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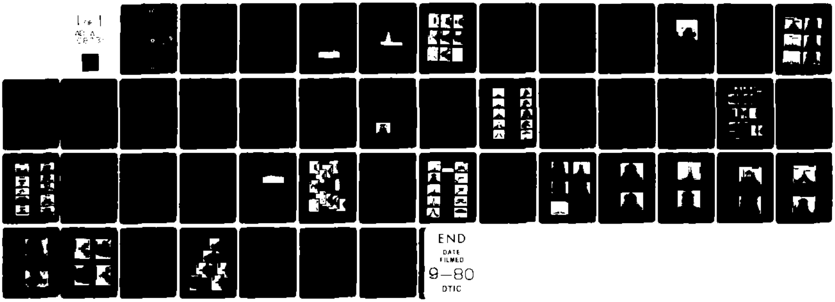

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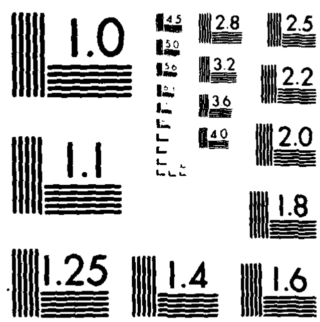

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TECHNICAL NOTE
(Project 213-060-78)

VHF OMNIDIRECTIONAL RADIO RANGE (VOR)

ELECTROMAGNETIC SPECTRUM MEASUREMENTS

(ref. 6050.23)

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U.S. DEPARTMENT OF TRANSPORTATION

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SYSTEMS RESEARCH AND DEVELOPMENT SERVICE

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16. Abstract

This report presents VOR electromagnetic spectrum measurement techniques applicable to site survey, installation, maintenance, and interference alleviation activities. Spectrum displays of the VOR emission contain valuable system performance information. These displays contain significant detail which can be used for analyzing the performance of various parts of the system. A basic set of VOR radiated spectrum displays taken at specific ground locations would be of value as a part of the basic facility records. Subsequent display samples could be taken remotely without disturbing the facility. Comparison of these with the site records would give insight into system performance and assist in the maintenance and flight inspection activities.

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VHF OMNI-DIRECTIONAL RADIO RANGE (VOR) ELECTROMAGNETIC SPECTRUM MEASUREMENTS

9.1 Purpose. To present VOR electromagnetic spectrum measurement techniques applicable to site survey, installation, maintenance and interference alleviation activities.

9.2 Operational/electromagnetic description. The VOR signals provide azimuth information centered on the facility for aircraft navigation purposes. The authorized emission is 21A9 (21 kHz bandwidth, A9 modulation). Between 108.00 and 111.95 mHz, VOR frequencies are interspersed with ILS localizer frequencies. The 112.00 - 117.95 mHz band is used exclusively for VOR at 50 kHz intervals. See references No. 1 and 2 for VOR and DME/TACAN channelization and pairing. Reference No. 3 contains geographical spacing of frequency assignments required to avoid intra-system interference. There are approximately 950 VOR stations in the U.S.A. This includes 910 conventional (four antennas) stations and 40 Doppler VOR (DVOR) stations (51 antennas).

9.2.1 Conventional VOR. Most of the conventional VOR facilities are of the type shown in Figure 9-1 with the antennas mounted above

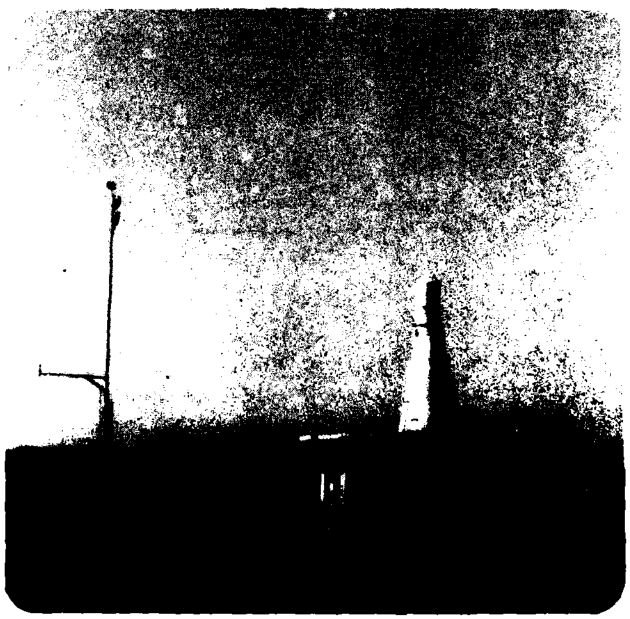


Figure 9-1. Conventional VOR facility. The four Alford Loop antennas are housed in the conical section. The DME or TACAN antenna is contained in the cylindrical top section. The monitor pole is to the left.

a counterpoise about 12 feet above the ground on top of the equipment room. Approximately 15% of the installations employ the "mountain top" configuration where the antenna housing is placed directly on a leveled off hill-top with no additional counterpoise as shown in Figure 9-2. The transmitter building is usually located beyond the "brow" of the hill below the ground plane coupled to the antennas through some 300 feet of low loss coaxial cable.

Figure 9-2. Mountain top VOR. The conical housing contains four Alford Loop antennas and the top cylinder the TACAN antenna. The monitor antenna is in the right background.

The electronics and resulting radiated spectrums of these two VOR types are similar. A 200 watt transmitter radiates emissions modulated 30% by both reference and variable 30 Hz azimuth information, 28% by voice, and 6% by 1020 Hz identification. The 30 Hz reference FM modulates a 9960 Hz (10 kHz abbreviation) subcarrier which amplitude modulates the carrier by 30% as shown in Figure 9-3 center. This subcarrier is derived from a tone wheel containing 332 magnetic teeth which rotates 30 rps past a magnetic pickup to develop (30 rps x 332 teeth) 9960 Hz. The variation in spacing between the teeth causes the rate at which the frequency is developed to vary (deviate) $\pm$ 480 Hz about the 9960 Hz average. This is characteristic of an FM modulation index of 16 (30 Hz x 16 = 480). The resultant emission bandwidth (2 x 480) is seen in

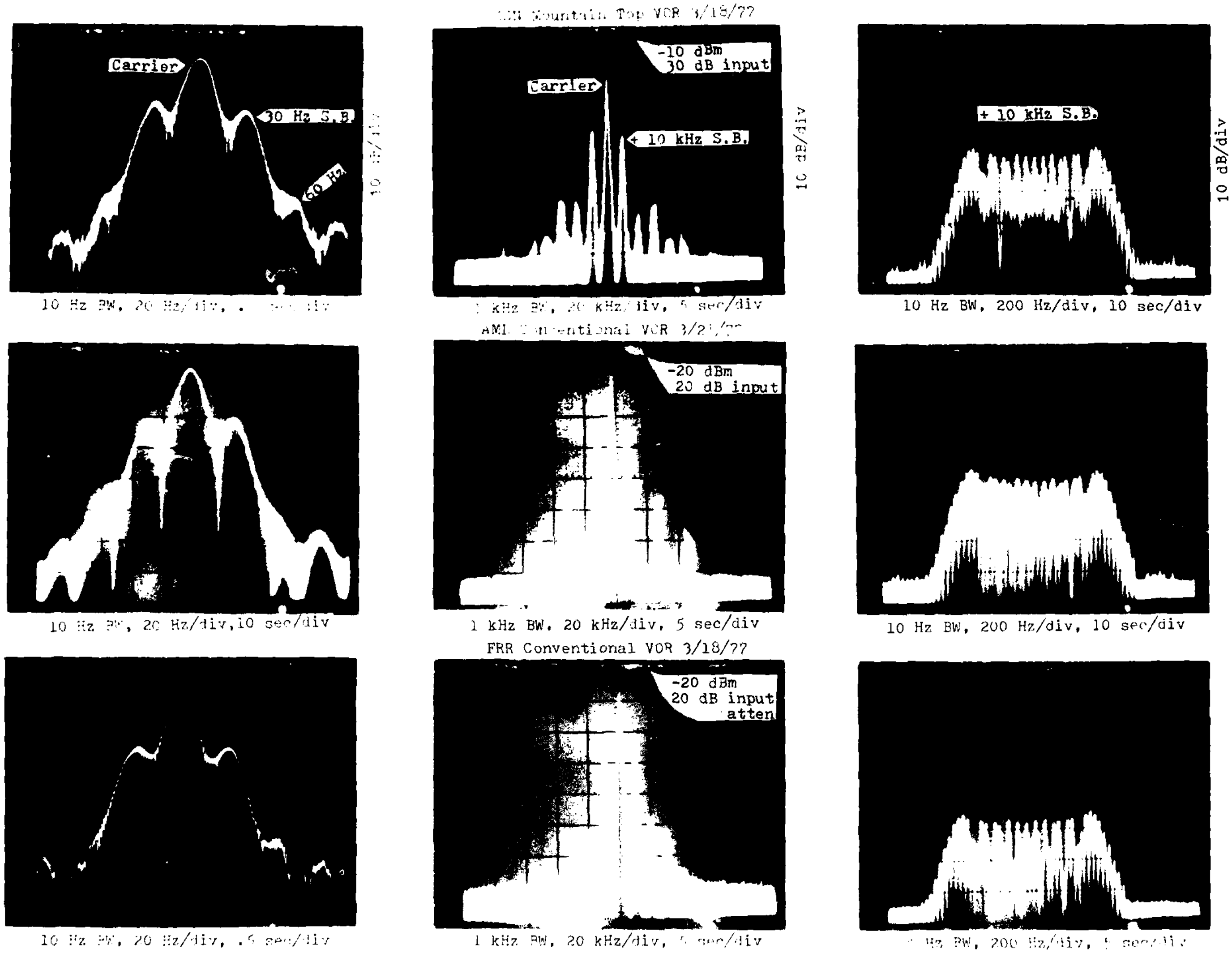


Figure 9-3 Spectrum comparison of three VOR facilities in the area. Note the oscillating amplitude roll-off of the harmonics in the upper facility which is accentuated on the middle facility, but negligible in the smoothed decay envelope of the lower facility. The imbalance between the ± 10 kHz subcarriers also appears in the ± 30 Hz sidebands of the upper facility. The variable pattern lobing is easily seen (15 Hz/.5 sec) in the ripple in the left hand displays.

Figure 9-3 right. The bessel amplitude of the carrier and sideband lines is shown in Figure 9-8. The reference carrier and ± 10 kHz subcarrier are fed in phase to all antennas to produce the circular pattern shown in Figure 9-4. The 30 Hz detected signal in the aircraft receiver will be a similar amplitude and phase at a particular distance and altitude on any azimuth around the facility from this reference emission. The 30 Hz variable signal is developed by the rotating sideband pattern

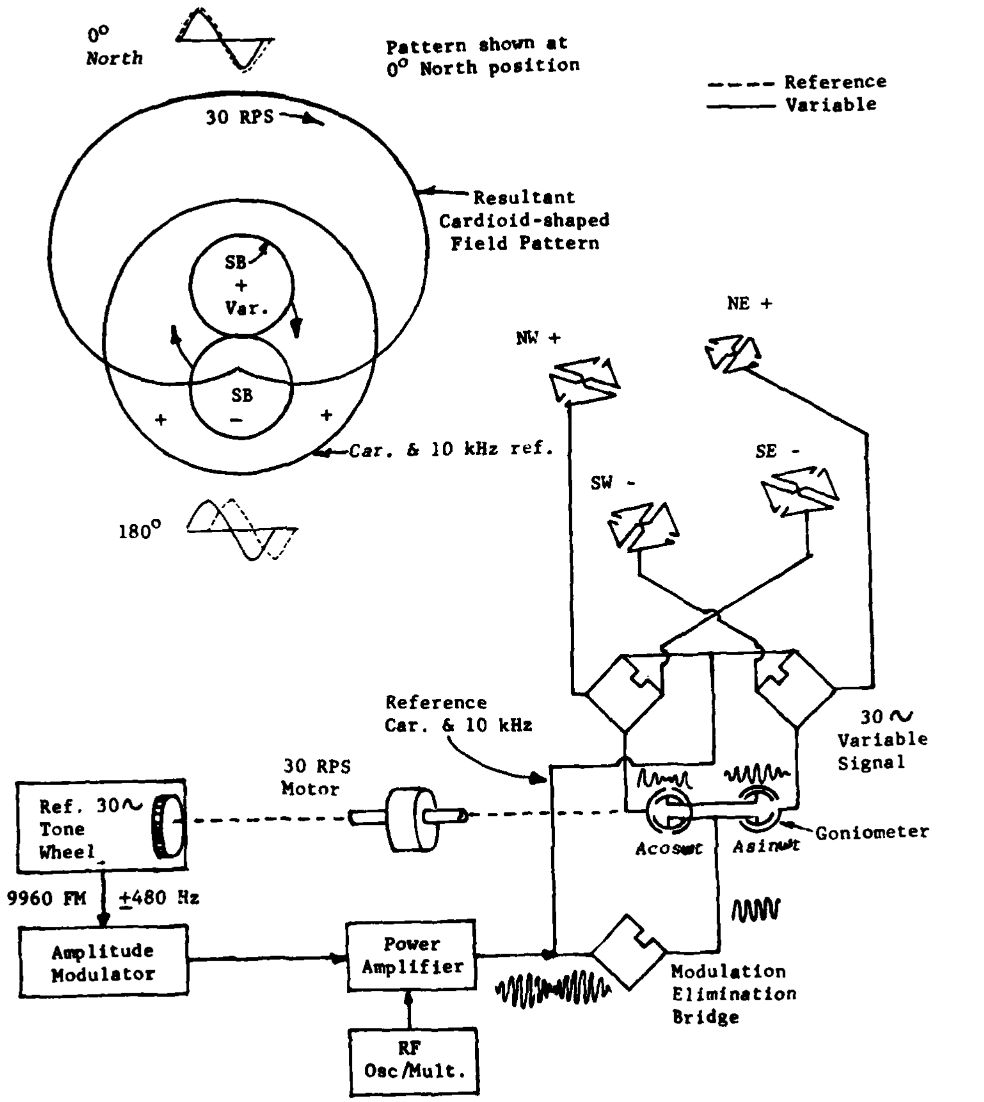


Figure 9-4 VOR Signal Generation Concept
As the pattern rotates clockwise the detected variable signal in the aircraft receiver lags the reference signal one degree in phase for each degree of azimuth traversed around the site.

