CHAPTER 3

Frequency Division Multiplexing Telemetry Standards

List of Tables

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Acronyms

dB	decibel
FM	frequency modulation
IF	intermediate frequency
Hz	hertz
kHz	kilohertz
ms	millisecond
RF	radio frequency
rms	root mean square
SNR	signal-to-noise ratio

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CHAPTER 3

Frequency Division Multiplexing Telemetry Standards

NOTE	This chapter contains standards for analog frequency modulation (FM) data, specifically dealing with frequency division multiplexing and subcarrier channels. It is readily apparent that the use of analog data has been superseded by digital data to a large extent. Therefore, while the standards in this chapter are valid for any and all FM data still in use, further development pertaining to FM data is not supported or encouraged.

3.1 General

In frequency division multiplexing, each data channel makes use of a separate subcarrier that occupies a defined position and bandwidth in the modulation baseband of the radio frequency (RF) carrier. Two types of FM subcarrier formats may be used. The data bandwidth of one format type is proportional to the subcarrier center frequency, while the data bandwidth of the other type is constant, regardless of subcarrier frequency.

3.2 FM Subcarrier Characteristics

In these systems, one or more subcarrier signals, each at a different frequency, are employed to frequency-modulate or phase-modulate a transmitter in accordance with the RF conditions specified in Chapter 2. The following subparagraphs set forth the standards for utilization of FM frequency division multiplexing.

Each of the subcarriers conveys measurement data in FM form. The number of data channels may be increased by modulating one or more of the subcarriers with a time-division multiplex format such as pulse code modulation.

The selecting and grouping of subcarrier channels depend upon the data bandwidth requirements of the application at hand and upon the necessity to ensure adequate guard bands between channels. Combinations of both proportional-bandwidth channels and constant-bandwidth channels may be used.

3.3 FM Subcarrier Channel Characteristics

The following subparagraphs describe the characteristics of proportional-bandwidth and constant-bandwidth FM subcarrier channels.

3.3.1 Proportional-Bandwidth FM Subcarrier Channel Characteristics

Table 3-1, Table 3-2, and Table 3-3 list the standard proportional-bandwidth FM subcarrier channels. The channels identified with letters permit ±15 or ±30 percent subcarrier deviation rather than ±7.5 percent deviation but use the same frequencies as the 12 highest channels. The channels shall be used within the limits of maximum subcarrier deviation. See Appendix 3-A for expected performance tradeoffs at selected combinations of deviation and modulating frequency.

Table 3-1. Proportional-Bandwidth FM Subcarrier Channels ±7.5% Channels

Channel	Center Frequencies (hertz [Hz])	Lower Deviation Limit (Hz)	Upper Deviation Limit (Hz)	Nominal Frequency Response (Hz)	Nominal Rise Time (millisecond [ms])	Maximum Frequency Response (Hz)	Minimum Rise Time (ms)
1	400	370	430	6	58	30	11.7
2	560	518	602	8	44	42	8.33
3	730	675	785	11	32	55	6.40
4	960	888	1032	14	25	72	4.86
5	1300	1202	1398	20	18	98	3.60
6	1700	1572	1828	25	14	128	2.74
7	2300	2127	2473	35	10	173	2.03
8	3000	2775	3225	45	7.8	225	1.56
9	3900	3607	4193	59	6.0	293	1.20
10	5400	4995	5805	81	4.3	405	0.864
11	7350	6799	7901	110	3.2	551	0.635
12	10,500	9712	11,288	160	2.2	788	0.444
13	14,500	13,412	15,588	220	1.6	1088	0.322
14	22,000	20,350	23, 650	330	1.1	1650	0.212
15	30,000	27,750	32,250	450	0.78	2250	0.156
16	40,000	37,000	43,000	600	0.58	3000	0.117
17	52,500	48,562	56,438	788	0.44	3938	0.089
18	70,000	64,750	75,250	1050	0.33	5250	0.06
19	93,000	86,025	99,975	1395	0.25	6975	0.050
20	124,000	114,700	133,300	1860	0.19	9300	0.038
21	165,000	152,625	177,375	2475	0.14	12,375	0.029
22	225,000	208,125	241,875	3375	0.10	16,875	0.021
23	300,000	277,500	322,500	4500	0.08	22,500	0.016
24	400,000	370,000	430,000	6000	0.06	30,000	0.012
25	560,000	518,000	602,000	8400	0.04	42,000	0.008
See notes at end of Table 3-3.							

