Use of Nonstandard FM Subcarriers for Telemetry Systems

James L. Rieger, PE/PTBW
Naval Air Warfare Center, Weapons Division, China Lake, California[1]

May 31, 1993

Abstract

Subcarrier use in telemetry has decreased in recent years due to emphasis on all-digital systems, but some cases lend themselves more easily to a mixed-service system carrying subcarriers along with a baseband signal. The 'IRIG 106' Telemetry Standards have maintained and expanded several series of FM subcarriers, but some uses are better served with 'non-standard' subcarriers that might be standard in other types of service, making components relatively easily available and inexpensive. This paper examines topics from the RCC study and describes some of the uses of subcarrier systems available to the telemetry designer.

Key Words: telemetry, multiplexing, subcarrier

1 Introduction

While the world has rapidly 'gone digital' in many ways from computers to compact music discs, the nature of much data is analog in its origin and its presentation to telemetry systems. A missile or aircraft may deal with data by digitizing it, and the telemetry system monitors various digital signals and sends them out, but it is often desired to also look at the raw analog signals that, the computers in the host are manipulating, or to measure the dynamic environment of the airborne devices. Signals resulting from seekers (imaging or not), from fuze and radar receivers, accelerometers, acoustic transducers, and audio and video defy convenient digitization due to wide bandwidth, dynamic range, phase relationships, or nonlinearity.

The Telemetry Group [TG] of the Range Commanders' Council [RCC], and the TG's Data Multiplex Committee, maintains the standards for the government test ranges, published as part of what is universally called **IRIG 106**, although that's no

[1]Research for this paper was funded in part by the Transducer Committee of the Telemetry Group of the Range Commanders' Council, White Sands Missile Range, New Mexico.

longer its name. The standards include constant bandwidth and constant deviation series of FM subcarriers, begun in the 1955 edition, when each subcarrier used at least two tubes. The series have been extended over the years to include higher carrier frequencies and wider deviations. Double-sideband subcarriers appeared in the 1971 edition of the standards, intended for use with high-frequency accelerometers, but the series was deleted from later editions. Two series of FM carriers, with ±30% and ±40% deviations, respectively, are used for analog tape recording of wide bandwidth and high signal-to-noise ratio, which are compatible with predetection recording systems but not with the multiplex series.

The published subcarrier standards can be used for many situations encountered in telemetry, but the standard subcarriers are optimum in situations where FM subcarriers are the main service on the transmitted telemetry composite. Use of IRIG subcarriers doesn't guarantee that a ground station has the capability to demodulate them. Conversely, some ground stations use frequency-agile demodulators which can tune a wide range of center frequencies, deviations, and bandwidths beyond those in the standards. The Transducer Committee acknowledges that use of nonstandard subcarriers, can be used effectively in systems which use mixed multiplexing systems or have a limited number of analog signals with a time-domain multiplexed baseband. This paper is a 'condensed' version of a publication to be issued by the RCC/TG as a guide to use of subcarriers to solve certain problems encountered in telemetry .

2 IRIG FM Subcarrier Standards

The IRIG FM subcarrier systems come in two types, called *proportional bandwidth*, or PBW, and *constant bandwidth*, or CBW. Within each, there are several series; the PBW series include ±7½, ±15 and ±30% deviation sets, and the CBW series use ±2, ±4, ±8, ±16, ±32, ±64, ±128, and ±256 kHz deviations.

2.1 PBW Subcarriers

The proportional bandwidth subcarriers have deviation which is a set percentage of the center frequency. The basic PBW ±7½% series starts with Channel 1 at 400 Hz and are spaced at an approximate 4:3 ratio up to 560 kHz, except for a larger gap at 17 kHz once used as a servo reference on tape recorders. Subcarriers from the wider deviation ±15 and ±30% series may be intermixed with the ±7½% series; using a ±15% subcarrier eliminates a ±7½% subcarrier on either side, for example. Bandwidth of each PBW subcarrier is specified for a modulation index of five (considered 'normal') and a modulation index of one (considered 'maximum'). Normal and minimum risetimes are given using the 10-90% points rather than the RC time constant.[2] Center frequencies, bandwidths, and risetimes for the PBW series are in IRIG 106, Chapter 3. The standards do not consider the characteristics of the discriminator used; bandwidths expressed are for the VCOs only. Appendix B of the standards recommends a 'three-halves power' pre-emphasis taper for PBW series systems, or 9 dB/octave, which is optimum when all subcarriers are from the same series and each use identical modulation indices.[3] Within the limits established by the taper, total carrier deviation is adjusted to a number which in turn is set by other forces.