as it space-amplitude modulates the carrier by 30% as shown in Figure 9-4 to produce the Figure 9-3 left and 9-6 spectrums. The essential functions for generating these antenna patterns are depicted in Figure 9-4. The relationship between the 30 Hz variable and reference signal timing is preserved by mounting the goniometer and tone wheel, respectively, on the same motor shaft. The RF phase relationship in the variable and reference signals is preserved by separating them after the power amplifier. The amplitude modulation is removed to present a constant amplitude signal to the goniometer. The two outputs of the goniometer reach their maximums 90° apart to produce sine and cosine inputs to their respective antenna pairs (which are 180° out of phase with each other). This combination creates a two lobe field pattern rotating at 30 rps. The reference signal is applied to a phase-shifting bridge to enable the carrier and 10 kHz subcarriers to be coupled to the four antennas in phase to produce an omni-directional pattern. The combination of this circular reference and the twin-lobe variable patterns creates a cardioidshaped resultant pattern rotating in space at a rate of 30 rps. The amplitude variation produced in the receiver as this pattern passes the aircraft can be seen as a ripple on the spectrum envelope in the lower left Figure 9-3 display of carrier and ± 30 Hz sidebands. As the airplane flies clockwise around the VOR, the detected variable signal in the receiver lags the reference signal one degree in phase per degree of azimuth traversed. It is noted that while the preponderance of VORs presently installed are configured to operate as described above, a new generation is being introduced which is solid-state and achieves the equivalent signal without rotary parts. A 30 Hz generator and phase shifter drive balanced modulators to produce the variable signal antenna inputs previously generated by the goniometer. The AFC utilized to maintain the RF phase relationship between the carrier, 10 kHz subcarrier, and variable sideband emissions may cause somewhat different spurious products at the 20, 30, 40, 50 kHz, etc. intervals than the conventional VOR.

9.2.2 VOR Spectrum Measurements. When making spectrum measurements the input levels to the instruments and I.F. gain adjustments must be within the linear range of operation in order not to contribute spurious components or distortion to the signal display. Tests were made on the analyzer used for the displays in this Chapter to determine linear conditions for a VOR type signal prior to making site measurements. Two generators were tuned 10 kHz apart with 11 dB amplitude difference (typical of a DVOR) in the 108-118 MHz band to provide input to the analyzer. The analyzer input attenuator and I.F. gain controls were adjusted in combination for particular reference level calibration to determine at what mixer input magnitude spurious signal components were self-generated by the instrument. While these spurious components were generally not objectionable for mixer inputs of -30 dBm, the input attenuator was adjusted to limit the mixer input in most of the actual measurements to -40 dBm or less to provide a margin of safety. In the top-center display of Figure 9-3, for example, the top line reference level is given as -10 dBm. An input attenuator setting of 30 dB is used which limits the displayed carrier at -23 dBm to -53 dBm at the mixer. Additionally, the maximum signal component can only exceed the selected reference level by a few dB before self-generated display non-linearities appear. When expanding a low amplitude emission to obtain more detail the main carrier may be off the display; however, it is still present at the mixer and will affect the linearity of the small component displayed if a safe level is exceeded. When optimizing the input attenuator and I.F. gain controls to obtain adequate display amplitude and low noise this carrier amplitude must be considered. When instrumentation modes are changed, the display validity is checked by varying the input attenuator to see if all the components reflect corresponding changes in amplitude. Internally generated spurious components as a rule do not reflect these changes directly (linearly, proportionally). The label on each spectrum photo or chart recording should contain the reference level, input attenuator setting, instrument bandwidth (resolution), and scan rate (Hz/div, time/div) to enable interpretation of the display. If absolute as well as relative magnitudes are important the antenna type, orientation, line losses, and any other factors affecting amplitude of signal display must also be included. The instrumentation used to obtain the spectrum photographs in this VOR chapter is shown in Figure 9-5. A biconical (frequency broadbanded) antenna was used; however, the choice of an antenna type is not critical so long as the same orientation is maintained for all spectrum measurements where relative amplitude is important. A tuneable dipole is more directional where direction finding is important and is much less vulnerable to high wind damage (preferable when mobile operation is envolved). The biconical offers some advantage over dipole antenna when frequency changes within its band limits are made often over a wider range than the tuneable dipole covers without readjustment of element lengths.

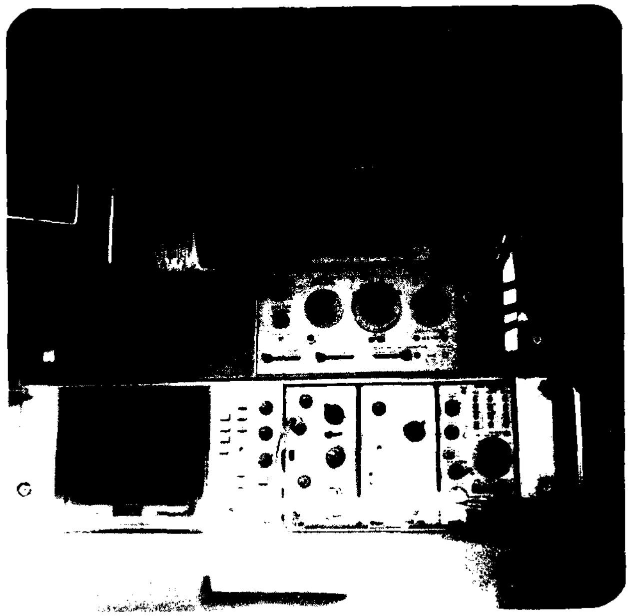
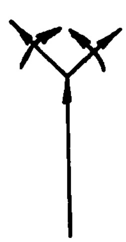


Figure 9-5 Spectrum Analyzer in the Spectrum Characteristics Analysis and Measurement Vehicle (SCAM) shown producing a linear display of the VOR 9960 Hz subcarrier. The equipments shown include HP141T Display Section with HP8553B-H26 (modified to tune through 118 MHz) RF plug-in at right of screen and HP8552B I.F. plug-in below it. The HP8445B Automatic Preselector above the 141T and the Tektronix Storage Oscilloscope Model 7622/R7633 with Dual Trace Amplifier Model 7A18/7A18N and Dual Time Base 7B53A/7B53AN below the 141T were not used in this measurement. The HP197A Oscilloscope Camera is swung to left of screen.

9.3 Analysis of Conventional VOR Spectrum. A random sampling of three VORs (including one "mountain top") in the vicinity produced the spectrum comparisons in Figure 9-3. Note the oscillation in $\pm$ 20, 30, 40 and 50 kHz harmonic roll-offs in the upper and middle facility spectrums (center) while the harmonics fall off in a more orderly manner on the lower facility. This variation in emission spectrums is typical of VORs operating in the 100 kHz channeling environment. Since the amplitudes vary in the display as a function of analyzer bandwidth there is international discussion on how the relative amplitudes are to be determined (see discussion concerning Figure 9-9 and in section 9.3.1 below). As the 50 kHz channeling is implemented the ability of the higher order harmonics from one facility to interfere (course errors) with the adjacent frequency channel becomes of interest. The associated question of how much these components need to be attenuated to make interfering effects negligible needs to be considered integrally with the question of how to measure them in order to enable a satisfactory information exchange between the engineers concerned with both problems. Note the unbalance in 10 kHz subcarrier levels in the top-center display. This may indicate a need to neutralize the transmitter. This unbalance also appears in the top-left 30 Hz sidebands which are developed from the composite addition of the reference and variable patterns. While these are primarily frequency domain displays, an amplitude versus time (time domain) effect is seen as 30 Hz ripple on the main display envelope of the bottom left display. The cardioid pattern passing the analyzer antenna at 30 rps causes this amplitude fluctuation to produce 15 peaks per division as the trace scans at 0.5 sec/div (15 peaks/div ÷ .5 sec/div = 30 peaks/sec).

9.3.1 Modulation % Measurements with Spectrum Analyzer. In the 300 Hz BW upper left display of Figure 9-6 the carrier is augmented by the 30 Hz variable sidebands contributing energy within the bandpass of the analyzer. This -23 dBm level drops about 2.3 dB to -25.7 dBm in the center-left photo as the narrowed bandwidth (10 Hz) removes the 30 Hz sidebands from the carrier envelope. While overall amplitudes vary over a period of time from power fluctuation, antenna orientation/propagation effects, etc. the correction factor 2.28 dB should be subtracted from VOR carrier amplitudes when the analyzer bandwidth is not narrow enough to separate the sidebands from the envelope if relative amplitudes of components within the display are being interpreted. This 2.28 correction for DSB modulation is calculated as follows:

E_s



$E_s = .15$

$E_c = 1$

$$m = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} = .3$$ For 30% modulation

$$m = 2E_s/E_c \times 100\%$$

Where: E_c = carrier
E_s = sideband

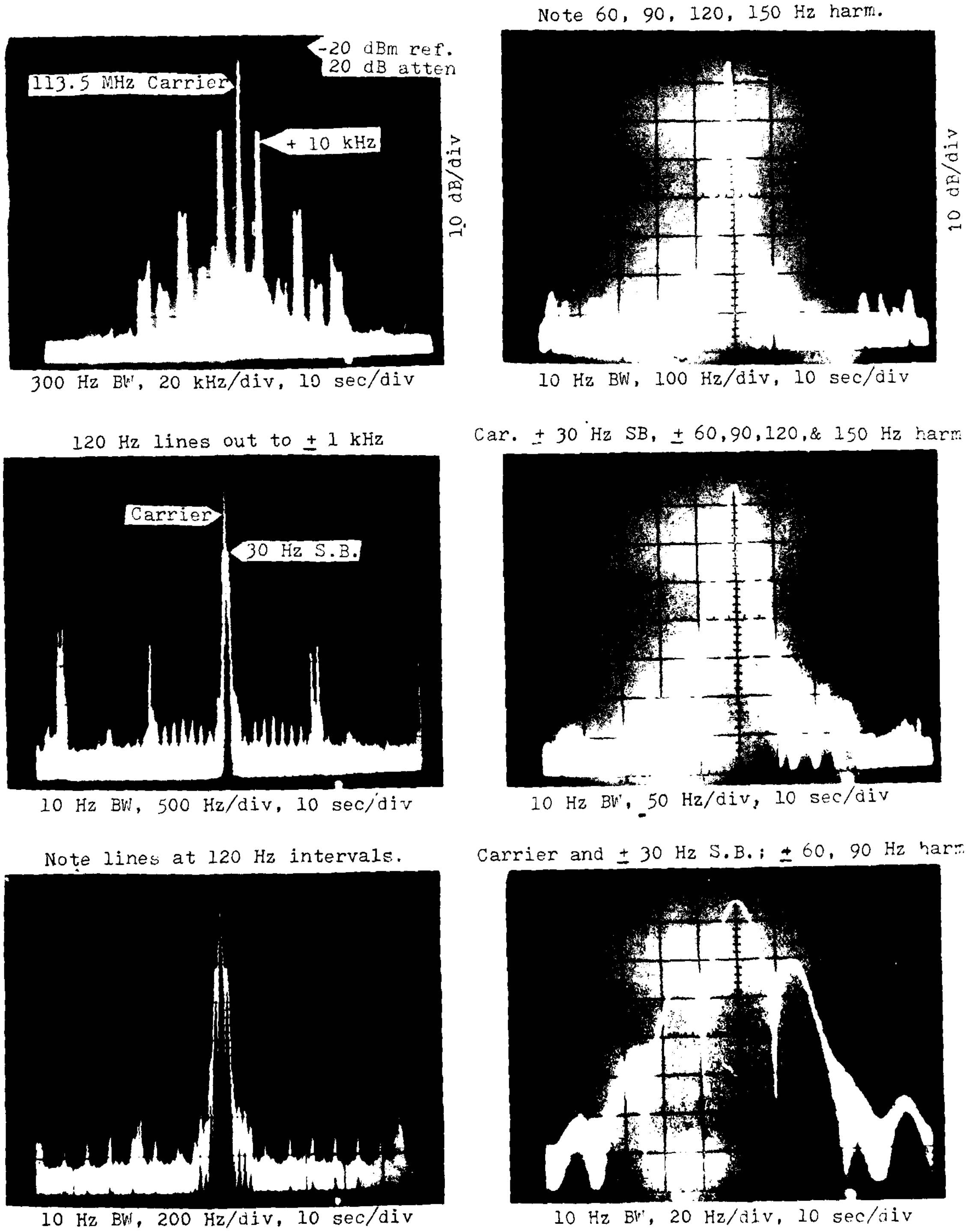


Figure 9-6 Conventional VOR spectrum with reference and variable sideband levels emphasized. The upper-left shows the ± 10 kHz subcarriers at -42 dBm (see Figure 9-9 for correction to -41.5 dBm.). See section 9.3.1 for decrease in carrier level with analyzer bandwidth, and carrier to sideband level differences. See section section 9.3.2 for 30 Hz harmonics. See 9.3.4 for analyzer drift effects.