Table 3-2. Proportional-Bandwidth FM Subcarrier Channel ±15% Channels

Channel	Center Frequencies (Hz)	Lower Deviation Limit (Hz)	Upper Deviation Limit (Hz)	Nominal Frequency Response (Hz)	Nominal Rise Time (ms)	Maximum Frequency Response (Hz)	Minimum Rise Time (ms)
A	22,000	18,700	25,300	660	0.53	3300	0.106
B	30,000	25,500	34,500	900	0.39	4500	0.078
C	40,000	34,000	46,000	1200	0.29	6000	0.058

D	52,500	44,625	60,375	1575	0.22	7875	0.044
E	70,000	59,500	80,500	2100	0.17	10,500	0.033
F	93,000	79,050	106,950	2790	0.13	13,950	0.025
G	124,000	105,400	142,600	3720	0.09	18,600	0.018
H	165,000	140,250	189,750	4950	0.07	24,750	0.014
I	225,000	191,250	258,750	6750	0.05	33,750	0.010
J	300,000	255,000	345,000	9000	0.04	45,000	0.008
K	400,000	340,000	460,000	12,000	0.03	60,000	0.006
L	560,000	476,000	644,000	16,800	0.02	84,000	0.004
See notes at end of Table 3-3.							

Table 3-3. Proportional-Bandwidth FM Subcarrier Channels ±30% Channels

Channel	Center Frequencies (Hz)	Lower Deviation Limit (Hz)	Upper Deviation Limit (Hz)	Nominal Frequency Response (Hz)	Nominal Rise Time (ms)	Maximum Frequency Response (Hz)	Minimum Rise Time (ms)
AA	22,000	15,400	28,600	1320	0.265	6600	0.053
BB	30,000	21,000	39,000	1800	0.194	9000	0.038
CC	40,000	28,000	52,000	2400	0.146	12,000	0.029
DD	52,500	36,750	68,250	3150	0.111	15,750	0.022
EE	70,000	49,000	91,000	4200	0.083	21,000	0.016
FF	93,000	65,100	120,900	5580	0.063	27,900	0.012
GG	124,000	86,800	161,200	7440	0.047	37,200	0.009
HH	165,000	115,500	214,500	9900	0.035	49,500	0.007
II	225,000	157,500	292,500	13,500	0.026	67,500	0.005
JJ	300,000	210,000	390,000	18,000	0.019	90,000	0.004
KK	400,000	280,000	520,000	24,000	0.015	120,000	0.003
LL	560,000	392,000	728,000	33,600	0.010	168,000	0.002

Notes:

1. Round off to nearest Hz.
2. The indicated maximum data frequency response and minimum rise time is based on the maximum theoretical response that can be obtained in a bandwidth between the upper and lower frequency limits specified for the channels. See Paragraph A.3 for determining possible accuracy versus response tradeoffs.
3. Channels A through L may be used by omitting adjacent lettered and numbered channels. Channels 13 and A may be used together with some increase in adjacent channel interference.
4. Channels AA through LL may be used by omitting every four adjacent double lettered and lettered channels and every three adjacent numbered channels. Channels AA through LL may be used by omitting every three adjacent double lettered and lettered channels and every two adjacent numbered channels with some increase in adjacent channel interference.

3.3.2 Constant-Bandwidth FM Subcarrier Channel Characteristics

Table 3-4 lists the standard constant-bandwidth FM subcarrier channels. The letters A, B, C, D, E, F, G, and H identify the channels for use with maximum subcarrier deviations of ±2, ±4, ±8, ±16, ±32, ±64, ±128, and ±256 kilohertz (kHz), along with maximum frequency responses of 2, 4, 8, 16, 32, 64, 128, and 256 kHz. The channels shall be used within the limits of maximum subcarrier deviation. See Appendix 3-A for expected performance tradeoffs at selected combinations of deviation and modulating frequencies.

3.4 Tape Speed Control and Flutter Compensation

Tape speed control and flutter compensation for FM/FM formats may be accomplished as indicated in Annex A.2, Subsection 17.4. The standard reference frequency used shall be in accordance with the criteria in Table 3-5 when the reference signal is mixed with data.

