THE IMPLEMENTATION AND UTILIZATION OF DSB/FM TELEMETRY SYSTEMS

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Summary Two different double sideband suppressed subcarrier telemetry systems have evolved in the past few years: the harmonic subcarrier method (HSM) and the independent subcarrier method (ISM). This paper provides information pertinent to the implementation and utilization of both systems. The important features of the two systems are discussed by comparing the circuits used in their implementation. Test data is used to illustrate some of the important points about the performance of a DSB/FM telemetry system.

Introduction AM subcarriers were occasionally used in missile telemetry systems in the late 1940’s. RF equipment used for these telemetry frequency multiplexing systems had nonlinearities which produced serious intermodulation distortion. The designers and users of the early systems overcame the intermodulation effects by using high deviation FM subcarriers. AM subcarriers fell into disuse until 1959 when the demands of the Saturn program for a large number of wideband channels brought a single sideband (SSB) subcarrier system into use again in telemetry. SSB channels make the most efficient use of telemetry transmitter’s video bandwidth. DSB channels use twice as much video bandwidth but provide a frequency response down to DC. The DC and very low frequency response is often important for some data transmission channels.

There are two other types of AM subcarriers in addition to SSB and DSB subcarriers. The usual nonsuppressed AM signal can be used as a subcarrier. It is not generally used because the presence of a carrier in the signal at all times wastes power. The other AM subcarrier uses a suppressed carrier and by means of a quadrature carrier overlays a second set of sidebands in the same spectral space. It is called Quadrature Double Sideband (QDSB) but has not been effectively implemented in the telemetry field to date because of the crosstalk problems created in demodulating the two sets of sideband occupying the same spectral space. The following discussion will center on DSB subcarrier multiplexes that are transmitted over a FM modulated RF carrier although

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much of the discussion could be applied to a system using the other types of AM subcarriers.

The implementation of an HSM system requires the selection of channel spacing interval. A spacing of 4 kHz permits the intermixing of the DSB subcarriers with constant bandwidth (CBW) FM subcarriers. An ISM system also uses 4-kHz channel spacing. By using the appropriate multiple of 4 kHz, the bandwidths for the DSB channels can be set at 1, 2, 4, and 8 kHz. It is possible to intermix DSB and proportional bandwidth (PBW) FM subcarriers, but since the channel spacing changes from channel to channel in the PBW system it is necessary to exercise care in the selection of the channels to insure that adequate guard bands are provided for both types of subcarriers.

The names of the two DSB methods descriptively identify the differences between them. The harmonic subcarrier method utilizes a frequency synthesizer to generate every subcarrier with an exact frequency and known phase relationship to every other subcarrier. The frequencies generated in the synthesizer are locked to a crystal oscillator running at some high multiple of 4 kHz. The crystal oscillator is a convenient means of obtaining a stable frequency standard for the synthesizer. Frequency dividers and phase lock loops (PLL) are used to reduce this crystal frequency to supply a subcarrier for each channel. It is essential that the phase relationships of the subcarriers generated by the synthesizer be defined so that a synthesizer in the ground equipment can reproduce the subcarriers for the demodulation. A zero phase reference point has been defined for the HSM system as the time when the common pilot tone and the ambiguity reference tone have simultaneous positive going zero crossings. This reference point occurs every 250 microseconds. The airborne synthesizer must also generate reference tones which carry the frequency and phase information needed by a ground synthesizer to reconstruct the whole multiplex of subcarrier frequencies. An HSM system must account for the phase shifts and phase nonlinearities across the baseband of the transmitting and receiving equipment and in most systems will have to provide each channel demodulator with a phase compensation adjustment that will compensate static phase errors.

The independent subcarrier method utilizes local channel oscillators that are adjusted to nominal 4-kHz intervals. The phase relationships of the oscillators need not be known. The output of the ISM channels can be summed and transmitted with little consideration being paid to the phase shifts of the system.