For double sideband: $E_{max} = (E_c + 2E_s)$

$E_{min} = (E_c - 2E_s)$

Substituting and rearranging we get $E_s = 0.15$ where the carrier $E_c = 1$. The difference between the peak amplitude appearing on the screen with the 30 Hz sidebands contained in the carrier envelope ($E_c + 2E_s = 1.3$) and the carrier seen without sidebands ($E_c = 1$) when the analyzer resolution bandwidth is reduced to 10 Hz is:

$$\Delta E^+ \text{ (dB)} = 20 \log E_{max}/E_c = 20 \log 1.3/1 = 2.28 \text{ dB}$$

The instantaneous lowering of the carrier due to the sideband vector cancellation within the bandpass envelope is in the order of:

$$\Delta E^- \text{ (dB)} = 20 \log E_c/E_{min} = 20 \log 1/.7 = 3.1 \text{ dB}$$

The peak to peak ripple (E_{pp}) to be anticipated on the bandpass envelope enclosing the carrier and 30 Hz sidebands is then:

$$E_{pp} \text{ (dB)} = 20 \log E_{max}/E_{min} = 20 \log 1.3/.7 = 5.377 \text{ dB}$$

This variation brightens the trace over this vertical range in displays when the analyzer controls are set to distinguish it. This variation can appear to be more or less when imposed on non-linear mechanisms in the emission and display process.

The carrier plus sideband envelope amplitude then can vary as much as E_{pp} (5.377 dB) if the antenna array is assumed to be omnidirectional so that the variation in pattern amplitude is due primarily to the sideband RF feed from the goniometer. Inspection of the lower left photo in Figure 9-3 indicates that this pattern fluctuation approaches zero near the carrier frequency as seen with a 10 Hz bandpass (discussed in section 9.3.8).

This antenna pattern ripple (as much as 6 or 8 dB) is seen in Figure 9-9 (lower left display). Whether the maximum envelope magnitude (incorporating the 2.28 dB correction) is recorded depends on whether the pattern lobe passes the measurement location during the time interval that the carrier is within the sweeping analyzer bandpass. To ensure a good recording of the maximum amplitude, several pattern rotations should occur while the bandpass is in the carrier vicinity. For example, if it is desired to measure the percentage of modulation the 10 kHz sideband offers the carrier, an arbitrary 5 kHz/division dispersion and 1 kHz bandpass would put the carrier under the analyzer bandpass for 1/5 division. A 1 sec/div sweep rate would then keep the carrier in the bandpass for 1/5 second to expose the screen to 30/5 = 6 rotations of the pattern. If the sweep rate is increased to 0.1 sec/div the bandpass would only encounter 0.6 rotation of the ripple cycle and might record the minimum instead of the maximum (or something in between). This problem is illustrated with other control settings in the lower left (10 kHz BW, 20 kHz, 0.2 sec/div) display of Figure 9-9. One antenna maximum occurred as the scan passed the carrier frequency and the peak-to-peak somewhat exceeds the 5.4 dB calculated in this section (although interpretation of this in this photo is complicated by the rapid fall-off of the bandpass characteristic). If the scan rate were changed to 0.1 sec/div the ripples recorded per division would be halved and an antenna pattern maximum might not have been displayed. This likelihood increases as the bandwidth is narrowed, the sweep time is reduced, and the dispersion (freq/div) is increased.

The difference in carrier and sideband magnitudes for both the 30 Hz and 10 kHz subcarrier cases is of interest for display interpretation. For 30% modulation (double sideband) this is:

$$E_c - E_s \text{ (dB)} = 20 \log E_c/E_s = 20 \log 1/.15 = 16.478 \text{ dB}$$

however, the displayed difference with a 1 kHz bandpass (wide enough to faithfully report the 10 kHz amplitude) will be 16.478 + 2.28 = 18.758 dB because of the presence of the 30 Hz sidebands in the carrier envelope. See the close agreement in the 1 kHz BW displays of Figures 9-3, 9-9.

To measure the amplitude difference between the carrier and the 30 Hz sidebands the analyzer bandwidth must be narrowed to 10 Hz (or something appreciably less than 30 Hz) to separate these components so the 2.28 dB error will not be present in the carrier magnitude.

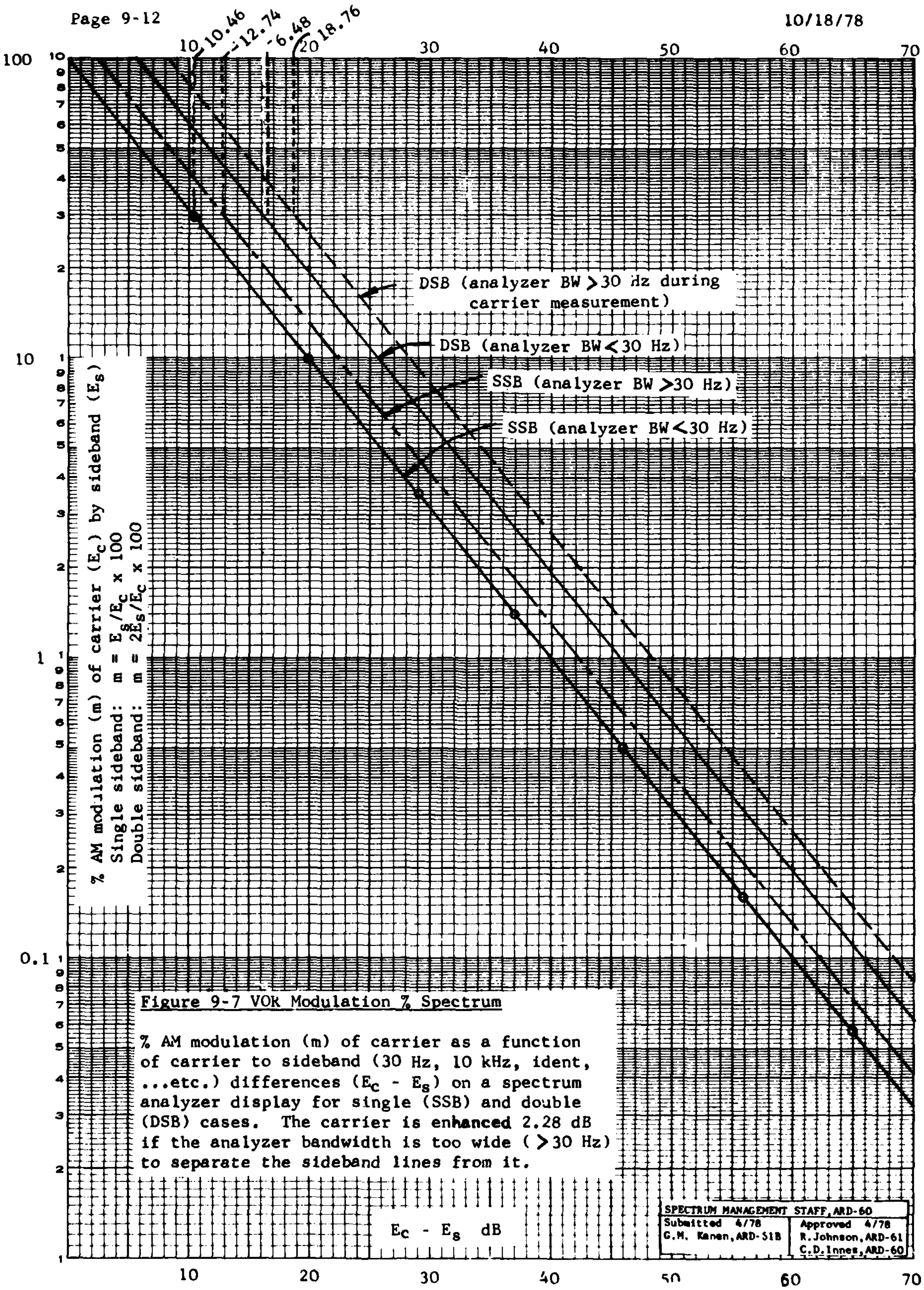


Figure 9-7 VOR Modulation % Spectrum

% AM modulation (m) of carrier as a function of carrier to sideband (30 Hz, 10 kHz, ident, ...etc.) differences ($E_c - E_s$) on a spectrum analyzer display for single (SSB) and double (DSB) cases. The carrier is enhanced 2.28 dB if the analyzer bandwidth is too wide (>30 Hz) to separate the sideband lines from it.

For <u>single sideband</u> as in the single sideband doppler (DVOR) E_s relative to E_c is determined as follows:

$$E_s = .3 \qquad m = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} = .3 \qquad \text{for 30\% modulation}$$

$$E_c = 1 \qquad \text{Where: } E_{max} = E_c + E_s,\ E_{min} = E_c - E_s$$

$$\text{Substituting we get: } E_s = mE_c = .3$$

The $E_c - E_s$ (dB) $= 20 \log E_c/E_s = 20 \log 1/.3 = 10.458$ dB

This 10.458 carrier to sideband difference will be displayed as (10.458 + 2.28) 12.738 for analyzer bandwidths too wide to separate the 30 Hz sidebands (such as the 1 kHz BW required to report the 10 kHz amplitude without correction). As in the double sideband case no correction for carrier amplitude will be necessary when the analyzer bandwidth has been narrowed sufficiently to separate the 30 Hz sidebands for modulation level comparison.

See Figure 9-7 for carrier and carrier plus sideband to sideband amplitude differences in the analyzer display as a function of modulation percentage for both the double and single sideband cases.

9.3.2 <u>Presence of 30 Hz harmonics in display</u>. The presence of 120 Hz lines is evident in the middle and lower displays in Figure 9-6 as well as the upper left. These are seen to originate near the carrier and increase out to about 600 Hz ± from the carrier and then decrease to disappear in the noise at about 1100 Hz. This type of display may prove useful to assist course error reduction efforts. See IMP 6790.4 Installation and Maintenance Handbooks (reference 4 and 5) for discussion of how 30, 60, and 120 Hz components produce duantal (1 positive and 1 negative excursion), quadrantal (4), and octantal (8) course errors, respectively. In general, if the 120 Hz components similar to those shown in the displays are sufficiently strong it may be expected to find octantal error on the facility. In the right hand displays 60, 90, 120, and 150 Hz products are evident. The 120 Hz is seen to be larger than the 90 or 150 Hz products and in the upper right multiples of 120 Hz decrease to a low at 240 Hz to begin the series discussed above for the middle-left display.

9.3.3 Voice and identification tones in spectrum. Voice emissions appear in the middle left display of Figure 9-6 at -2.2, 1.2, and 2.5 kHz, separated by 60 and 30 seconds scan time, respectively. The voice may show anywhere within the approximately ± 3 kHz emission bandwidth if the timing of the scan coincides with the voice transmission interval; whereas, the tone appears at the 1020 Hz locations when these are being traversed during identification intervals. In addition these audio voice and tone signals intermix and appear in the higher order harmonic emissions ± 20 or 40 kHz, for example, as shown in Figure 9-12 and 9-13 with augmenting discussion in section 9.3.1.