2.2 CBW Subcarriers

The constant bandwidth series subcarriers have deviation which is a fixed percentage of subcarrier frequency, Consequently the bandwidth, delay, and risetimes of subcarriers from the same series but with different center frequencies *can* maintain phase and time coherence between them if (and only if) the discriminators used at the receiving end maintain the same coherence, which generally means that the discriminators must all use the same IF frequency. CBW subcarriers are such that a tape recording played back at half- or quarter-speed decreases the center frequency and deviation of all subcarriers such that they are still standard PBW channels, although of lower frequency and deviation, allowing analysis of transient events. CBW channels are pre-emphasized by a 6 dB/octave taper rather than the 9 dB/octave taper in PWB systems.

3 FM Subcarriers

FM carriers, like FM carriers, trade wider bandwidths for lower noise than other types of subcarriers, and are, within limits, relatively immune to noise and crosstalk between channels—even adjacent channels whose spectra overlap slightly—and to intermodulation products that fall within the subcarrier's passband. FM subcarriers were in the standards published in 1955, and were used in telemetry systems dating back to the 1930s—since it takes fewer tubes to make an FM subcarrier than an AM one.

---

[2]The two measures of risetime differ by a factor of about 2.2, with the RC time constant giving a lower number.

[3]Appendix B, and the references cited therein examine the basis of signal-to-noise ratios for any combination of deviation and injection levels.

3.1 Capabilities

The basic FM subcarrier is a *voltage controlled-oscillator*, or VCO,[4] meaning the output frequency of the VCO is a function of the voltage at its input. The oscillator's center frequency is called f_0 (or sometimes f_c, although the latter term should be reserved for the carrier frequency on non-FM systems, and may or may not be the 'center' frequency in FM), and the upper and lower deviation limits are called f_u and f_ℓ respectively. Typically the center frequency is halfway between f_ℓ and f_u, but it need not be, and depends on the offset used and the nature of the oscillator's deviation linearity, the latter as noted in §3.1.2. An FM subcarrier system, owing to its DC response, can be treated in some instances as if it were a piece of wire from the source to the ground station.

3.1.1 Deviation Sense

IRIG FM subcarriers are polarized such that a rising voltage at the VCO's input causes a rise in the output frequency. This deviation sense should result in no polarity reversal when decoded with an IRIG standard demodulator.

3.1.2 Linearity

The nature of 'linearity' for an FM subcarrier has at least two meanings, In the traditional sense, a system may be said to be linear if within the range between f_ℓ and f_u, and *for either deviation sense*, the deviation is a constant number of Hertz per input volt. This is the meaning of linearity when referring to IRIG subcarriers, and stretches the mathematical concept of linearity only slightly, by translating the universe to hinge about the point defined as zero output voltage.

Another meaning of linearity is based on octaves of frequency deviation rather than on Hertz. Deviation is then said to be 'linear' if the voltage that causes an upward carrier deviation produces the same number of octaves of downward deviation when negative. In this case, the center frequency is no longer centered between f_ℓ and f_u. To make matters murkier still, deviation in octaves may be expressed with respect to f_0 or to zero Hertz (DC); demodulation equipment which inverts the input spectrum distorts the demodulated signal even if both the modulator and demodulator are both linear in this sense. Many types of FM demodulators are 'linear' only in this sense, but are treated as being linear in the other sense because deviation as a fraction of the carrier frequency is low. Linearity of an FM subcarrier system depends on both ends of the link.

---

[4]The term SCO is sometimes seen, which stands for subcarrier oscillator, which may or may not be FM.

3.1.3 Noise Performance

An FM subcarrier typically improves the signal-to-noise ratio of the signal carried on it, at least when the modulation index of the subcarrier is relatively high. The major source of interference in a properly-designed FM subcarrier system is crosstalk due to adjacent channels and intermodulation distortion between other carriers in the channel. FM systems are such that they do not fade gracefully when signal-to-noise ratio on the channel degrades, but rather degrade significantly below some 'knee' which can be predicted within limits. Use of pre-emphasis, generally with some attention given to the respective modulation indices of the individual subcarrier channels and the relation to the baseband signal, is generally arranged so that as SNR drops below some threshold all subcarriers go to noise simultaneously.

3.1.4 DC Response

DC response of an FM subcarrier is easily provided, but a DC offset occurs as a result of any difference between the values of f_0 in the VCO and in the demodulator. The offset depends in turn on the electronics on both ends. An offset can also occur as a result of doppler shift from the telemetry signal from a path whose length varies rapidly, but the effects are minimal. An offset can occur in playback of a tape-recorded version of a subcarrier, since a 1% difference between record and playback speed will cause a DC offset of more than 6% of scale with as ±7½% channel. Offset due to speed mismatch is even more extreme with some CBW channels whose deviation may be less than ±1%.