Table 3-4. Constant-Bandwidth FM Subcarrier Channels

Frequency Criteria\Channels:	A	B	C	D	E	F	G	H
Deviation Limits (kHz)	±2	±4	±8	±16	±32	±64	±128	±256
Nominal Frequency Response (kHz)	0.4	0.8	1.6	3.2	6.4	12.8	25.6	51.2
Maximum Frequency Response (kHz)	2	4	8	16	32	64	128	256
Notes: The constant-bandwidth channel designation shall be the channel center frequency in kilohertz and the channel letter indicating deviation limit; for example, 16A, indicating f_c = 16 kHz, deviation limit of ±2 kHz. The indicated maximum frequency is based upon the maximum theoretical response that can be obtained in a bandwidth between deviation limits specified for the channel. See discussion in Appendix 3-A for determining practical accuracy versus frequency response tradeoffs. Prior to using a channel outside the shaded area, the user should verify the availability of range assets to support the demodulation of the channel selected. Very limited support is available above 2 megahertz.	Center Frequency (kHz)							
	8	16	32	64	128	256	512	1024
	16	32	64	128	256	512	1024	2048
	24	48	96	192	384	768	1536	3072
	32	64	128	256	512	1024	2048	
	40	80	160	320	640	1280	2560	
	48	96	192	384	768	1536	3072	
	56	112	224	448	896	1792	3584	
	64	128	256	512	1024	2048		
	72	144	288	576	1152	2304		
	80	160	320	640	1280	2560		
	88	176	352	704	1408	2816		
	96	192	384	768	1536	3072		
	104	208	416	832	1664	3328		
	112	224	448	896	1792	3584		
	120	240	480	960	1920	3840		
	128	256	512	1024	2048			
	136	272	544	1088	2176			
	144	288	576	1152	2304			
	152	304	608	1216	2432			
	160	320	640	1280	2560			
	168	336	672	1344	2688			
	176	352	704	1408	2816			

Table 3-5. Reference Signal Usage
Reference Frequencies for Tape Speed and Flutter Compensation
Reference Frequency (kHz ±0.01%)
960[1]
480[1]
240[1]
200
100
50
25
12.5
6.25
3.125
Note: [1] These frequencies are for flutter compensation only and not for capstan servo speed control. In addition, the 240 kHz reference signal may be used as a detranslation frequency in a constant-bandwidth format.

If the reference signal is recorded on a separate tape track, any of the listed reference frequencies may be used provided the requirements for compensation rate of change are satisfied.

If the reference signal is mixed with the data signal, consideration must be given to possible problems with intermodulation sum and difference frequencies. Also, sufficient guard band must be allowed between the reference frequency and any adjacent data subcarrier.

APPENDIX 3-A

Use Criteria for Frequency Division Multiplexing

A.1. General

Successful application of frequency division multiplexing telemetry standards depends on recognition of performance limits and performance tradeoffs, which may be required in implementation of a system. The use criteria included in this appendix are offered in this context as a guide for orderly application of the standards presented above. It is the responsibility of the telemetry system designer to select the range of performance that will meet data measurement requirements and at the same time permit operation within the limits of the standards. A designer or user must also recognize the fact that even though the standards for FM/FM multiplexing encompass a broad range of performance limits, tradeoffs such as data accuracy for data bandwidth may be necessary. Nominal values for such parameters as frequency response and rise time are listed to indicate the majority of expected use and should not be interpreted as inflexible operational limits. It must be remembered that system performance is influenced by other considerations such as hardware performance capabilities. In summary, the scope of the standards together with the use criteria is intended to offer flexibility of operation and yet provide realistic limits.

A.2. FM Subcarrier Performance

The nominal and maximum frequency response of the subcarrier channels listed in Table 3-1, Table 3-2, Table 3-3, and Table 3-4 is 10 and 50 percent of the maximum allowable deviation bandwidth. The nominal frequency response of the channels employs a deviation ratio of five. The deviation ratio of a channel is one-half the defined deviation bandwidth divided by the cutoff frequency of the discriminator output filter.

The use of other deviation ratios for any of the subcarrier channels listed may be selected by the range users to conform to the specific data response requirements for the channel. As a rule, the root mean square (rms) signal-to-noise ratio (SNR) of a specific channel varies as the three-halves power of that subcarrier deviation ratio.