9.3.4 Spectrum analyzer (or other instrument) drift effects on displays. When the bandwidth and scan/division of the spectrum analyzer have been reduced to bring out details of components over a small frequency range it is necessary to increase the scan time in order to remain in calibration. At these greater scan time/division writing rates any appreciable drift of the analyzer oscillator causes a non-linear frequency display such as appears in the Figure 9-6 lower right-hand photo. To compensate for a display drift to the left, the carrier was manually tuned to the right of center so that by the time the single-sweep scan was initiated and had time to sweep 5 divisions at 10 seconds/division (50 seconds) the carrier had drifted to center the display. In the process the -30 Hz sideband was traced before it had time to drift the amount needed so it appears at -28 Hz (2 Hz high), and in turn, the upper +30 Hz sideband has had too much time and has drifted down to +28 Hz (2 Hz low) relative to the carrier. This non-linear frequency error occurs whether the signal is initially offset to compensate for the drift or not. When both the analyzer and signal are drifting a stable generator marker can be injected to assist analysis. In general, if the marker display is drifting but maintains a fixed offset from the signal the analyzer is at fault; whereas, if the marker display remains fixed on the screen and the signal is drifting the analyzer is stable. When both the analyzer and the signal being measured are drifting the operator must stay loose and work fast with the offset principle in order to obtain a centered display and not lose the signal in the process. A considerable loss in time occurs when the operator runs out of "fine tuning" range and has to broaden the frequency scan, bandwidth, disable the stabilizer, reset the "fine tuning" to center of range, re-tune the "coarse tuning" in order to find the signal and start the "gathering in" (re-bracketing) process. Re-tuning is required at each reduction of scan range and bandwidth combination, and care must be exercised not to move the "coarse tuning" control after the stabilizer circuit is a actuated Drift effects can be reduced by employing faster sweep rates and wider scan ranges as is seen in a comparison between the middle and lower left hand photos in Figure 9-3. When the writing speed is increased from 10 sec/ div to 0.5 sec/div (20 times as fast) the display error decreases by a factor of 20. The ± 30 Hz sidebands which were displayed at ± 28 Hz at 10 sec/division are then traced at ± 29.9 Hz with the 0.5 sec/division because of the drift error reduction to 2/20 Hz.

A further increase in writing speed at this frequency scan width and resolution bandwidth would present an uncalibrated display and therefore limits any further improvement by this method.. It is important to recognize these effects in the instrumentation so that the error is not attributed to the facility emission. The drift can be minimized by allowing adequate warm-up time, holding constant ambient temperature (opening and closing windows, cycling the heater or air conditioner, etc. aggravate the effect), and maintaining constant input voltage to the analyzer.

9.3.5 Bessel Function nulls as a function of Modulation Index in VOR 9960 FM sidebands. The amplitude distribution of the various FM sidebands (multiples of the 30 Hz baseband in the VOR case) on the 9960 Hz subcarrier are a function of the modulation index (m). The modulation index, m = deviation/baseband which is nominally 480/30 Hz = 16 for the VOR. The deviation in the rate at which frequency is generated results from a corresponding variation in the gap between the teeth of the tone wheel presented to the magnetic pickup furnishing the output. The 332 teeth in this tone wheel are rotating at 30 rps to produce an average frequency output of (332 x 30) 9960 Hz. The deviation (16 x 30) about this 9960 Hz center frequency is ± 480 Hz. This duration produces a bandwidth (2 x 480) of 960 Hz between 9480 and 10440 Hz. The Bessel function curves in Figure 9-8a were produced from Polynominal Approximations in section 9.4 of the National Bureau of Standards "Handbook of Mathematical Functions, 1964, edited by M. Abramowitz and I.A. Stegun. These were programmed on the Wang Calculator for sideband orders through 17 and modulation indices through 20. Three printouts separate the various traces to facilitate analytical efforts.

The 9960 Hz subcarrier in Figure 9-8b was obtained in linear rather than logarithmic mode to more easily see the relationship to the curve amplitudes of Figure 9-8a. The center line labeled J_o in the photo corresponds to the trace labeled "Carrier (J_o)" on the graph above. All the bessel lines appear positive in the photo after detection; however, the relative amplitudes correspond to positive and negative deflections in the graph above for a modulation index equal to 16. The sideband lines are numbered to left and right of center. The lower amplitude sidebands on the graph agree with pronounced nulls in the 9-8b presentation for J_1, J_3, J_5, J_8, J_{11}, J_{12}; whereas, J_2, J_4, J_6, J_7, J_9, J_{10}, J_{13}, J_{14}, J_{15} are quite high on both the photo and graph. The J_o, J_7, and J_{16} are about the same amplitude. The amplitude beyond the J_{16} line falls off steadily so that for practical purposes the 6 dB bandwidth (see upper right display in Figure 9-9 for logarithmic presentation) is contained within 2 x 480 Hz deviation = 960 Hz. This is seen to occupy about 4.8 divisions of the display at a scan rate of 200 Hz/division. The high amplitude grouping of J_{13}, J_{14}, and J_{15} produces the large spikes

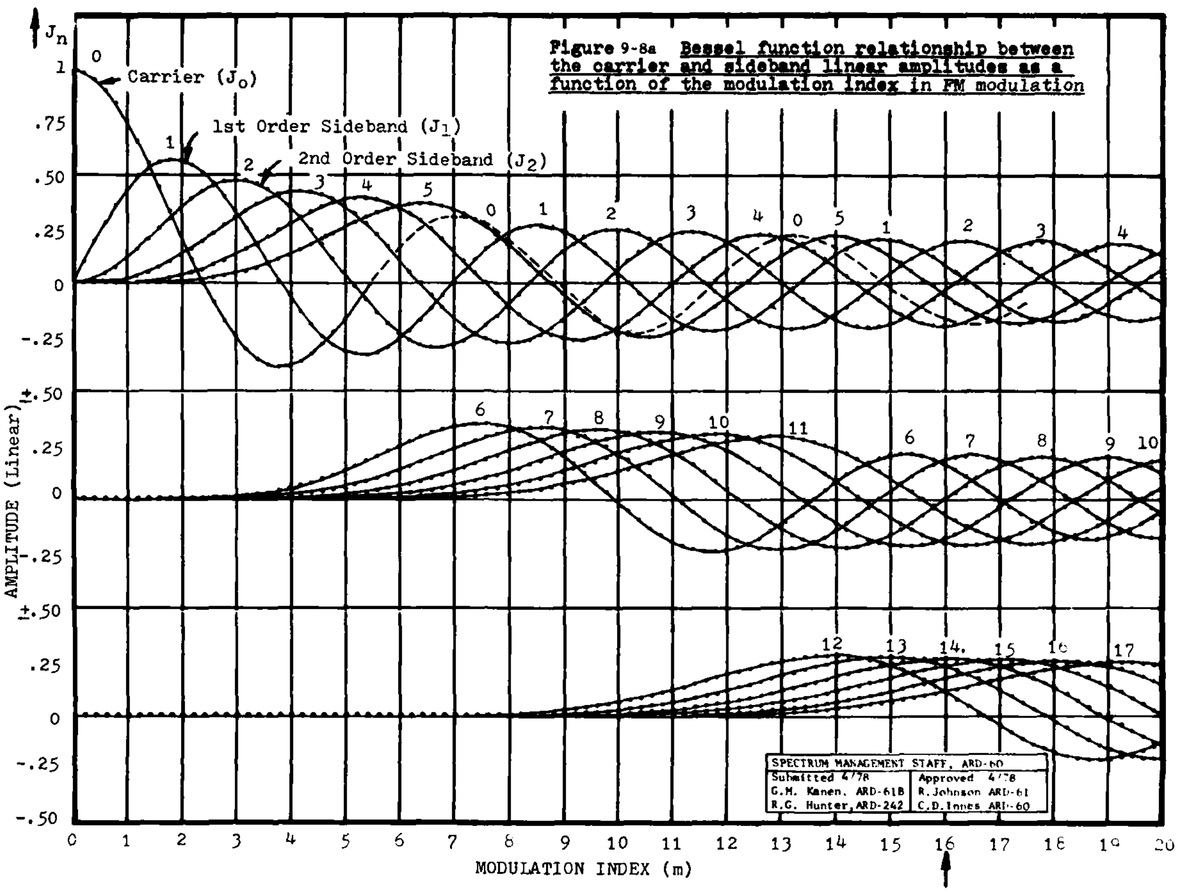
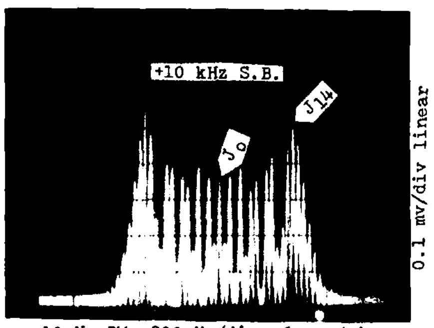


Figure 9-8a Bessel function relationship between the carrier and sideband linear amplitudes as a function of the modulation index in FM modulation



10 Hz BW, 200 Hz/div, 5 sec/div

Figure 9-8b Linear vertical display of the FM modulation on the VOR 9960 Hz subcarrier.

Negative excursions of the J_n curves above appear as positive lines after detection in the 9960 Hz FM spectra at left. Note the extremely deep null at J_8 correlation with the bessel number 8 sideorder (0 amplitude) above. The $J_{1,3,5,8,11}$ nulls are most useful in the establishment of m = 16; however, the J_{14} maximum is also seen to be in good agreement. The bandwidth between $\pm J_{17}$ lines ($\frac{1}{2}$ amplitude of J_{14}, 6 dB drop) is about 960 Hz...or twice the maximum deviation (2 m x 30 Hz = 2 x 480 Hz).

on the outer edges of the 9960 Hz component and its harmonics when the analyzer bandwidth is adequate to merge two or more lines simultaneously within the bandpass. These effects are discussed in sections 9.3.6 and 9.3.7 in connection with Figures 9-9 and 9-12, respectively.

9.3.6 Spectrum FM component amplitudes on a conventional VOR as a function of emission and analyzer bandwidths. The left-hand series of displays in Figure 9-9 indicate how the absolute and relative amplitudes of the signal components vary as a function of both the emission width and the analyzer bandpass used. The 10, 20, 30, 40, and 50 kHz components ± from the carrier are 1,2,3,4, and 5 kHz wide, respectively. The carrier is narrow band* and therefore does not vary in amplitude as the analyzer band pass is widened. The 10 kHz subcarrier amplitude display is seen to grow with analyzer bandpass widening as more FM 30 Hz sideband lines furnish energy to the trace deflection (right hand series in Figure 9-9). The individual lines spaced at 30 Hz intervals can be distinguished with the analyzer 10 Hz BW. As the bandwidth is widened to 30 Hz no longer can individual lines be distinguished. The amplitude of the outer peaks is seen to jump about 5.5 dB as two FM subcarrier lines are now contained in the bandpass simultaneously.

The J_{13}, J_{14}, J_{15} lines are like individual sine wave generators with outputs of the form E sin $(n)\omega t$ where $= 2\pi f$ and f = 30 Hz. The three sine waves then become E_{13} sin$13\omega t$, E_{14} sin $14\omega t$, and E_{15} sin$15\omega t$, and will be reasonably in phase (Figure 9-10c) from time to time while within the sweeping analyzer bandpass. The amplitudes from Figure 9-8b lower peak are E_{13} = .48, E_{14} = .55 and E_{15} = .47. Assume that J_{13} and J_{14} amplitudes are preserved in the nose of the bandpass, and that J_{15} is negligible because of excessive attenuation on the bandpass skirt. The amplitude jump as the analyzer is switched from 10 Hz BW (seeing J_{14}) to 30 Hz BW (seeing J_{13} and J_{14} added) is then:

$$E_{30-10}\ (\text{dB}) = 20 \log E_{30}/E_{10} = 20 \log (.55 + .48)/.55$$

$$= 5.45\ \text{dB}$$

*Exception is per section 9.3.1 when the analyzer bandwidth is narrowed to below 30 Hz. The carrier and 30 Hz sideband then look like broadband signal to the analyzer and the carrier amplitude drops 2.28 dB as only one signal at a time drives the amplifier.

Figure 9-9 Spectrum component amplitudes in a conventional VOR as a function of spectrum analyzer bandwidth. All displays were made with the same bi-connical antenna orientation at counterpoise height from a range of 100 yards. The vertical scales are all 10 dB/division. The top line reference level for all displays is -20 dBm (analyzer input attenuator is 20 dB so that a full scale reading is actually -40 dBm at the mixer to ensure linearity). An additional 10 dB is inserted at the Master Panel in the antenna line. In the overall VOR spectrum series on the left the 10, 20, 30, 40 and 50 kHz components ± from the center narrow-band carrier are 1, 2, 3, 4 and 5 kHz wide, respectively. It is observed that as the analyzer bandwidth approaches the emission bandwidth of the particular spectrum component of interest, a further increase in display amplitude is negligible with additional increase in analyzer bandwidth. For example, the 1 kHz wide upper 10 kHz sideband increase in amplitude as the analyzer is switched from 100 to 300 Hz and to 1 kHz has essentially stopped with the 1 kHz B.W. so that no noticeable change is seen when the instrument is widened to 3 kHz B.W.