3.1.5 Spectrum Occupancy

An FM subcarrier occupies more spectrum space on the telemetry channel baseband than any other subcarrier type, a tradeoff made for noise performance which can be greater than the telemetry baseband itself. Occupied bandwidth of an FM subcarrier is greater than the difference between f_u and f_R, which is the absolute minimum case; for a modulation index of five, bandwidth is five times the highest frequency at the baseband input. The spectrum of an FM subcarrier with modulation is a bessel function for sinusoidal modulation, a *sinc* function for square-wave modulation, and something else for any 'real' modulation. Fortunately, FM spectra can overlap with one another without degradation up to a certain point, a feature not shared by most other modulation systems. 'Most' of the energy in the spectrum of an FM signal is contained within the bandwidth described by Carson's Rule, which is $B = 2 \times (f_{max} + \Delta f)$ where f_{max} is the highest frequency contained in the input signal and Δf is the maximum deviation from f_0. When the input signal is not band-limited, such as a digital signal, the value of f_{max} is a bit arbitrary, but is often treated as being the bit rate in NRZ signals. There are a few other considerations to consider when sending digital information on subcarriers as well, such as sideband energy from a digitally-modulated subcarrier causing some degradation in the baseband signal and spectrum of other subcarrier types.

3.2 Modulator Types

The purchaser of a prepackaged subcarrier oscillator is insulated from knowing the inner workings of the device, which may be good or bad—especially if the device wasn't intended for the sometimes harsh environments required for telemetry, or if the terms used by the manufacturer to describe the device characteristics don't have the same meaning we think they have.[5] The designer can also build a VCO from parts or modules.

The most-common type of FM subcarrier is an astable multivibrator, which can produce an output with the general shape of a square wave. Integrated circuit devices called *frequency-to-voltage converters* sound ideal for use as a VCO, but typically produce pulses of the same duration, with spacing between pulses varied to produce the output 'frequency'. Output waveform of some VCOs may involve internal filtering.

Ideally the output waveform of a VCO is sinusoidal, but since the first unwanted harmonic of a square wave is its third harmonic and at a level 9.5 dB below the fundamental, the harmonic content in the output is masked significantly by pre-emphasis, and ultimately by any premodulation filtering implicit or explicit in the transmission channel. However, it is not considered good practice to place subcarriers of any other modulation type above the spectrum of FM subcarriers, and if baseband signals are place above FM subcarriers the passband of the higher-frequency signal should be preceded by trapping.

A VCO with a sinusoidal output can be made using traditional sinusoidal oscillator techniques, with frequency modulation accomplished by voltage-variable capacitances, etc., but deviation percentages on such circuits are low, and since frequency change is due to the square root of capacitance, linearity is seldom acceptable for the purposes.

A crystal oscillator can be used as a VCO by using a voltage-variable capacitor across the crystal to modulate the resonant frequency of the crystal slightly. Such a system can produce only over a small deviation of f_0 of ±0.1% or less, and mechanical limitations in the crystal limit high-frequency response to 20 kHz or so. Wider deviations are produced by translating the crystal oscillator frequency downward with a second, unmodulated crystal oscillator.

---

[5]"Linearity" comes to mind, but also drift, power-supply rejection, and a host of others.

3.3 Demodulator Types

Demodulators for FM signals are available in greater variety than are modulators, since bandwidths, DC response, tuning range, deviation sensitivity, circuit complexity and linearity are all considerations in any system. Again, the user is often isolated from knowledge of what the nature of the demodulation used, sometimes with unexpected consequences. Telemetry subcarrier discriminators in the mid-1960s were each 3½" in rack height per channel, and each rack of discriminators required a power line stabilizer to prevent output with variations in line voltage. A discriminator built today on a few square inches of PC board generally outperforms those of 30 years ago.

The purpose of an FM demodulator is to act as a frequency-to-voltage converter, sometimes called a *discriminator*, producing at its output a voltage proportional to the frequency at its input compared to an assumed f_0. Ideally an FM discriminator is unaffected by changes in the amplitude of its input signal nor by other signals present on its input intended for other demodulators. As with receivers, performance of a discriminator approaches the ideal, but does not fully achieve it. Discriminators fall into a number of categories:

Slope detector. The slope detector is the simplest type of discriminator and converts frequency to voltage by measuring the DC value of the voltage resulting from the input signal being at a different frequency than that to which the detector is tuned. Since the amount of signal passing through such a tuning system is lower if its frequency is further from the tuned frequency, the constant-voltage FM signal is amplitude modulated, and the amplitude variation is measured with a rectifier detector. The disadvantages of the slope detector include a high sensitivity to amplitude variations at the input, and lack of linearity and DC response.

