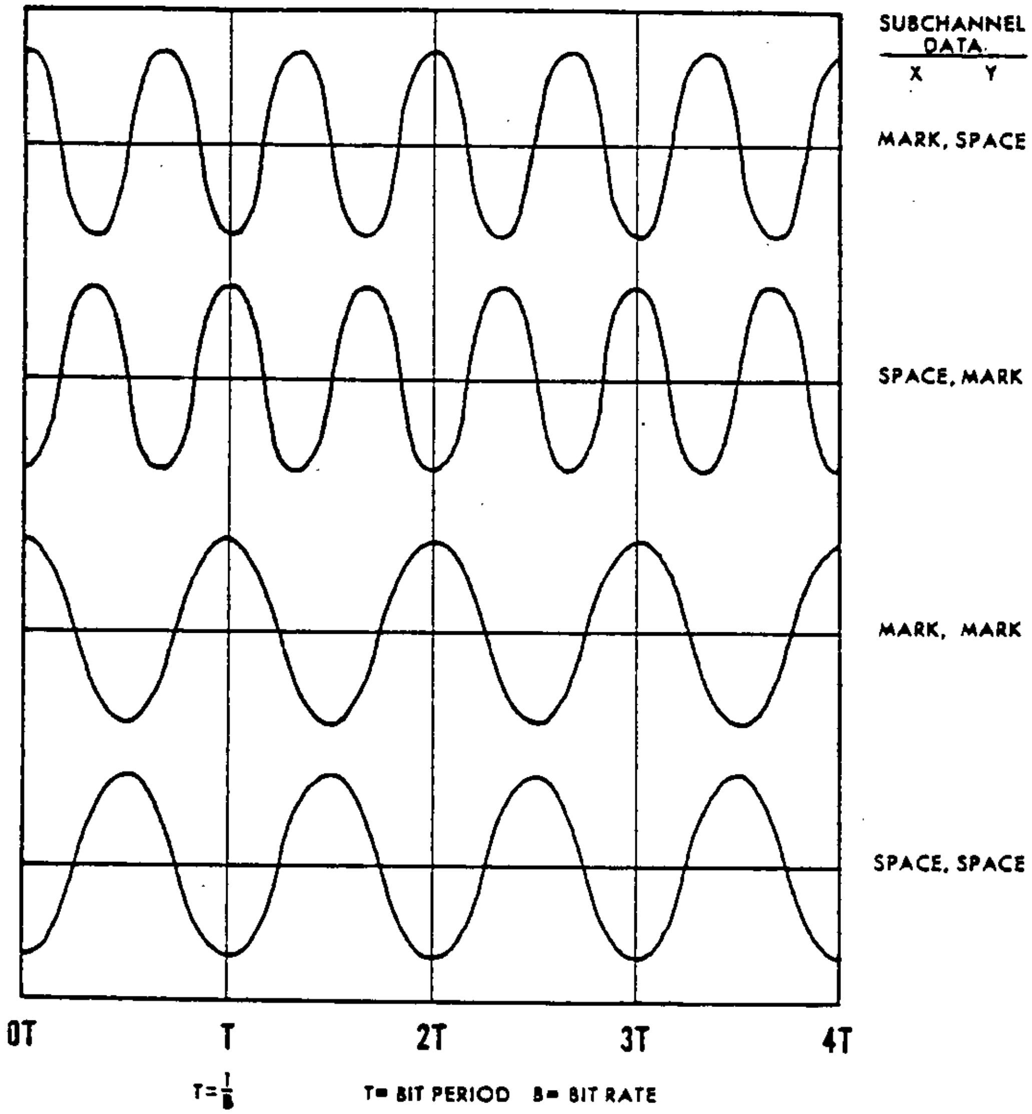


FIGURE 6. The four allowable waveforms for MSK modulation.