The upper 10 kHz S.B. from the series on the left has been expanded in the series on the right to describe in more detail the mechanism involved in the amplitude growth with increasing analyzer bandwidth. At 10 Hz B.W. the individual FM Bessel frequency lines spaced at 30 Hz intervals can be distinguished. Note the low amplitudes of the $J_{1,3,5,8,11}$ lines and the high amplitude groupings of the $J_{13,14,15}$ lines about the midpoint which is characteristic of a modulation index = 16. In the 30 Hz BW display two lines are furnishing power to the response at any instant so the amplitude approaches $10 \log k(e_1^2 + e_2^2)^{\frac{1}{2}}$ with some allowance to analyzer response curve and produces an amplitude increase in the order of 6 dB. The 100 Hz B.W. display sees 3 lines to produce an amplitude in the order of $10 \log k(e_1^2 + e_2^2 + e_3^2)^{\frac{1}{2}}$ resulting in another increase of about 6 dB. Very little further increase results from changing the B.W. to 300 Hz because several low amplitude components are involved (also true of 1 kHz)

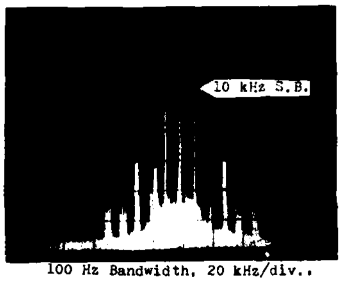
Shadowed trails in the 100 and 300 Hz BW displays result as the higher amplitude groupings evident in the 30 Hz BW display are encountered on the higher attenuation regions of the sweeping analyzer filter. The intensity increases as more lines fill the filter "nose" and then decreases as the analyzer sweeps past the midpoint to mirror the effect. The flat top evident in the 300 Hz and 1 kHz BW displays is the shape of the analyzer response curve seeing the average power of up to 34 lines simultaneously.

Voice identification emissions appear in the upper left display on the R.H. edge of the -20 kHz harmonic.

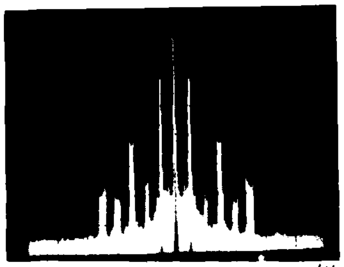
In the 300 Hz B.W. display on left it was possible to avoid voice emissions appearing every 30 seconds by increasing the sweep rate to 2 sec/div and still remain in amplitude calibration... (6 div x 2 sec/div = 12 seconds). During intervals when voice was present it was quite audible when passing through ± 20 kHz regions. In the 3 kHz BW configuration voice could be readily heard when the analyzer was sweeping through ± 40 kHz regions.

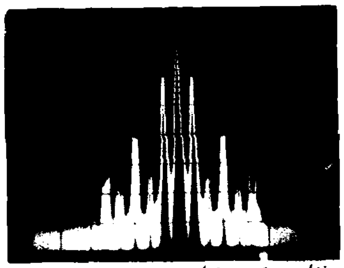
Note that the narrowband carrier in the left hand displays does not change amplitude as the analyzer bandwidth is increased except for a small amount in the bottom exposure where all components are contained within the bandpass.

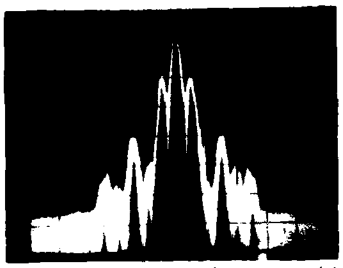
The 10 kHz B.W. encompasses all the components so the display approaches the shape of the analyzer bandpass characteristic. The envelope ripple is due to the passage of antenna pattern lobe at 30 Hz rate (6 peaks in 0.2 sec.).

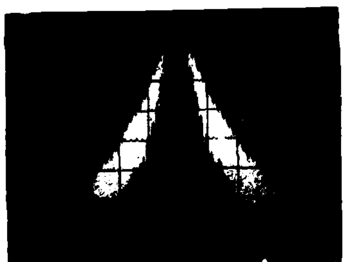


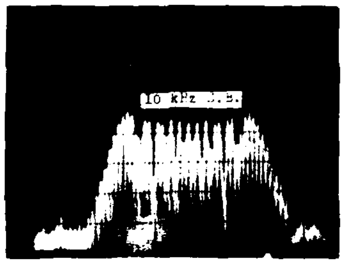
100 Hz Bandwidth, 20 kHz/div.,


300 Hz Bandwidth, 20 kHz/div., 2 sec/div.

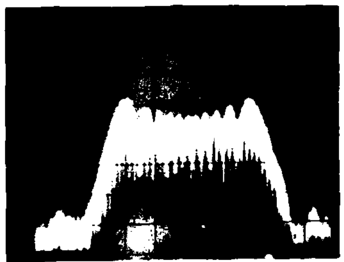

1 kHz Bandwidth, 20 kHz/div., 5 sec/div.

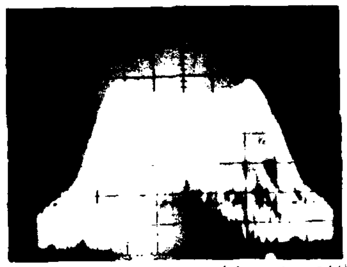

3 kHz Bandwidth, 20 kHz/div., 5 sec/div.


10 kHz Bandwidth, 20 kHz/div., 0.2 sec/div

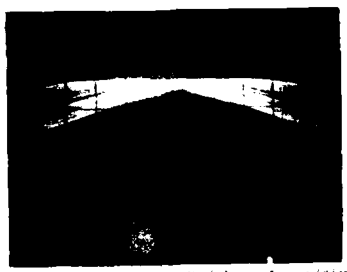


10 Hz Bandwidth, 200 Hz/div., 5 sec/div


30 Hz Bandwidth, 200 Hz/div., 5 sec/div


100 Hz Bandwidth, 200 Hz/div., 5 sec/div


300 Hz Bandwidth, 200 Hz/div., 5 sec/div


1 kHz Bandwidth, 200 Hz/div., 5 sec/div

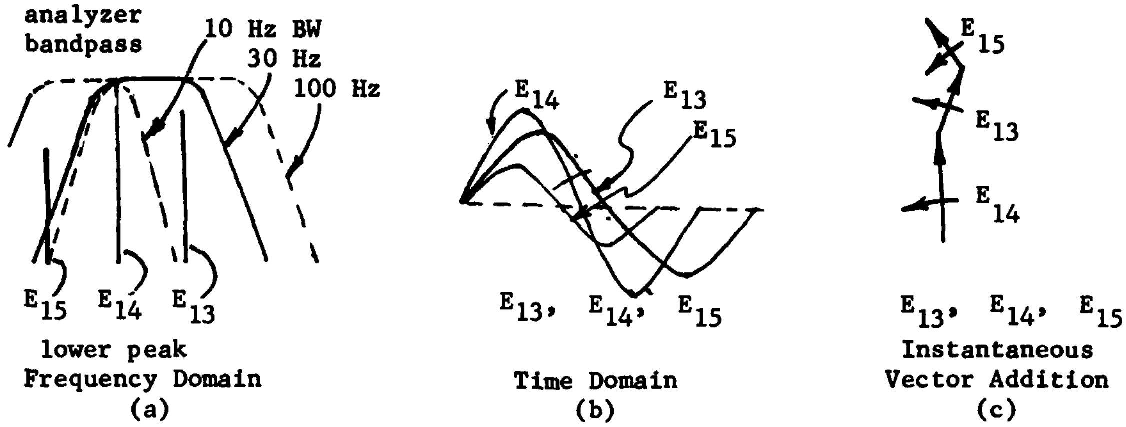


Figure 9-10 FM J_{13}, J_{14}, J_{15} sideband component instantaneous addition in the analyzer bandpass at the outer peaks of the 9960 emission envelope.

Note the variation in amplitude of the 11 peaks making up the Figure 9-9 right-hand 30 Hz BW display. This dip towards the center occurs because while the extreme peaks contain several J_n components, the next two pairs on either side only contain two of significant amplitude and the five center ones only contain one. The amplitude increase of the center region is relatively slight (2 dB) as the analyzer bandpass is widened from 10 to 30 Hz.

The vertical width of the trace results as the various sine wave vectors are in different states of cancellation and addition to produce the instantaneous deflection voltage over this range of amplitudes from moment to moment.

As the bandwidth is increased to 100 Hz these individual narrower line grouping peaks can no longer be separated and merge to form a valley between the two end peaks. The amplitude of the end peaks has increased another 6 dB as more lines appear simultaneously in the bandpass although the valley between the humps is maintained because the 100 Hz BW sees a line pattern with frequent nulls for about 600 Hz of sweep.

The peaks appear to have moved outward (apart) as the widened bandpass skirts furnish energy to maintain the peak amplitude farther off center frequency. These energy concentrations are lumped as evident in the 30 Hz BW display and produce the bright "trails" in the shadowed regions below the envelope in the 100, 300, and 1000 Hz BW displays as they are encountered by the lower regions of the bandpass. The narrowest analyzer bandwidth (10 Hz in this case) should be used to determine actual signal bandwidth.

The 300 Hz BW display has filled in the valley and widened the apparent emission bandwidth to the extent that the outer ends of the envelope are largely the shape of the analyzer bandpass rather than presenting the signal format. This effect is aggravated further as the bandpass is widened to 1 and 3 kHz. Finally, all the carrier, subcarrier and harmonics are lost in the 10 kHz lower-left display. This is predominantly the analyzer bandpass envelope to the extent that only the 30 Hz envelope ripple gives a hint that this is a VOR response as the antenna pattern rotates past at 30 rps. The ripple is detected by adjusting the sweep time rate to 0.2 sec/division since the effect is more time than spectrum derived.

It is observed that the peaks on either end of the 10 kHz FM display and its harmonics stop increasing significantly when the analyzer encompasses the higher amplitude line grouping beyond the J_{11} null; however, the center valley continues to build up to the peak level until the analyzer bandwidth approaches about one-third of the signal bandwidth. For this reason, the 50 kHz harmonic is believed to have essentially reached full amplitude in the 3 kHz BW display although it is absorbed in the 10 kHz BW display before establishing this. A plot of how the FM component amplitudes increase as a function of analyzer and signal bandwidths is contained in Figure 9-11. These curves have been developed from a combination of measurement data, Fourier analysis, and generous portions of draftsman's prerogative; however, they do support the operating observations stated earlier in this paragraph and are useful for establishing measurement procedures. For some empirically experienced reason most of the display amplitude has been achieved when the analyzer BW approaches 1/3 of the FM emission bandwidth 2(30 + 480) = 960 Hz or 300 Hz (nearest BW setting on the instrument used). However, 1 kHz may be the best compromise choice to describe the overall carrier, sidebands and harmonics.

Inspection of Figure 9-12 shows 30 Hz line spacing preserved in the higher ordered "harmonics." The number of these lines present in a particular component is proportional to the order of the harmonic. For example, the 30 kHz harmonic contains 3 times the number of 30 Hz spaced lines as contained in the 10 kHz sideband or 32 and 96, respectively. The lobe structure of the odd 30 and 50 kHz harmonics is well defined, whereas, the 20 and 40 Hz even harmonics contain much more distortion or noise.

The number of lobes on the 30 Hz BW pattern of the 10 kHz subcarrier in Figure 9-9 is multiplied by the harmonic number to produce the number contained in the various harmonics in Figure 9-12 ...i.e. ...the -30 kHz display has 3 x 11 = 33 lobes. The