**Comparison of Airborne Systems**  Table I lists the features of the two systems as shown in the block diagrams (Figures 1 and 2) and indicates whether each feature is essential, limited, optional, or technique dependent. The meaning assigned to the terms will be clarified in the discussion of each feature.
TABLE I

<table>
<thead>
<tr>
<th>System Features</th>
<th>HSM</th>
<th>ISM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulator</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Channel Band Filter</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>Premodulation Filter</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Transmitter Modulation Control (TMC)</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Subcarrier Oscillator</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Subcarrier Synthesizer</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Reference Generator</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Pre-emphasis Network</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Common Pilot Tone (CPT)</td>
<td>E</td>
<td>L</td>
</tr>
<tr>
<td>Ambiguity Reference Tone (ART)</td>
<td></td>
<td>L</td>
</tr>
<tr>
<td>Channel Reference Tone (CRT)</td>
<td>O</td>
<td>L</td>
</tr>
</tbody>
</table>

E - Essential  O - Optional  L - Limited  T - Technique Dependent

The modulator is the heart of either system and, of course, is essential. It may be either a linear or a nonlinear product multiplier. The bandpass filter is not required if the subcarrier is generated using a sinusoidal oscillator and a linear multiplier. A square wave oscillator and a nonlinear switching type multiplier generate a number of undesired products that must be removed by a bandpass filter. The use of a channel output filter in an HSM system introduces another source of possible data error, since the ground synthesizer has to be capable of compensating for the channel-to-channel delay differences in the airborne filters.

The premodulation filter is optional and is used only when there is the possibility that the frequencies modulating the channel would be high enough to cause adjacent channel interference. The channel bandpass filter is generally designed to remove the third and higher harmonics and therefore is too wide to be useful in eliminating data frequency components that could interfere with the adjacent channels.

A DSB airborne system generally uses an automatic gain control circuit or as labeled in this system, a transmitter modulation control (TMC) to take advantage of the dynamics of the random data being transmitted by the various channels. The TMC circuit attempts to keep the transmitter’s input voltage at a constant value so that the transmitter’s deviation will be close to the maximum chosen value. The operation is explained by the following equation.
e₁ ... eₙ = RMS input voltage of a given DSB subcarrier channel
a₁ ... aₙ = Gain of a given subcarrier channel
Aₜ = Gain of the TMC amplifier
Sₙ = Sensitivity of the FM transmitter in kHz per volt
Fₕ = RMS output deviation of the transmitter.

If all the gains of the various subcarriers are equal (that is, there is no pre-emphasis applied to the subcarriers in the multiplex) and if all the input voltages are equal, then the equation simplifies to

\[ \sqrt{n(ae)^2} \quad AₜSₙ = Fₕ \]  \hspace{1cm} (2)

\[ \sqrt{n} (ae) \quad AₜSₙ = Fₕ \]  \hspace{1cm} (3)

The notation ae represents the output of any subcarrier channel. Aₜ must vary to keep the product of \( ae \sqrt{n} Aₜ \) equal to a constant value. If the TMC functions reasonably well, the deviation of the transmitter will remain constant.

The DSB subcarrier multiplex or any AM suppressed subcarrier multiplex is “adaptive” in two senses. First, the input voltage, e, to a channel directly effects the deviation of the FM transmitter. In an FM subcarrier multiplex the voltage-controlled oscillator (VCO) is modulated by e but the voltage output of VCO remains constant. If e increases in amplitude two or three times, the VCO can cause adjacent channel interference. In the case of a DSB channel, peaks two or three times e’s normal value will hardly be noticed by the RMS summing process. This feature permits the designing of DSB channels with the capability of handling large dynamic swings of the input data signal which might occur when transmitting random data.

The TMC operation also permits a second “adaptive” feature. This is the improvement of the signal-to-noise ratio at the output of the ground demodulator. If the total overall amplitudes of the input voltages (e’s) decrease, the TMC will increase Aₜ, which will effectively increase each subcarrier’s deviation of the FM transmitter. If a number of channels have no or low data activity, then the increased transmitter deviation of the other channels will improve their output S/N.
The trade-off of data activity and S/N can be related through the following equation.

\[
(S/N)_d = (S/N)_c \left( \frac{B_c}{F_{nd}} \right)^{1/2} \left( \frac{1}{f_s} \right) \left( f_{dc} \right)
\]  

(4)

- \((S/N)_d\) = Output signal-to-noise ratio of the channel demodulator
- \((S/N)_c\) = Output signal-to-noise ratio of the receiver IF amplifier
- \(B_c\) = IF amplifier bandwidth
- \(F_{nd}\) = Channel demodulator low-pass filter bandwidth
- \(f_s\) = Center frequency of the subcarrier channel
- \(f_{dc}\) = RMS deviation of the FM carrier due to the subcarrier voltage.