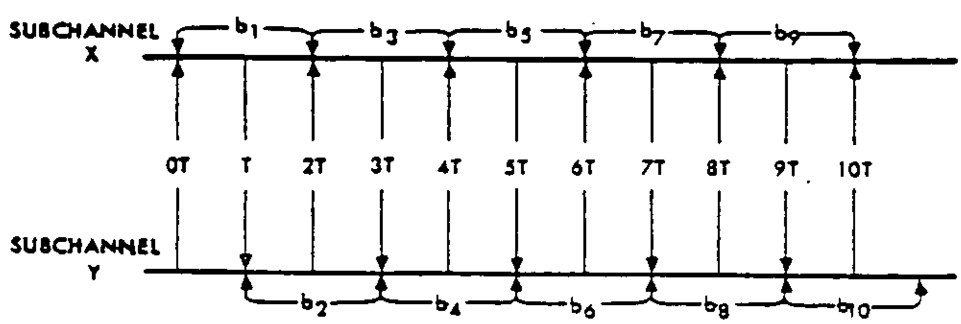


FIGURE 7. Input data timing.

TABLE II. Allowable data transitions

(a) For even multiples of T, where t = 2T, 4T, 6T . . . 2nT, only subchannel X can change as follows:

Subchannels X	Subchannels Y		Subchannels X	Subchannels Y
M	M	Subchannel X changes to →	S	M
S	S		M	S
M	S	(Subchannel Y does not change)	S	S
S	M		M	M

(b) For odd multiples of T, where t + T, 3T, 5T . . . (2n + 1)T, only subchannel Y can change as follows:

Subchannels X	Subchannels Y		Subchannels X	Subchannels Y
M	M	Subchannel Y changes to →	M	S
S	S		S	M
M	S	(Subchannel X does not change)	M	M
S	M		S	S

M = Mark
S = Space
n = 0, 1, 2, 3,....

By reference to TABLE II it is evident that by lengthening the bit period to 2T for each subchannel and by delaying the lengthened bits of one subchannel with respect to the lengthened bits of the other subchannel by T, mark/mark to space/space transitions (and vice versa and space/mark to mark/space transitions (and vice versa) will not be present.

However, in order to ensure phase continuity in the allowable data transitions indicated in TABLE II the upper radian frequency ($\omega_0 + \omega_f$) and the lower radian frequency ($\omega_0 - \omega_f$) must be uniquely related. For a modulation index of 0.5 and a given subcarrier radian frequency (ω_0, the subcarrier or center frequency is not transmitted), the upper and lower radian frequencies and the weighting function radian frequency (ω_f) are determined by the bit rates, B, of the X and Y channels as follows:

$$\frac{(\omega_0 + \omega_f) - (\omega_0 - \omega_f)}{2\pi} = 0.5B = \frac{0.5}{T} = 2f_f$$

from which

$$T = \frac{1}{4f_f} = \frac{T_f}{4}$$ (where f_f is defined as frequency of weighting function)

or

$$T_f = 4T$$ (where T_f is defined as period of weighting function)

The period of the weighting function is therefore four times the data channel input bit period.

20.4.3.2.3 MSK demodulation. To demodulate the MSK waveform the frequency shifts between the upper and lower radian frequencies (between $\omega_o + \omega_f$ and $\omega_o - \omega_f$) could be detected in order to obtain the digital data from the transmitted MSK waveform. A more efficient method, however, is the detection of the phase shifts in the modulated signal over a bit period, T, relative to the subcarrier radian frequency (ω_o). If ($\omega_o + \omega_f$) is the upper transmitted radian frequency and ($\omega_o - \omega_f$) is the lower transmitted radian frequency, the phase shifts in the modulated signal over a bit period, T, can be determined from an application of:

$$\omega = 2\pi f = \frac{\Delta\phi}{\Delta T}$$

or

$$\Delta\phi = \omega\Delta T$$

from which

$$\Delta\phi U = \left[(\omega_o + \omega_f) - (\omega_o)\right] \Delta T$$

$$\Delta\phi L = \left[(\omega_o - \omega_f) - (\omega_o)\right] \Delta T$$

$\Delta\phi U \equiv$ Upper Radian Frequency Phase Shift

$\Delta\phi L \equiv$ Lower Radian Frequency Phase Shift

$$\Delta\phi U = 2\pi f_f \Delta T$$

$$\Delta\phi L = -2\pi f_f \Delta T$$

now

$$f_f = \frac{1}{4T}$$

and if the phase shift is determined for a bit period, T, then

$$\Delta T = T$$

and

$$\Delta\phi U = \frac{\pi}{2} = 90^o$$

$$\Delta\phi L = -\frac{\pi}{2} = -90^o$$

The MSK demodulator therefore need detect only positive and negative phase shifts of 90 degrees in order to recover the digital data from the transmitted MSK signal.

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