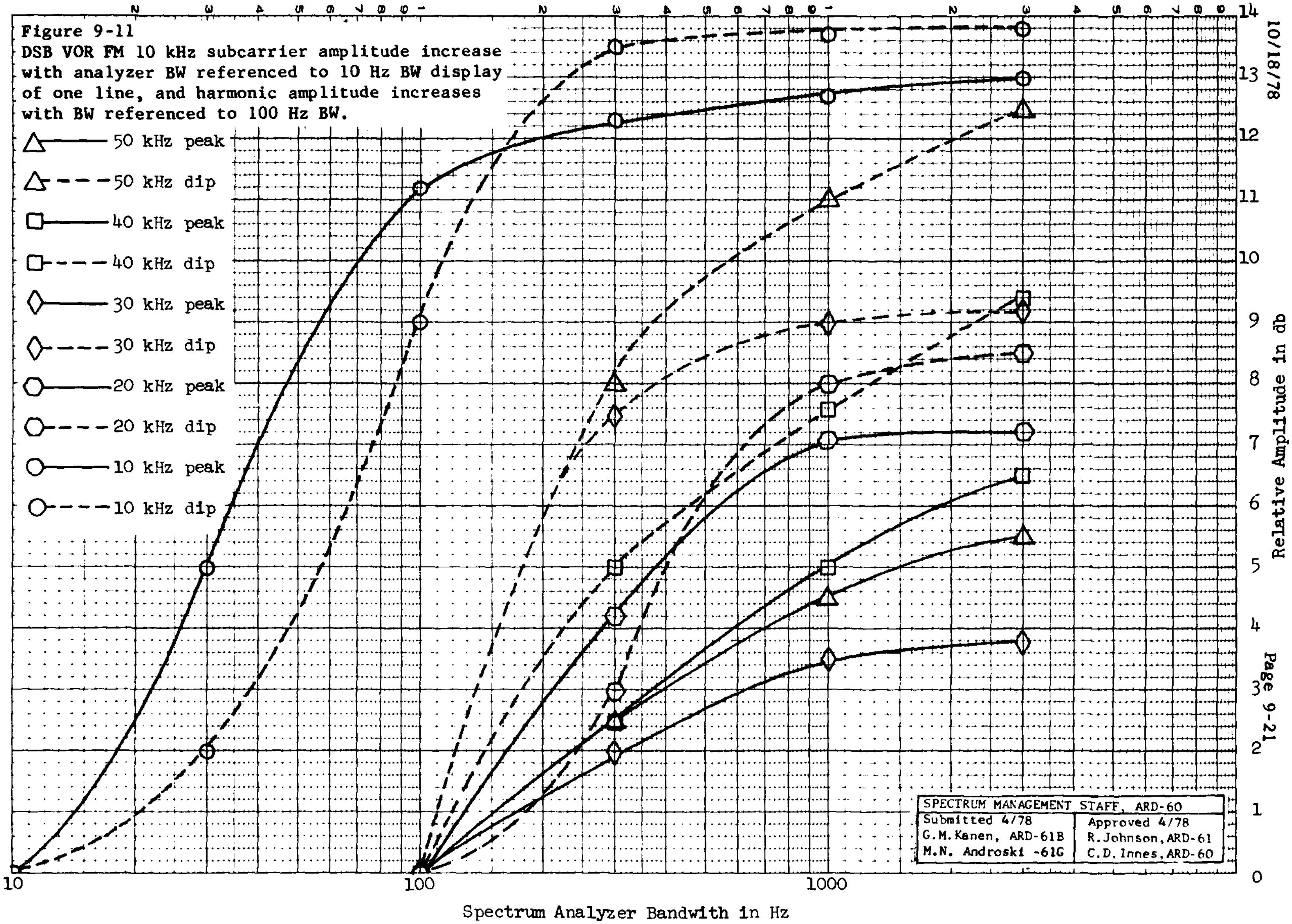
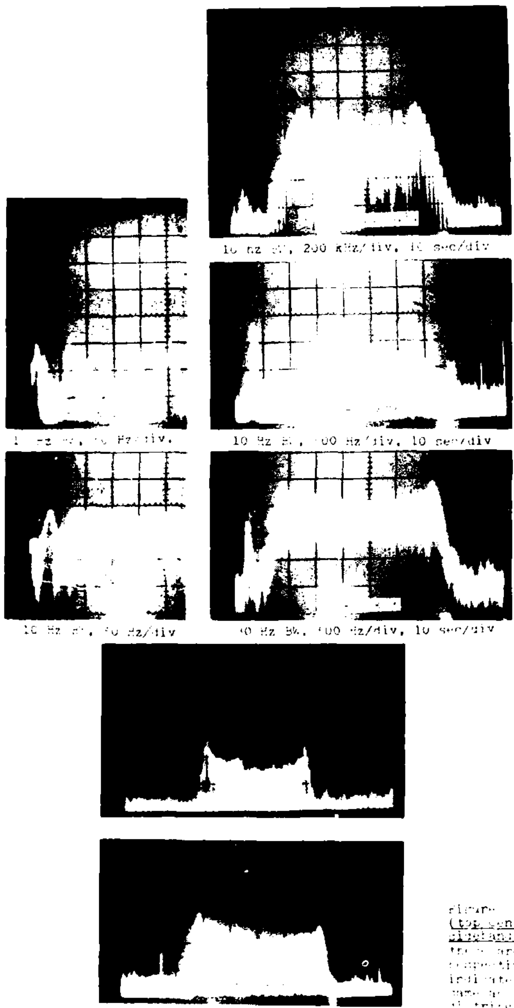
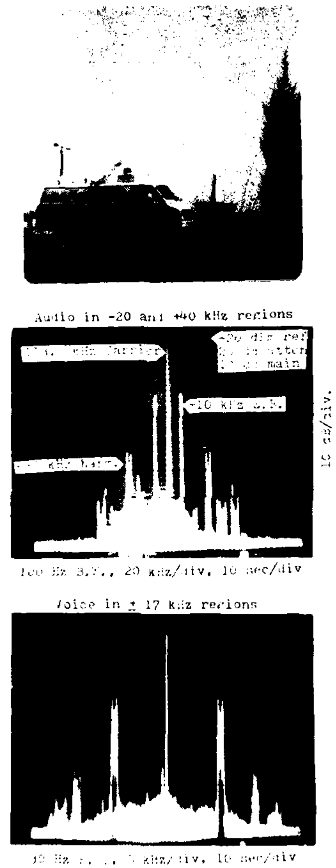


Figure 9-11
DSB VOR FM 10 kHz subcarrier amplitude increase with analyzer BW referenced to 10 Hz BW display of one line, and harmonic amplitude increases with BW referenced to 100 Hz BW.





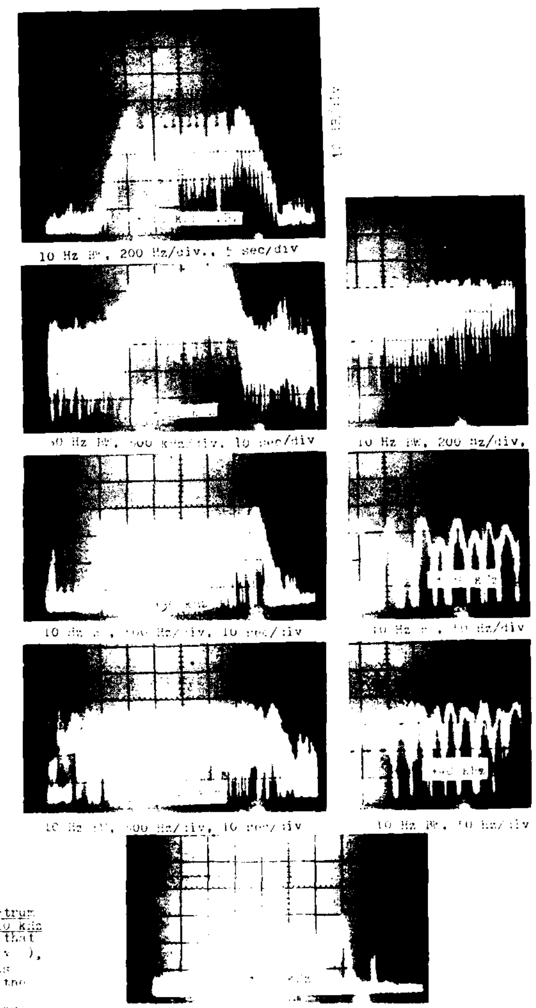


Figure [illegible] Conventional [illegible] ([illegible] kHz) overall spectrum (top center) expanded [illegible] to provide detail on the ± 10 kHz [illegible] and ± 20, 30, 40 and [illegible] kHz harmonic components. Note that there are about 1, 2, 3, [illegible] kHz [illegible] (± [illegible] x 1, 2, 3, 4 [illegible]), respectively. [illegible] further expansion of these harmonic components indicate that [illegible] at [illegible] intervals the same as the fundamental [illegible] the [illegible] amplitude distribution are not identical. [illegible] center [illegible] kHz/division display was obtained with [illegible] input attenuator settings on the spectrum analyzer [illegible] (full scale -40 dBm [illegible]). An additional [illegible] was [illegible] in line to the [illegible] antenna [illegible] all displays are 10 dB/vertical division. [illegible] amplitude [illegible] a function [illegible] that the ± [illegible] kHz [illegible] in that the left hand end of [illegible] than the right end. This [illegible] insight into the [illegible] created.

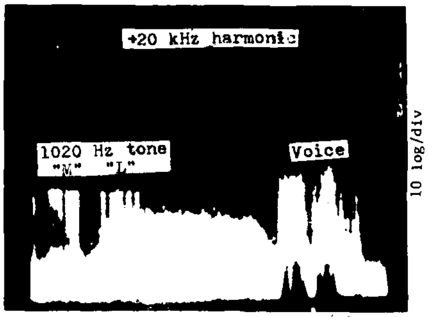
observation that the left hand peak (low frequency end) in both the ± harmonics is of greater magnitude than the right hand end is useful in determining the mechanism by which they are generated.

9.3.7 <u>Voice and 1020 Hz tone identification emissions in the 20, 30, 40, 50, etc. kHz harmonics on a conventional VOR.</u>

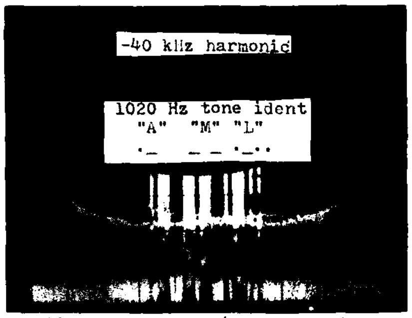
Voice and tone modulations occuring as the spectrum analyzer is sweeping in the vicinity of the harmonic frequencies are detected in both the display and audio outputs (See Figure 9-12) Either tone or voice amplitude modulations are initiated about every 10 seconds and have altered the - 20 and + 40 kHz harmonic displays markedly in the center photo (i.e...the +40 kHz appears greater than 5 kHz wide, the -20 kHz too wide, etc.).

Figure 9-13 expands the harmonics to show the voice and 1020 Hz tone identification intermixes. The sweep rate was adjusted appropriately to display the audio transmissions (for example, the 3 second duration tone ident would be displayed in 3 divisions out of 10 by selecting a 1 sec/div sweep rate). This audio display was positioned by actuating the single-sweep mode a proper interval before the modulations start (for example, in the upper photo of the -40 kHz harmonic series the sweep was started 3.3 seconds prior to the first character of the tone ident) in order to center the tone display. The tone amplitude is relatively constant over the frequency range displayed indicating that this is more a "time domain" (amplitude as a function of time) presentation (see section 9.3.8 for a further discussion on discerning or separating time and frequency effects). The even and odd numbered harmonics appear to the left and right sides of Figure 9-13, respectively to show the amplitude addition and subtraction impact of the audio on the spectrum envelope. In general the audio adds to the even numbered harmonics and subtracts from the odd numbered ones. In the -40 kHz series the identification tone AML (._ __ ._..) appears to be inserted in the bowl-shaped harmonic spectrum which is a "frequency domain" (amplitude as a function of frequency) display.

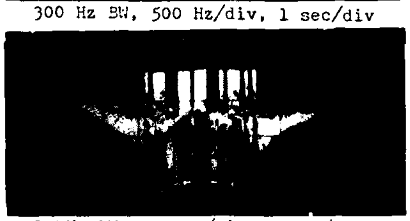
In the 300 Hz BW display of the -40 kHz harmonic the darkened end sections appearing like the wide open ends of a pipe elbow are essentially the bandpass response of the 300 Hz filter which darkens as one half sweeps beyond the emission envelope limit. This is seen to hold true as the bandpass was widened (3:1) to 1 kHz. The broadband "white" noise presents the bright "grass" threshold along the base. The darkened areas represent regions where no energy level exists for long enough to print at the intensity used. The uppermost bright areas represent the signal envelope where the rate of change of amplitude of the composite signal peaks is changing slowly enough to illuminate the screen. The darkened "V" at the center of the 1 kHz BW displays occurs as equal amounts of high energy are encountered in both bandpass "skirts" to maintain



300 Hz BW, 500 Hz/div, 1 sec/div

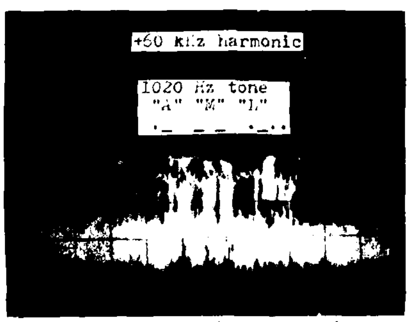


300 Hz BW, 500 Hz/div, 1 sec/div

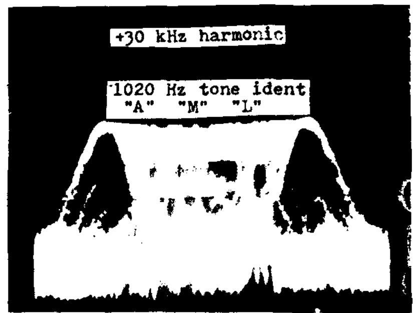


1 kHz BW, 500 Hz/div, 1 sec/div

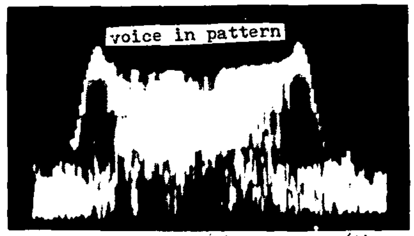
kHz BW, Hz/div, 0.5 sec/div



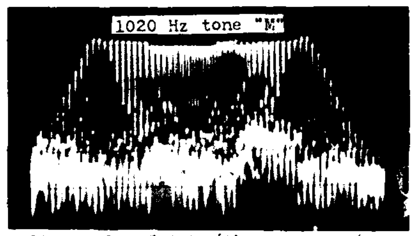
300 Hz BW, 1 kHz/div, 1 sec/div



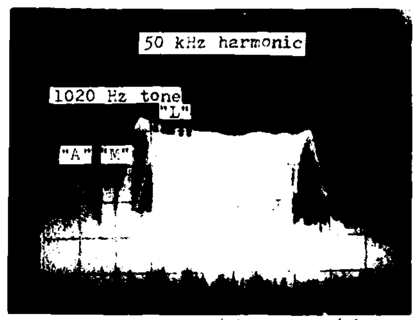
300 Hz BW, 500 Hz/div, 1 sec/div



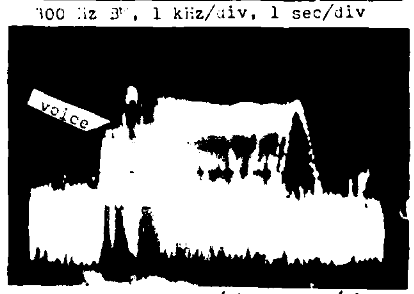
100 Hz BW, 500 Hz/div, 0.5 sec/div



300 Hz B 500 Hz/div, 0.2 sec/div



300 Hz BW, 1 kHz/div, 1 sec/div



300 Hz BW, 1 kHz/div, 1 sec/div

Figure 9-13 Voice and 1020 Hz tone in the 20, 30, 40, and 50 kHz harmonics of a conventional VOR emission spectrum. The interference is manifested in an amplitude increase in the even (20, 40, 60 kHz) harmonics; whereas a decrease in amplitude occurs on the odd harmonics.