The RMS deviation, \(f_{dc}\), is equal to the output of a channel in the airborne package, \((ae)A_t\), times the sensitivity of the transmitter, \((S_f)\). From Equation (3),

\[
f_{dc} = (ae)A_tS_f = F_d \left( \frac{1}{\sqrt{n}} \right)
\]  

(5)

The value for \(f_{dc}\) is substituted into Equation (4).

\[
(S/N)_d = (S/N)_c \left( \frac{B_c}{F_{nd}} \right)^{1/2} \left( \frac{1}{f_s} \right) \left( f_{dc} \right) \left( \frac{1}{\sqrt{n}} \right)
\]  

(6)

If the TMC operates effectively to hold \(F_d\) constant, Equation (6) for comparison purposes becomes

\[
(S/N)_d = K \frac{1}{\sqrt{n}}
\]  

(7)

where K is a constant value. A plot of the \((S/N)_d\) versus the number of inactive channels is shown in Figure 3 and is labeled Curve A. Curves B and C show some experimental data taken on a 20-channel DSB system. The ISM system multiplex also contains one common pilot tone adjusted to the same amplitude as a full-scale 2.5 vDC signal would produce on a channel. Curve B is for \(f_s\) equal to 24 kHz, and Curve C is for \(f_s\) equal to 88 kHz. Each active channel was loaded with a random noise signal to simulate a data signal. The measured ratios shown are really \(\sqrt{S^2 + N^2/N}\) which approximately equals S/N for low noise levels.

Although the curves B and C show agreement with Curve A in the increase of \((S/N)_d\) this is not altogether due to the increase in \(f_{dc}\). Equation (4), upon which Curve A is based, only gives an \((S/N)_d\) approximation based upon thermal noise effects in the transmitter-receiver link. Intermodulation noise due to the nonlinearities in the transmitter-receiver link is a significant factor in the output signal-to-noise ratio of a channel in any
frequency multiplex. As the number of channels in the multiplex is decreased, the intermodulation noise will also decrease thereby also improving (S/N)_d.

Another factor is that the output of the TMC did not remain constant. The change is shown by Curve D. The gain in (S/N)_d from the decrease in intermodulation was partly lost because the TMC output dropped with the decrease in the number of operating channels. Comparing test data collected back-to-back and with an (S/N)_c equal to 33 dB indicates that about half of the signal-to-noise improvement came from the action of the TMC and the other half from a decrease in intermodulation.

The amplitude changes caused by the TMC must be tracked out by another gain control circuit on the ground called the baseband level control (BLC). The tracking between the two circuits can cause momentary errors. The minimum error is obtained with a slow time constant in the TMC and much faster time constant in the BLC. The trade-off in times must be made by considering if large dynamic surges in the data channels might occur which would momentarily over-deviate the FM transmitter.

If a TMC is used in the system, then it is necessary to supply a common pilot tone (CPT) for the control of the ground station BLC system. The CPT comes from the synthesizer for HSM and from a reference generator on the ISM. A channel reference tone (CRT) can be used on either system but is primarily a feature of the ISM system used to provide ambiguity resolution in the ground station and a secondary level control capability. Omitting the ambiguity reference tone (ART) from the HSM system produces a limited system. Without the ART the ground station synthesizer can no longer determine the correct phase for its reconstructed subcarriers. A CPT is always needed in an HSM system even when no TMC is being used since the CPT carries the frequency information for the synthesizer. An ISM system without a TMC needs the CPT to resolve the phase ambiguity of each channel. A limited system results if the CPT is not used with the ISM. Data demodulate without the proper phased subcarrier is still useful for power spectral density measurements.

An alternate method for generating the CRT and CPT for an ISM system is also shown in Figure 1. It uses a VCO output to function as the CPT and allows the CRT to modulate the VCO. There are some disadvantages to this technique. A wider filter will be needed in the ground station to receive the CPT from the multiplex and this will cause a decrease in the signal-to-noise ratio of the tone. The phase of the CRT is exceptionally important for ambiguity resolution in the ISM system. Transmitting the CRT on a VCO and demodulating it from an FM subcarrier will introduce additional phase shifts that complicate the ambiguity resolution of an ISM channel.