Foster-Seeley dual-slope detector. The Foster-Seeley discriminator can be thought of as a pair of slope detectors, one tuned below f_R and the other above f_u. Adjustment of the exact tuning can be provided in such a way that a DC term is produced proportional to the difference between the center frequency of the discriminator and the average value of the modulated signal; this voltage can be used to vary the frequency of the local oscillator to provide an automatic fine tuning of the system; the resulting system is a 'frequency-locked loop'. Linearity of a Foster-Seeley discriminator does not occur naturally, but as a result of serious tweeking. Amplitude modulation at the input of a Foster-Seeley discriminator results in distortion on the output which resembles a full-wave rectified version of the AM signal.

Hedlund detector. A Foster-Seeley discriminator can be quite linear and otherwise quite effective at its design frequency, but operates poorly when attempts are made to make it operate at other frequencies, due in part to the necessarily slightly different *Q* values in the two tuners necessary for best linearity in the percent deviation sense of the term. As a radio receiver converts the incoming frequency to which the front end is tuned to the discriminator at a constant IF frequency, a Hedlund detector uses a fixed-frequency intermediate frequency to demodulate any selected input subcarrier frequency to baseband.

Quadrature detector. A quadrature detector detects FM as well as PM and AM signals; for FM detection the AM component must be removed. A quadrature detector works at a single IF frequency by generating a frequency identical to the carrier frequency but shifted 90E in phase. The incoming signal is multiplied by the local oscillator frequency, resulting in zero output if the two signals are indeed in quadrature. If the incoming frequency changes in phase with respect to the local oscillator (which it will do if it is of a different frequency), detector output is proportional to the phase difference.

Duty-cycle detector A duty-cycle detector feeds the signal to be demodulated into the input of a comparator which is in turn connected to a monostable multivibrator, also known as a 'one-shot'. A simple pulse-duration discriminator is shown in Figure 1.

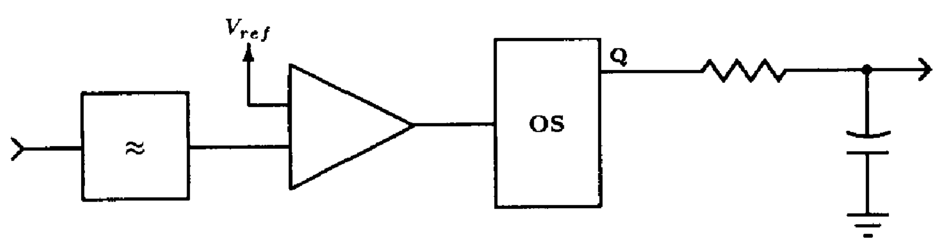

Figure 1: Duty-Cycle Discriminator

Since the one-shot produces pulses of the same amplitude and duration no matter how often it is pulsed, a higher input frequency will produce pulses which are closer together, and the integrated average of the pulses is a measure of frequency of the input signal. Because the comparator serves the purpose of removing amplitude variations from the signal, a duty-cycle detector is insensitive to input level variations, including amplitude modulation of the carrier; however, the circuit itself is not frequency sensitive. Variations on duty-cycle detectors using crystal-controlled pulse lengths or with triggering on both rising and falling slopes of the input (see Figure 2) can decrease carrier leakthrough and improve DC response.

The response of a duty-cycle detector is by nature more linear than a Foster-Seeley discriminator. Duty-cycle discriminators operate over a wide range of center frequencies and deviations. While digital components are used in a duty-cycle detector, the circuit is not really a digital circuit.

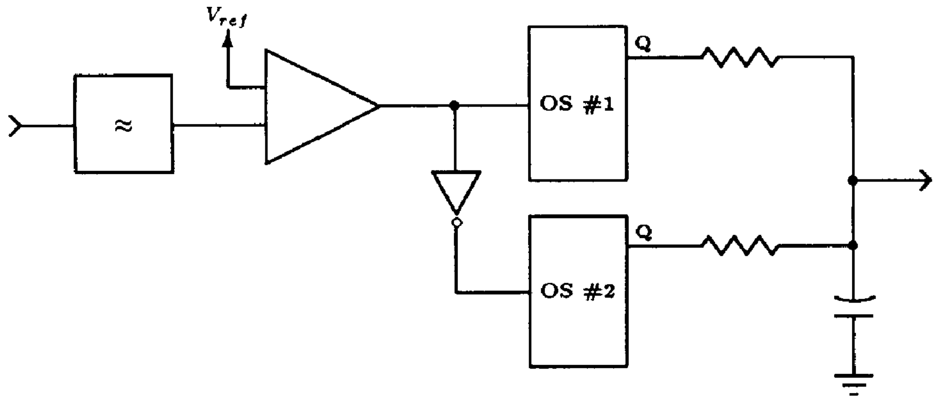

Figure 2: Double-Pulse Duty-Cycle Discriminator

Pulse-count detector. A pulse-count detector is a digital discrimination circuit which operates by changing the incoming FM subcarrier signal to a series of pulses and counts how many pulses are present in some time interval. Since the output of the pulse counter is already digital, it can be manipulated by digital means—the center frequency can be subtracted, the numbers multiplied for scaling, or whatever. The counting interval must be at least twice the rate of the required demodulated bandwidth, but that still can extend to Megahertz with some effort.