the illumination threshold at its highest point. The composite (addition & subtraction) effects of the azimuth pattern and unmodulated tone carrier create the bright stripes in the darkened area between tone characters (dots and dashes); whereas, during tone modulation the bright upper limits of the envelope appear to be largely a function of the tone amplitude. The open bowl effect in the upper (300 Hz BW) -40 kHz display is created as the more slowly varying regions of the antenna pattern (max/min = 5 dB... ...see Figure 9-9, 10 kHz BW) passing 30 times per division combine with the composite energy contained within the bandpass at the particular sweep location, instant by instant, to record two distinct levels in the upper envelope. This combined time and frequency domain effect coupled with antenna pattern modulation is also very evident in the +60 kHz display. The rather noisy +20 kHz display indicates that the 1020 Hz tone amplitude appears relatively constant whether superimposed on the noise threshold or on the +20 kHz envelope. The difference in tone amplitude in the +20 kHz display and the voice which commences 4 seconds later is in the order of 5 or 6 dB. This harmonic mix tone/voice difference is not consistant with the 13.5 dB amplitude variation expected from the 6 and 30% modulations (see Figure 9-7) in the basic processes before the spurious generation.

It is evident in the right hand series of odd harmonic displays in Figure 9-13 that the phasing of the tone and voice carrier subtracts from the harmonic carriers in a manner to create a negative modulation effect on the spectrum envelope. In the upper 50 kHz harmonic photo the "A" and "M" appear positive with respect to the noise but the "L" appears to be a negative excursion as it is imposed on the harmonic envelope. The apparent 30 Hz lines are a time rather than frequency function as discussed in section 9.3.8 following.

9.3.8 <u>Distinguishing between time and frequency domain effects in spectrum displays.</u> A variation of bandwidth, dispersion, and sweep rate controls is used to distinguish whether lines in the display are due to frequency or time varying characteristic in the emissions being measured. For example in Figure 9-8 the bandwidth has been narrowed to 10 Hz to distinguish between FM spectrum lines 30 Hz apart. The number of lines appearing per division using a dispersion of 200 Hz/division is then 200/30=6.66. Similarly, in Figure 9 -12, a 10 Hz bandwidth has been used to examine a portion of the +30 kHz harmonic and the lines making up this emission are seen to occupy 30/50 of a division at 50 Hz/div dispersion. A further refinement for counting results from counting 10 peaks (10 x 30 = 300) in 6 divisions (6 x 50/div = 300). These lines are characteristic of a particular frequency modulation process so that the display amplitude is primarily a function of frequency. The $\pm$30 Hz AM variable signal spectrum lines evident in Figures 9-3, 9-6 result from the 30 cps rotation of the antenna variable pattern; however, the Figure 9-3 envelope ripple (15 peaks per division per 0.5 sec = 30 Hz) from this same antenna pattern source is a time domain function superimposed on the frequency domain presentation (lower left display). While this space modulated sideband pattern is developed by feeding carrier to the modulation bridge and goniometer the resulting effect in space (as seen by examining the amplitude ripple on the lower left display of Figure 9-3) is as if a negligible amount of carrier is contained in the rotating pattern. This conclusion is based on the antenna pattern ripple which is prevalent on the bandpass envelope in the vicinities of 30 Hz and its' 60, 90, etc. harmonics, but decreases in amplitude to approach zero (barely perceptible threshold) at the carrier frequency. The ripple amplitude is difficult to assess as it is contained on the bandpass slope; however, if the bandpass is broadened to 10 kHz to contain most of the higher energy lines of the emission as in Figure 9-9 (lower left) the peak-to-peak difference in antenna composite pattern gain is seen to be in the order of 5 or 6 dB (ref. section 9.3.1). The amplitude range of brilliance shading in the right-hand displays of Figure 9-9 are more a function of the vector addition range of values over the interval (see Figure 9-10) than due to fluctuation of antenna pattern level, because the 9960 Hz originates from the constant amplitude omni-directional reference portion of the emission (see Figure 9-4).

The relationship between the time interval (t) for a periodic waveform to complete a cycle and the frequency (f) of occurence is expressed by the relationship f = 1/t. In Figure 9-13 the lower photo in the +30 kHz harmonic series contains 6 lines per division or per 0.2 second which relates to (lines/div x 1/t/div = 6 x 1/.2) 30 Hz. To distinguish whether this is primarily a 30 Hz time or frequency product the frequency selective control and display aspects are investigated. The 300 Hz bandwidth used is not capable of separating spectrum lines spaced at 30 Hz intervals. It is further noted that at a dispersion of 500 Hz/div the six lines/division would be separated by 500/6 = 83.3 Hz which does not seem to be a meaningful or likely product of the VOR mechanisms. Changing the sweep rate further confirms the time dependant aspect as in the middle photo where 15 lines per division appear over an interval of 0.5 seconds indicating a 30 Hz characteristic. The number of spectrum lines (frequency dependant) per division will not vary with change of sweep rate (they are not a time function). Increasing the sweep time to 1 sec/div doubles the lines (30 lines/div...merge to appear continuous). The number of lines is proportional to the sweep rate if they are time dependant. Confusion can arrive when the analyzer controls are set to give conflicting results if the time and frequency analysis answers are in close agreement. If the operator expects to find 30 Hz spectrum lines (middle photo... 500 Hz/div) and miscounts the 15 time dependant lines (one line error) to get 500/30 = 16.6 lines/division he may draw the wrong conclusion. The likelihood of doing this increases with the difficulty of counting the lines as in the lower photo of the -40 kHz series where the lines are run together with the wider bandpass (1 kHz/100 Hz); however, it is realized that the 1 kHz bandwidth could not distinguish between spectrum lines separated by 30 Hz. These lines can be detected on top of the code characters. The prime contributor to time display effects in this discussion is the variation in signal resulting from the 30 cps rotation of the VOR antenna pattern. A brief inspection of the Figure 9-4 composite pattern sketch shows that the rate of change of signal amplitude is much less in the maximum and minimum gain regions (top and bottom as pictured) than the quadrature regions (sides). This characteristic intensifies the spectrum waveform during passage of the slowly changing level portions (when the intensity control is adjusted to distinguish these levels). This time varying amplitude in conjunction with frequency line variations enhances or creates unusual displays such as the bowl-shaped (2 level upper envelope) effect in the -40 kHz upper and the +60 kHz photos. Judicious manipulation of the analyzer controls as illustrated in the above examples can produce much added information about the emission provided that both operational and analytical procedures are employed to avoid false conclusions.

9.4 DOPPLER VOR (DVOR). The DVOR employs 50 Alford Loop antennas around the perimeter of a 44 foot diameter circle (see Fig. 9-14) to reduce reflection errors in adverse terrain environments. The AM and FM sideband roles are interchanged from the conventional VOR configuration so that the FM sideband contains the variable signal. The aircraft receiver FM detector "capture effect" then minimizes the impact of weaker reflected FM variable signal components containing course errors.

A distributor feeds the sideband antennas consecutively around the 44' circle 30 times per second. This cyclical variation in distance about the mean range between the center of the facility array and the aircraft produces a nominal $\pm$ 480 Hz Doppler shift with similar characteristics in space about the f_c + 9960 Hz carrier as are produced by the tone wheel FM modulation on the $\pm$ 9960 subcarrier sidebands in the conventional VOR. The carrier antenna in the center of the array is simultaneously radiating an RF signal from the higher powered carrier transmitter at a frequency, f_c. The heterodyning of these two signals in the receiver produces an effective 9960 Hz subcarrier deviated $\pm$ 480 Hz to provide a post-detection 30 Hz variable signal.

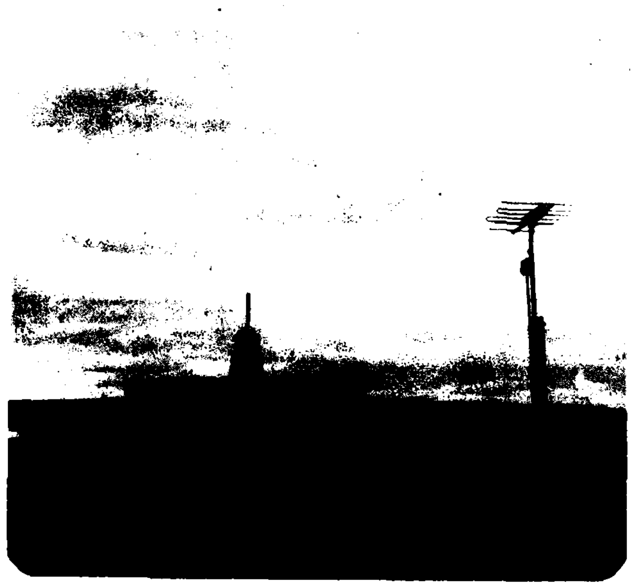
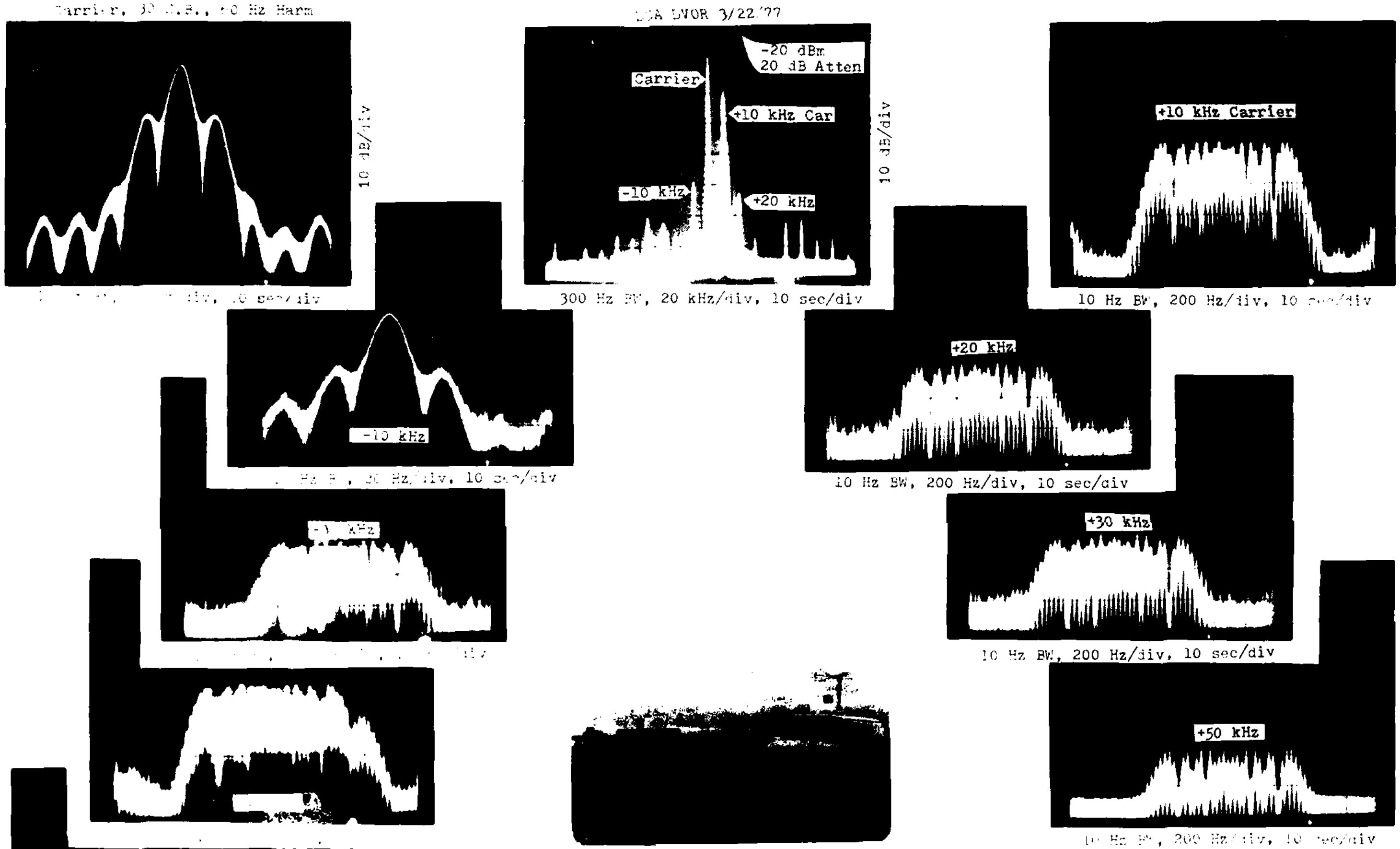


Figure 9-14. DVOR showing 44' diameter circle of 50 Alford Loop antennas above a 150' diameter counterpoise. The carrier loop is housed in the conical enclosure which is topped off with the DME antenna. The monitor antenna is in the right foreground.