The range of the drift of the airborne oscillator of an ISM channel is important. If the drift becomes great (i.e., 200 or 300 Hz off of the center frequency), the channel
performance may be degraded because the phase lock loop (PLL) in the ground
demodulating station may not have sufficient range to lock onto the subcarrier
frequency. The low-pass filter in a phase lock loop is generally rolled off at about 300
Hz as a compromise between signal-to-noise in the loop and the expected tape flutter that
the PLL might have to track. Even if the acquisition of the range of the PLL is sufficient
to lock-up on a subcarrier that has drifted, the PLL may have difficulty tracking tape
recorder flutter with an offset error in the loop.

A problem can be encountered if an HSM system is used to transmit a large number of
DC signals on the channels. There is a possibility that the composite multiplex signal
(CMS) would over-deviate the FM transmitter. When the phases of all HSM subcarriers
are the same, they add up to produce doublet function every 250 \( \mu \)sec. This set of
positive and negative spikes does not contribute much energy to the total RMS value
deviating the transmitter, but it does instantaneously over-deviate the FM transmitter. An
example of this is shown in Figures 4 and 5. Figure 4 shows a 20-channel HSM
composite multiplex signal with the doublet. Figure 5 shows the resulting FM spectrum
that comes from the transmitter. A solution to the problem is to flip the input polarity of
a number of the channels so that the phase of the output of each channel will be flipped
180 degrees. Changing the polarity will reduce the doublet (Figure 6) and produce the
RF spectrum as shown in Figure 7. Another alternative is to stagger the phases of the
subcarriers from the synthesizer. Staggering the subcarrier phases is easy to do for the
synthesizer but produces added difficulties for the ground station. The ground station has
to be able to demodulate a number of the arbitrarily selected phases.

Adding pre-emphasis to a DSB system (see Figures 1 and 2) can, under certain
circumstances, defeat the purpose of a TMC. If the high data channels should decrease
with the pre-emphasis implemented as shown, the transmitter deviation would drop
below the select average deviation. If the pre-emphasis network were placed before the
TMC or the channel outputs individually adjusted to produce pre-emphasis, then the
TMC could, if the low channels decreased in activity, cause over-deviation of the
transmitter. Using a pre-emphasis network on an HSM system could introduce phase
ersors in the transmission path unless an exact inverse network is placed in the ground
equipment. The equalization of the baseband phase shifts is especially critical for the
HSM system since the CPT and the ART will be in different parts of the baseband from a
number of the channels. Any phase shift of the data or the tones will produce static error
in the data when the channel signal is multiplied by the reconstructed subcarrier.

Pre-emphasis is used to overcome the thermal noise characteristics of the FM receiver’s
demodulator. However, this source of the noise is not the only one to be considered
because intermodulation noise can be very detrimental to low-frequency channels and
thereby defeat the purpose of pre-emphasis which is to obtain equal signal-to-noise -
ratios for all channels. Figure 8 shows some experimental data on a 20-channel ISM
system without pre-emphasis applied. Each channel was loaded with random noise for the test.

**Comparison of Ground Systems**  The block diagrams for the two systems are shown in Figures 9 and 10. Table II summarizes the features of these two systems.

### TABLE II

<table>
<thead>
<tr>
<th>System Features</th>
<th>HSM</th>
<th>ISM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseband Level Control (BLC)</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Common Pilot Tone Filter</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Channel Bandpass Filter</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>Product Multiplier</td>
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<td>E</td>
</tr>
<tr>
<td>Low Pass Filter</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Channel Level Control (CLC)</td>
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<td>O</td>
</tr>
<tr>
<td>Channel Reference Tone Filter</td>
<td>O</td>
<td>L</td>
</tr>
<tr>
<td>Channel Reference Tone Reject Filter</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Subcarrier Generator Circuit</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>ISM Phase Comparator</td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>HSM Synthesizer</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>Ambiguity Reference Tone (ART)</td>
<td>O</td>
<td></td>
</tr>
</tbody>
</table>

E - Essential  O - Optional  L - Limited  T - Technique Dependent

The important differences between the two ground systems can be briefly described as follows: The HSM uses a synthesizer to reconstruct all the frequencies from the CRT and ART sent from the airborne package. The ISM uses a local subcarrier generation circuit which processes the channel signal through a nonlinear circuit to derive the second harmonic of the subcarrier frequency. The second harmonic is divided to produce the channel subcarrier.