Phase-locked loop. A phase-locked loop is a feedback-controlled oscillator which is synchronized to the incoming frequency and (depending on the circuit used) the local oscillator is in phase with the incoming signal or displaced from it by 90E. The feedback signal used to keep the local oscillator in synchronization with the input is thus also the demodulated output, so demodulated output voltage and linearity are identical to the characteristics of the VCO in the discriminator, and not necessarily like those of the VCO on the sending end. If the two VCOs *are* identical, the output is linear with the input, no matter what the modulation characteristics of the VCOs actually are.[6] Most phase-locked loop discriminators are insensitive to amplitude variations in the incoming carrier and insensitive to other frequencies present at the input. A phase-locked demodulator takes some finite (and random) time to achieve its initial lock.

---

[6]There are some limitations even so—the VCOs must be monotonic and have no flat spots over the range used.

Before lock is achieved, the output of a phase-locked loop may be well outside the linear range of the demodulator, so output is inhibited until lock is obtained, a condition which the PLL discriminator can identify.

3.4 Subcarriers from Broadcasting

FM subcarriers are used in commercial broadcasting, both in radio and in television sound. Subcarriers are used in a more unusual way in AM and in two-way radio.

3.4.1 FM Broadcast

A standard FM broadcast, in addition to its main broadcast program (and possibly a stereo system, which uses a DSSB subcarrier as described in §5), may include subcarriers which carry other services (background music, medical training, foreign language, road conditions, etc.). Typical subcarrier channels are on 67, 92, and 110 kHz on all systems, and 22 and 40 kHz on mono systems; deviation is normally ±5 or ±7 kHz, modulation response of the carrier is normally limited to 5 kHz, and 75 Fsec pre-emphasis is standard. Some systems also transmit a low-fidelity (2.5 kHz bandwidth) subcarrier on 57 kHz, three tines the stereo subcarrier frequency. Injection of any subcarrier is limited to ±7.5 kHz, 10% injection on a ±75 kHz system. The total deviation of all subcarriers is limited to 30% of the station's total deviation. Subcarriers are sometimes used to transmit data, which (if done with an FM subcarrier) sends a phase and amplitude-keyed data signal with data rates as high as 38,400 bits/second and corresponding baud rates as high as 4800, greater than that attainable on a telephone circuit.

A subcarrier of low injection (±3 kHz) may also occupy the 10-25 Hz region of the station's baseband, to convey remote meter readings; a low-frequency subcarrier is typically read by a pulse-counting detector. FM channel spacing is 200 kHz, but since adjacent channels are not used, a typical receiver IF bandwidth of about 300 kHz is common.

3.4.2 Broadcast Television

Television audio (which can be considered to be a 4.5 MHz subcarrier inserted above the video band which ends at 4.2 MHz) may use subcarriers whose injection is not counted with the baseband in deviation limits, so their use does not require a decrease in the ±25 kHz deviation of the audio baseband. In addition to the stereo signal present on some broadcasts, FM subcarriers may be present on the audio subcarrier which include a 10 kHz bandwidth audio subcarrier at a frequency of five times the horizontal oscillator frequency (about 15,734 Hz), and injected at ±15 kHz, and a second 3-kHz bandwidth subcarrier at 6.5 times the horizontal frequency and injected at ±3 kHz level. Some audio subcarriers use pre-emphasis and/or companding. The channel in which the television audio subcarrier sits is limited on the lower side by the video signal, and on the upper side by the channel bandedge, but can safely occupy 300 kHz.

3.5 Subcarriers from Satellite Technology

When audio subcarriers are sent along with a television picture on separate subcarriers,[7] or when unrelated audio signals are added above the video baseband on a satellite transponder, the audio subcarrier spacing is usually a great deal wider than that used for broadcast television, where a subcarrier of 5-20% injection is added to the VSB picture carrier. Television subcarriers have used 5.5 MHz to transmit a DS-l, 1.544 Mb/s carrier with multiple audio tracks for stereo, foreign language, or cueing. The common arrangements today involve relative wide deviation (±75 to ±100 kHz) subcarriers on frequencies of 6.2, 6.8, 7.5, and 8.2 MHz or more closely spaced narrow-deviation channels with bandwidths of from 3 to 10 kHz. Signals thus sent are almost exclusively audio, and may use companding and pre-emphasis.