The nominal and minimum channel rise times indicated in the tables listed above have been determined from the equation which states that rise time is equal to 0.35 divided by the frequency response for the nominal and maximum frequency response. The equation is normally employed to define 10 to 90 percent rise time for a step function of the channel input signal; however, deviations from these values may be encountered because of variations in subcarrier components in the system.

A.3. FM Subcarrier Performance Tradeoffs

The number of subcarrier channels that may be used simultaneously to modulate an RF carrier is limited by the RF channel bandwidth and by the output SNR that is acceptable for the application at hand. As channels are added, it is necessary to reduce the transmitter deviation allowed for each individual channel to keep the overall multiplex with the RF channel assignment. This reduction lowers the subcarrier-to-noise performance at the discriminator inputs. Thus, the system designer's problem is to determine acceptable tradeoffs between the number of subcarrier channels and acceptable subcarrier-to-noise ratios.

Background information relating to the level of performance and the tradeoffs that may be made is included in Telemetry FM/FM Baseband Structure Study, volumes I and II[1]; which were completed under a contract administered by the Telemetry Working Group of the Inter-Range Instrumentation Group in 1965. The results of the study show that proportional bandwidth channels with center frequencies up to 165 kilohertz (kHz) and constant bandwidth channels with center frequencies up to 176 kHz may be used within the constraints of these standards. The test criteria included the adjustment of the system components for approximately equal SNRs at all of the discriminator outputs with the receiver input near RF threshold. Intermodulation, caused by the radio-link components carrying the composite multiplex signal, limits the channel's performance under large signal conditions.

With subcarrier deviation ratios of four, channel data errors on the order of 2 percent rms were observed. Data channel errors on the order of 5 percent rms of full-scale bandwidth were observed when subcarrier deviation ratios of two were employed. When deviation ratios of one were used, it was observed that channel-data errors exceeded 5 percent. Some channels showed peak-to-peak errors as high as 30 percent. It must be emphasized, however, that the results of the tests performed in this study are based on specific methods of measurement on one system sample and that this system sample represents a unique configuration of components. Systems having different performance characteristics may not yield the same system performance.

System performance may be improved, in terms of better data accuracy, by sacrificing system data bandwidth; that is, if the user is willing to limit the number of subcarrier channels in the multiplex, particularly the higher frequency channels, the input level to the transmitter can be increased. The SNR of each subcarrier is then improved through the increased per-channel transmitter deviation. For example, the baseband structure study indicated that when the 165-kHz channel and the 93-kHz channel were not included in the proportional-bandwidth multiplex, performance improvement can be expected in the remaining channels equivalent to approximately 12 decibels (dB) increased transmitter power.

Likewise, elimination of the five highest frequency channels in the constant bandwidth multiplex allowed a 6-dB increase in performance.

A general formula,[2] which can be used to estimate the thermal noise performance of an FM/FM channel above threshold, is as follows:

$$\left(\frac{S}{N}\right)_d = \left(\frac{S}{N}\right)_c \left(\frac{3}{4}\right)^{1/2} \left[\frac{B_c}{F_{ud}}\right]^{1/2} \left(\frac{f_{dc}}{f_s}\right) \left(\frac{f_{ds}}{F_{ud}}\right) \quad \text{Eqn. B-1}$$

[1] Campbell, E. B. and W. R. Hubert. *Telemetry FM/FM Baseband Structure Study*. 2 vols. 14 June 1965. Available at http://www.dtic.mil/dtic/tr/fulltext/u2/621139.pdf and http://www.dtic.mil/get-tr-doc/pdf?AD=AD0621140.