The CRT supplies sideband energy to keep the PLL locked up in the ISM ground equipment. If the CRT is not present, demodulation cannot start until phase lock loop in the subcarrier generator circuit locks up. If a CRT is used, the channel level control (CLC) will adjust the signal level to each individual demodulator. If the CRT is not used, then there must be some means for deactivating the CLC. It is possible to use a CLC circuit in the HSM system if the airborne package transmits CRT’s. If the CRT is present, then it may be desirable to remove it from the data output. One way to remove the CRT is to use a very sharp rejection filter which is shown here as a second filter with a deep notch. The lowpass filter generally has the notch filter incorporated into it.
The difficult problem in either DSB system is the resolving of the phase ambiguity of the regenerate subcarriers. The HSM synthesizer can generate a set of subcarriers from the CPT. The difficulty is insuring that all of the synthesizer subcarriers have the correct phase. Phase correction requires a phase comparison scheme utilizing the ART and a properly timed reset pulse to all frequency dividers in the synthesizer. The ambiguity resolution problem of an ISM channel might appear to be simpler since it is only necessary to compare the phase of the baseband CPT to the phase of a CRT coming through the data channel and derived a reset pulse which can be used to set the proper state into frequency dividers.

It is, however, possible for the CRT to incur greater phase shifts than the CPT. The CPT passes through only one filter. The CRT in the data channel passes through the channel bandpass filter, the demodulator circuits, and the CRT bandpass filter, which is identical to the CPT filter. All of these additional delays can use up any phase margin and make the phase comparator circuit sensitive to small phase changes in either the CPT or CRT. Any data signals near the frequency of the CRT can pass through the CRT bandpass filter and perturb the phase comparator.

An important concept to explore in a DSB ground system is the possibility of building a compatible ground station that would work with either an HSM or ISM airborne package. An ISM station, if provided with the proper CPT and CRT, will demodulate the signals from an HSM airborne package. A ground station could be built with suitable switching features which would include all of the features in Table I. The major features of both systems are common such as the BLC, channel filters, product multipliers, low-pass filters, and would serve for both systems. The difference would be incorporating in each channel, a carrier reconstruction circuit and providing for the total system, a synthesizer. This combination might provide economic savings to a ground installation that would be required to demodulate both types of DSB systems. However, the story might change considerably if the installation had to consider the possibility of demodulating SSB/FM or QDSB/FM.

**Conclusion**  A DSB/FM system’s adaptive capability offers a potential user wideband random data channels that will accept large dynamic ranges of data. The system will compensate itself for low data activity in some channels and improve the output signal-to-noise ratio in the active channels if a TMC and BLC are used. The user also has the choice of including or not including a number of options such as the use of preemphasis or channel level controls.

The designer has three basic design approaches to use in implementing a DSB/FM system. He may design to exclusively use either an HSM or an ISM system or he may design a system which is compatible with either basic method. In any case the designer or user should carefully consider the circuitry used to achieve the ambiguity resolution.
The problems associated with determining the proper phase for the reinserted demodulation subcarrier are perhaps some of the most difficult to implement in actual practice.

**References**


![Fig. 1 - Block Diagram of an Independent Subcarrier Method Airborne System.](image-url)
Fig. 2 - Block Diagram of a Harmonic Subcarrier Method Airborne System.

Fig. 3 - Changes in \((S/N)d\) and TMC Output Voltage Versus the Number of Inactive Data Channels.
\((S/N)_c = 9\ dB\).
Fig. 4 - Output of HSM 20-Channel Airborne System. +2.5 Volts on all Channels. (Scope set at 1 volt/cm and 0.1 ms/cm.)

Fig. 5 - RF Output of Transmitter Modulated by Signal in Figure 4. Deviation: ±125 kHz rms. (Spectrum analyzer set at 200 kHz/cm.)

Fig. 6 - Output of HSM 20-Channel Airborne System. 2.5 Volts on all Channels, but Polarity of the Voltage Randomly Alternated. (Scope set at 1 volt/cm and 0.1 ms/cm.)
Fig. 7 - RF Output of Transmitter Modulated by Signal in Figure 6. Deviation: ±125 kHz rms. (Spectrum analyzer set at 200 kHz/cm.)

Fig. 8 - Channel (S/N)$_d$ Performance.
Fig. 9 - Block Diagram of an Independent Subcarrier

Fig. 10 - Block Diagram of a Harmonic Subcarrier