When subcarriers are sent with a television picture on a single transponder, the signal is taken down to baseband and subcarriers are present at the same demodulator as the video signal. In systems where two television pictures are sent on the same transponder ('half-transponder') the transponder is taken to baseband and each channel demodulated from that point. In Europe, sound and auxiliary subcarriers are transmitted on the baseband directly and the picture is on a subcarrier of its own. In US satellite systems not involving a picture, all carriers are directly on the baseband and there's no standard for deviation or modulation.

4 PM Subcarriers

Phase modulated subcarriers can easily be generated from a crystal-controlled source, or by multiplication of some pilot tone in the system. Other PM subcarriers are operated differentially, with the modulation is conveyed by the amount of each phase jump compared to the last state. Data modems use a combination of phase and amplitude modulation to carry as many bits per transmitted bandwidth as possible. Most telephone microwave operates in this way, with as many as 128 phase states.

---

[7] The system used to prevent nonsubscribers from decoding some signals is sent through time-domain multiplexing within the picture transmission, so not all video signals have sound carriers associated with them.

5 DSB Subcarriers

Double-sideband subcarriers transmit signals in twice the bandwidth of the baseband signal, a limiting case for FM and PM. Unlike FM and PM, the DSB subcarrier falls to zero with no modulation. FM and PM subcarrier RMS deviations add vectorially; DSB carriers can be added to a greater level depending on how independent modulation is. A DSB signal (or any AM-like system) is not resistant to noise in the passband due to other sources (such as sideband energy from other subcarriers or intermodulation products), but has a 2:1 noise advantage over the background. Pairs of DSB subcarriers may be operated on the same frequency and be separated to a large extent at the receiver. The stereo separation signal on FM and television broadcasts is DSB; the color signal on television is two DSB signals in quadrature. A DSB signal needs a carrier reference available at the transmitting and receiving ends; this may be transmitted at a different time (as in color television), at a submultiple of the needed frequency (as in FM stereo), or using some other attribute of the modulation system. A single 'pilot tone' can serve as a reference for many subcarriers.

6 SSB Subcarriers

Single-sideband Subcarriers are the same as *translation*, which offsets every frequency in a system by the same amount; if the offset is negative the sense of the frequencies in the translated signal is reversed. Almost all SSB signals are detranslated to their original form, possibly by sampling the subcarrier signal at a rate greater than twice the desired bandwidth—which has the same effect as sampling the baseband signal. As with DSB, detranslation of an SSB signal requires that the offset frequency (the missing carrier) and its phase be precisely known. An system built at the Corona Laboratories (around 1967) used a 100 kHz offset to place a set of IRIG subcarriers above the spectrum of a 25 kHz NRZ PAM signal to take advantage of the bandwidth made possible by UHF telemetry. Translation of fuze or target video is also possible; translation has the advantage of decreasing the number of octaves in the signal, decreasing the problem of intermodulation.

7 Companding

Since the signals we wish to transmit are often analog in nature, concerns with the signals include bandwidth (which may or may not include DC), preservation of the waveshape (which may involve concern with clipping and with phase shift in the channel), and signal-to-noise ratio over the dynamic range that the signal may cover. A way to deal with the dynamic range or signal-to-noise or a varying AC signal is with a compressor-expander pair, jointly referred to as a c*ompander*. The gain of the channel is compressed, so that low-amplitude signals are amplified more than high-amplitude signals, so that when signal amplitude is low it doesn't get buried in channel noise. A simple compressor can be made as shown in Figure 3. The light bulb at the output of the amplifier gets brighter for strong signals, decreasing the resistance of a light-dependent resistor, lowering the amplifier gain.

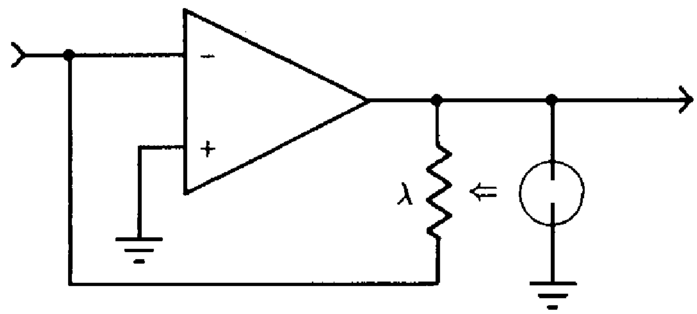

Figure 3: Analog Compressor

The gain control may be based on the half- or full-wave rectified average, RMS value, or peak value of the signal. Modern designs don't use light bulbs.