[2] K. M. Uglow. *Noise and Bandwidth in FM/FM Radio Telemetry*, “IRE Transaction on Telemetry and Remote Control,” (May 1957) pp 19-22.

where $\left(\frac{S}{N}\right)_d$ = discriminator output signal-to-noise ratio (rms voltage ratio)

$\left(\frac{S}{N}\right)_c$ = receiver carrier-to-noise ratio (rms voltage ratio)

B_c = carrier bandwidth (receiver intermediate frequency bandwidth)

F_{ud} = subcarrier discriminator output filter: 3-dB frequency

f_s = subcarrier center frequency

f_{dc} = carrier peak deviation of the particular subcarrier of interest

f_{ds} = subcarrier peak deviation

If the RF carrier power is such that the thermal noise is greater than the intermodulation noise, the above relation provides estimates accurate to within a few decibels. Additional information is contained in RCC Document 119, Telemetry Applications Handbook.[3]

The FM/FM composite-multiplex signal used to modulate the RF carrier may be a proportional-bandwidth format, a constant-bandwidth format, or a combination of the two types provided only that guard bands allowed for channels used in a mixed format be equal to or greater than the guard band allowed for the same channel in an unmixed format.

A.4. FM System Component Considerations

System performance is dependent on all components in the system. Neglecting the effects of the RF and recording system, data channel accuracy is primarily a function of the linearity and frequency response of the subcarrier oscillators and discriminators employed. Systems designed to transmit data frequencies up to the nominal frequency responses shown in Table 3-1, Table 3-2, Table 3-3, and Table 3-4 have generally well-known response capabilities, and reasonable data accuracy estimates can be easily made. For data-channel requirements approaching the maximum frequency response shown in the tables listed above, oscillator and discriminator characteristics are less consistent and less well-defined, making data accuracy estimates less dependable.

The effect of the RF system on data accuracy is primarily in the form of noise because of intermodulation at high RF signal conditions well above threshold. Under low RF signal conditions, noise on the data channels is increased because of the degraded SNR existing in the receiver.

Intermodulation of the subcarriers in a system is caused by characteristics such as amplitude and phase nonlinearities of the transmitter, receiver, magnetic tape recorder/reproducer, or other system components required to handle the multiplex signal under the modulation conditions employed. In systems employing pre-emphasis of the upper subcarriers, the lower subcarriers may experience intermodulation interference because of the difference frequencies of the high-frequency and high-amplitude channels.

[3] Range Commanders Council. *Telemetry Applications Handbook*. RCC 119-06. May 2006. May be superseded by update. Retrieved 3 June 2015. Available at http://www.wsmr.army.mil/RCCsite/Documents/119-06_Telemetry_Applications_Handbook/.

The use of magnetic tape recorders for recording a subcarrier multiplex may degrade the data channel accuracy because of the tape speed differences or variations between record and playback. These speed errors can normally be compensated for in present discriminator systems when the nominal response rating of the channels is employed and a reference frequency is recorded with the subcarrier multiplex.

A.5. Range Capability for FM Subcarrier Systems

The following subparagraphs outline additional range capabilities.

A.5.a. Receivers and Tape Recorders.

The use of subcarrier frequencies greater than 2 megahertz may require tape recorders of a greater capability than are in current use at some ranges. It is recommended that users, who anticipate employing any of the above channels at a range, check the range's capability at a sufficiently early date to allow procurement of necessary equipment.

A.5.b. Discriminator Channel Selection Filters.

Inclusion of the higher frequency proportional-bandwidth channels and the constant-bandwidth channels may require the ranges to acquire additional band selection filters. In addition to referencing Table 3-1, Table 3-2, Table 3-3, and Table 3-4 for acquiring channel-selector filters, consideration should also be given to acquiring discriminators corresponding to the predetection carrier frequencies shown in Annex A.2, Table A.2-9. In applications where minimum time delay variation within the filter is important, such as tape speed compensation or high-rate pulse amplitude modulation or pulse code modulation, constant-delay filter designs are recommended.

APPENDIX 3-B

Citations

Campbell, E. B. and W. R. Hubert. *Telemetry FM/FM Baseband Structure Study*. 2 vols. 14 June 1965. Available at http://www.dtic.mil/dtic/tr/fulltext/u2/621139.pdf and http://www.dtic.mil/get-tr-doc/pdf?AD=AD0621140.

K. M. Uglow. *Noise and Bandwidth in FM/FM Radio Telemetering* in "IRE Transactions on Telemetry and Remote Control," May 1957, pp 19-22.

Range Commanders Council. *Telemetry Applications Handbook*. RCC 119-06. May 2006. May be superseded by update. Retrieved 3 June 2015. Available at http://www.wsmr.army.mil/RCCsite/Documents/119-06_Telemetry_Applications_Handbook/.

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