Companding techniques were used to increase the apparent signal-to-noise ratios on the original sound films and in telephone circuits; the 'hi-fi' audio tracks on a videocassette machine use companding as well. In telemetry applications, companding can deal with voice circuits, which vary in level considerably, and with wide dynamic range signals such as high-frequency accelerometers. For signals such as radar and sonar, whose echoes fall in amplitude with the fourth power of distance, dynamic range compression is a necessity. In some cases, it is not necessary to expand the signal at the receiver.

8 Practical Applications

A subcarrier system will be in addition to whatever is on the telemetry baseband, which in turn is typically a PCM signal a television (video) signal, a PAM signal, or a wideband sonar or radar video image. While it would theoretically be possible to insert one or more subcarriers into the same spectrum that is occupied by the baseband signal (as with the color signal in broadcast television), most practical systems are limited to use of the spectrum available in the channel that exceeds what is in use without subcarriers present. Subcarriers decrease the signal-to-noise ratio of the signals already present, which can often be minimized by design. Even in this digital age, subcarrier systems are the optimal way to carry certain types of signals.

8.1 Audio Transmission

Audio associated with a telemetry signal often is associated with a 'hot mike' in the test vehicle or annotations from an observer. Bandwidth needed is about 3 kHz, and a signal-to-noise ratio of 20 dB may suffice—although companding may improve subjective quality. Use of a subcarrier is generally preferable to dealing with the audio signal directly .

8.2 High-Frequency Accelerometers

Accelerometers whose active element is a crystal can have frequency responses from as low as DC (although the DC term is not always carried) and up to 25 kHz or higher. Dynamic range of such an accelerometer can easily exceed 60 dB, higher than the 40-50 dB is typical for telemetry systems. A digitized version of an accelerometer signal might require 10 bits per sample and at least 50,000 samples per second, which—even without formatting nor accounting for other telemetry data—is 500 kB/s. If more than one accelerometer is needed, the 500 kB/s signal is for *each* accelerometer. The accelerometer's requirements would represent a large portion of the total digital bitstream for most telemetry systems.

Sending the rest of the telemetry data as a PCM stream is a possibility, with the accelerometer signals placed above the spectrum of the PCM signal. If the data rate for the NRZ PCM stream is 500 kB/s, for example, the spectrum above 500 kHz or so on the baseband can be considered available. The sidebands of the accelerometer subcarriers cannot extend into the range below 500 kHz in this instance, so the highest IRIG proportional bandwidth channel is the only one that could be considered, and then only with 7½% deviation, to prevent the lower sideband from intruding into the digital data area. Selecting subcarriers instead from group E (±32 kHz deviation) CBW channels, the first two channels available are 640 and 768 kHz center frequencies; if ±64 kHz channels are used, the first two group F channels available are 768 and 1024 kHz. The choice of group E or F would be dictated by the desired modulation index and the injection level for the subcarriers. If a 2 MHz bandwidth is desired for the telemetry signal, then the group E channels and fairly low subcarrier injection, on the order of ±250 kHz for the higher channel and ±208 kHz for the lower channel would be used. Assuming a 50 dB carrier-to-noise ratio for the composite at the ground station, the demodulated signal-to-noise ratios for the two subcarriers is

$$316 \times \sqrt{\frac{3}{4}} \times \sqrt{\frac{2 \cdot 10^6}{1 \cdot 10^6}} \times \frac{250 \cdot 10^5}{768 \cdot 10^5} \times \frac{32 \cdot 10^3}{25 \cdot 10^3} = 161 = 44 \text{ dB}$$

assuming that a one-MHz lowpass filter is used in the receiver and a 25 kHz lowpass filter in the discriminator.

If two accelerometers are used, the accelerometers can be sent on a single DSSB quadrature carrier placed at least 25 kHz above the data bandwidth. Practical considerations would raise the actual frequency somewhat, but even if 750 kHz were used, sideband energy would not go beyond 775 kHz. If the data signal is 500 kHz, the data clock signal can create the 750 kHz carriers required at the sending and receive end. Synchronous demodulation and the double-sideband transmission mode each increase the signal-to-noise ratio obtained on the demodulated signal, so the overall channel noise is actually decreased, although compression of the data will still be necessary to get 60 dB dymanic range. Overall modulation from the system is due to the digital signal (whose deviation is around ±350 kHz) and to the subcarriers, so deviation varies with modulation on the subcarriers. Transmitter deviation is set with both subcarriers operating with maximum input level, which can be around twice as great as the deviation due to the PCM stream itself. This system is close to optimum assuming that (1) the lowpass filter on the data eliminates most noise in the subcarrier passband, and (2) phase coherence can be maintained at a level which will reduce electrical crosstalk to a level below that which occurs mechanically in the transducers. There is no reason why multiple subcarrier frequencies can't be generated from the data clock signal, each operating as an AM, DSSB, SSB, or PM subcarrier.

8.3 Timing Signals

The standard IRIG time signals used at test ranges consist of a pulse-duration modulated binary signal usually riding (as an approximately 90% modulated AM envelope) on a 1- or 10-kHz sine wave. The timing signal may be received from a range radio, from a satellite, or generated on board. The timing signal serves as a timing reference in playback of a telemetry tape. The data sent on the sinusoidal carrier modulates the carrier at a rapid rate in comparison to the carrier frequency, so if a 10 kHz IRIG timing signal is simply mixed into a telemetry composite, the sideband energy extends 2 kHz on either side of the signal or so. Allowing this much space on a telemetry composite at that frequency is rarely convenient, so the timing signal is often placed on an FM subcarrier, which occupies still more space and generally degrades the data quality.[8] On the other hand, *translation* of the timing signal to a higher frequency and retaining it as an AM signal is usually preferable. The translation reference can be some other attribute in the data (such as three times the clock rate for the PCM data) or can be generated from the timing signal itself, so long as a way to regenerate the carrier from the data signal is possible.

---

[8]The timing signal is disturbed less by noise than by phase shifting, which distorts the corners of the signal where the data is.

8.4 Television

A television signal, whether monochrome or color, occupies a bandwidth of several megahertz. For a television picture of the standard NTSC variety to have equal vertical and horizontal resolution, over 6 MHz is needed—more than is transmitted by commercial broadcasting. A color TV signal contains a subcarrier already, centered at the 227½th harmonic of the horizontal frequency, which contains two color component signals transmitted in quadrature. The sound carrier at 4.5 MHz may be considered as a subcarrier, and it may contain subcarriers of its own. When a telemetry system carries a television picture, there often exists 'side data' that must be transmitted along with it, corresponding to other telemetry readings usually of data of far lower bandwidths. While a two-transmitter design may be optimum in some cases, more likely the video and data are best sent on a single composite, using less DC and RF power than the two-transmitter arrangement and typically uses less total RF bandwidth. As noted in §3.4.2, an FM subcarrier at 4.5 MHz, with a deviation of between ±25 kHz and ±110 kHz, depending on what's on it, is used to send sound, stereo, foreign language programming, data, and a few other possibilities, but the frequency choice limits the baseband video to about 4.2 MHz, which may not be adequate for telemetry uses. Moreover, any nonlinearities in the system cause the color subcarrier and the audio carrier to interact, causing a coarse pattern on the picture centered at 920 kHz which jumps when audio is present. When a telemetry subcarrier is used to send digital data, this problem becomes pretty obvious. Since the television signal requires a signal-to-noise ratio on the order of 40-46 dB, sideband energy and intermodulation products should be less than that. Failing that, if intermodulation products fall between harmonics of the horizontal oscillator frequency, the effects are least obvious.

Telemetry systems are not limited in their bandwidth to 4.5 MHz, and an audio subcarrier sent with the video signal is far from 'standard'. Consequently, telemetry subcarriers often use the higher frequencies used in satellite service, beginning at 5.5 or more commonly at 6.2 MHz. Because the spacing between the top of the video band and the lower sidebands of the subcarrier can be larger than with broadcast TV, deviations of up to ±250 kHz are useful, allowing transmission of an NRZ data rate of 400 kB/s or more. If greater data rates are needed, use of a multiple phase-shift keyed carrier is possible. In either case, the data rate can be locked to a harmonic-and-a-half of the horizontal frequency to minimize sideband Interference. The use of fewer subcarriers with more data on them to more subcarriers with less data is preferable.

8.5 Radar, Sonar, and Fuze 'Video'

Radar, sonar, and fuze receiver signals are called 'video' but do not produce a television picture and may not represent a two-dimensional image at all. Signals of this type are characterized by wide bandwidth, large dynamic range (often varying with the fourth power of the distance between the receiver and target). Digitization of such signals, especially if phase relationships are to be preserved, is generally difficult and produces a very large number of bits. If the signal is intermittent, a digital signal containing the wideband data and other 'normal' data is inefficient. Single- or double-sideband transmission of such signals after analog companding or limiting should be considered.

9 Conclusion

A telemetry system using a mixture of a wideband signal or digital composite can be optimum if subcarriers are used in the ways suggested herein, even if a digital signal dictates the basic telemetry system type. A more comprehensive discussion of the issues involved in use of IRIG standard subcarriers and other nonstandard types will be published by the RCC in a book to be issued in the next year.