9.4.1 DVOR spectrums. A typical DVOR spectrum as received in space is shown in Figure 9-15. Note in the center display that the transmitter driving the higher frequency carrier is adjusted to produce about 10.46 dB less power in space than the main carrier transmitter; however, a greater difference is seen on the spectrum analyzer (approaching 12.7 dB as covered in section 9.3.1 and Fig. 9-7) at bandwidths greater than 30 Hz.

Inspection of the upper left display indicates a carrier to 30 Hz sideband fixed-phase signal difference in excess of 16.48 dB because of the analyzer display problem just referenced above (see Fig. 9-7). Note the similarity to conventional VOR Fig. 9-3 upper left display.

The 10 kHz spaced side products are seen to be the same width in a DVOR emission instead of getting progressively wider as they



[illegible] V R ([illegible]) spectrum showing modulation details of the reference and +10 kHz variable [illegible] (intermod) components. The +10 kHz carrier is seen to be about 10.5 dB lower [illegible] carrier (see text). The +20, +30, +50, -30, -40, and -[illegible]0 kHz intermods are seen [illegible] with [illegible] tail structure as the +10 kHz carrier; however, the -10 kHz is seen [illegible] expanded displays) to have the same characteristic as the reference carrier... [illegible] indicates this is not typical of all [illegible] spectrums. The -20 and +40 kHz intermods [illegible] amplitude. The measurements were made at about 100 yards distance using a bi-connical [illegible] height. And additional 10 dB attenuation was in the line over that shown on [illegible] intensity calculations the reference shown (-[illegible] dBm) would be converted to [illegible] of the intermods employs 10 dB [illegible] vertical deflection was read, a linear output [illegible] in Figure depart from the carrier as characteristic of the VOR. This lends insight as to how they are produced and suggests that they might be more properly referred to as intermods than harmonics. These may be generated by the 9960 Hz reference voltage in the automatic frequency control (AFC) equipment. The normal D.C. voltage output to maintain the sideband transmitter exactly 9960 above the carrier picks up some undesirable RF and the resulting heterodyne of 9960 Hz "frequency" modulates the sideband transmitter. A number of "modulation products" spaced at 10 kHz intervals on either side of the carrier result which are single-tone or CW in nature before being space modulated by the distributor/antenna system. In space the modulation products appear with similar FM characteristics to those of the desired sideband carrier, namely $\pm$ 480 Hz.

In the conventional VOR a 9960 Hz tone is generated with $\pm$ 480 Hz FM modulation which is then amplified and plate modulated on the carrier transmitter. Non-linearities in the amplifiers and transmitter RF power amplifier cause true harmonics to be generated before being applied to the antenna system. These are symmetrically distributed about the carrier although improper transmitter neutralization can introduce some non-symmetry. Since these are true harmonics, the deviation on them increases with the harmonic number so that the second harmonic located 20 kHz above the carrier is twice as wide as the desired 10 kHz sideband (2x 2 x 480 = 1920 Hz, instead of 980 Hz BW), the third is deviated three times as much (3 x 480 = 1440, or 2 x 1440 = 2880 Hz BW), etc.

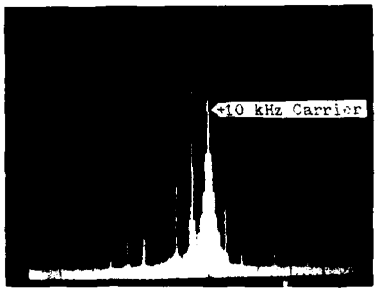
Since the output voltage of a slope detector is proportional to the amount of frequency deviation in the signal, the third harmonic of a conventional VOR could produce three times as much error as the third modulation product of a DVOR in the aircraft receiver.

Inspection of the +10 kHz carrier and the +20, +30, $\pm$50, -40, and -50 kHz intermods in Figure 9-15 shows the same bessel null structure and bandwidth.

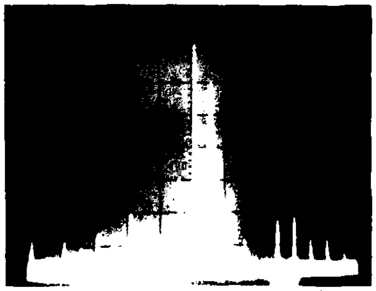
In Figure 9-15 the -20 and +40 kHz intermods are of negligible amplitude. Variations in intermod structure at different DVOR facilities is discussed in section 9.4.3.

9.4.2 <u>DVOR spectrum-component amplitudes as a function of spectrum analyzer BW</u>. Note in Figure 9-16 that the main (narrowband) carrier does not vary in amplitude as the analyzer BW is changed until the 10 kHz BW is reached (both xmtr powers are then driving the I.F. simultaneously). The relative amplitudes of the various intermods is preserved as the analyzer bandwidth exceeds 1 kHz, whereas the wider emissions in the conventional higher ordered harmonics continue to grow.

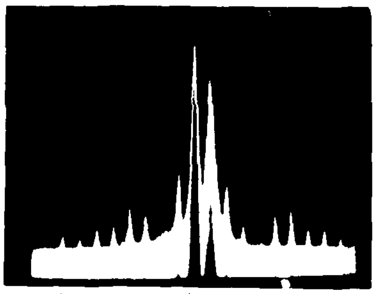
DCA DVOR



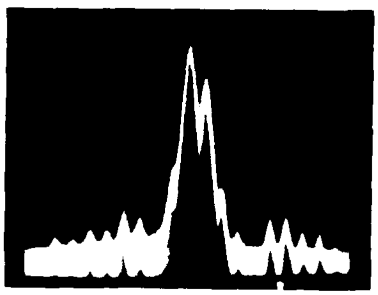
100 Hz BW, 20 kHz/div, 10 sec/div



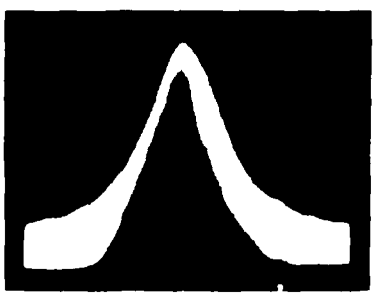
300 Hz BW, 20 kHz/div, 10 sec/div



1 kHz BW, 20 kHz/div, 10 sec/div



3 kHz BW, 20 kHz/div, 10 sec/div



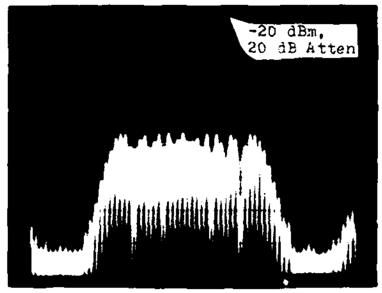
10 kHz BW, 20 kHz/div, 10 sec/div

Figure 9-16 Doppler VOR (DVOR) spectrum component amplitudes as a function of spectrum analyzer bandwidth. The narrowband reference carrier in the left series does not change amplitude with analyzer bandwidth until the 10 kHz BW display where the +10 kHz carrier is present within the bandpass simultaneously. (see text for increase calculation). The -10 kHz intermod is predominantly narrowband (see Figure 9-18 for detail); however it's amplitude does grow at a lesser rate with bandwidth due to other distortion. This will vary with characteristics of this -10 kHz intermod at different DVOR facilities. The amplitude jump of about 5 dB in switching from 100 Hz BW to 300 is more pronounced than in the conventional VOR because the Bessel nulls are not as emphasized (see right hand series for the + 10 kHz carrier)... although the same ± $J_{3,5,8,11}$ lines are attenuated. Note the swayback effect in Figure for the 100 Hz BW detail on the + 10 kHz carrier compared to the humpback (rise at mid-envelope) at center-right. In the left-hand series the + 10 kHz amplitude increases until the 1 kHz BW encompasses essentially all the significant lines (upper-right...about 34) and then shows relatively no increase as the BW is widened to 3 kHz...this is seen to be true for the various intermod components also since they are the same width (which differs from the conventional VOR case in Figure 9-9).

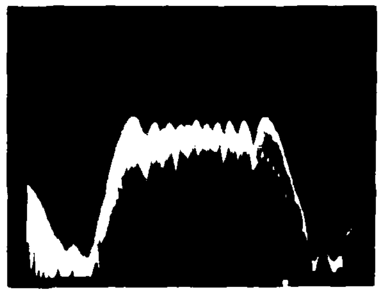
The shadowed trail structure evident in the 100 and 300 Hz BW displays to the right are formed as the line groupings (about 11) shown in the 30 Hz BW display are encountered by the higher attenuation regions of the analyzer bandpass "skirt" as it sweeps through the signal from left to right. In the left-hand series as the bandpass is widened to exceed the width of the emission the envelope becomes largely that of the analyzer filter being used. In the upper left the series of shoulders on the + 10 kHz carrier are formed by 1800 Hz (30 Hz commutator rps x 60 antennas) switching transients.

The intermods are seen to decrease in amplitude in an oscillating manner (like sin x/x) ...see Figure 9-17 for a comparison of spectra from a number of different DVOR sites.

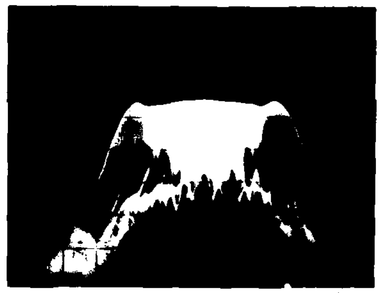
+10 kHz Carrier



10 Hz, 200 Hz/div, 10 sec/div



30 Hz BW, 200 Hz/div, 10 sec/div



100 Hz BW, 200 Hz/div, 10 sec/div

300 Hz BW, 200 Hz/div, 10 sec/div

1 kHz BW, 200 Hz/div, 10 sec/div

The amplitude jump of about 5 dB in switching from 100 to 300 Hz BW is more pronounced than in the conventional VOR because the Bessel nulls are not as pronounced. This also accounts for the center hump (Fig. 9-16, right-center) in the DVOR using 100 Hz bandwidth as compared with the sway-back in Figure 9-9 (right-center).

9.4.3 Differences in DVOR modulation product amplitude roll-offs at various facilities. The fall-off in amplitude of the modulation products at 10 kHz intervals varies from an orderly exponential type of decay as a function of frequency departure from the carriers at some facilities to an oscillating sinx/x type of roll-off about the sideband carrier at others. This is illustrated in Figure 9-17. The decay is rapid and non-oscillating in the top two displays. In the middle left a few intermods are distinct but decay rapidly with frequency. In the lower left and right displays the intermods are evident for more than 100 kHz departure from the 10 kHz sideband carrier and exhibit a sinx/x type of roll-off superimposed on the exponential decay envelope.

Changing transmitters on the Figure 9-17 lower-right facility had little effect on the radiated spectrum as shown in Figure 9-18; however, the output from facility "A" upper-right was altered noticeably by changing transmitters as indicated in Figure 9-19.

At several facilities the intermod 10 kHz below the main carrier was found to be decidedly narrowband (CW spike) compared to the intermods.

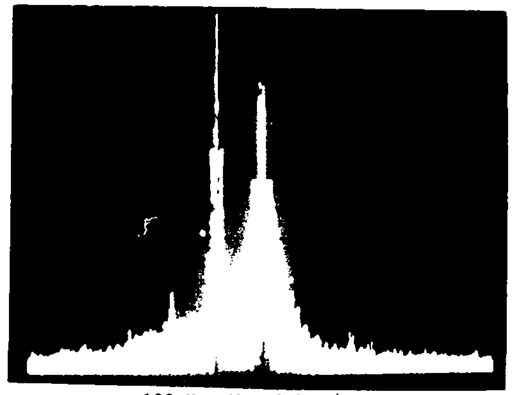
9.4.4 Switching transients. A switching transient is generated as the distributor couples by the gap feeding the 50 antennas 30 times per second producing a composite 1500 Hz pulse spectra. This is shown for the SEA facility in Figure 9-20.

In Figure 9-21 there is little difference in the radiated spectra when transmitters are switched with respect to the switching transients disposed about the C + 9960 carrier.

In Figure 9-22 the SMO DVOR switching transients produce spectra about the 9960 sideband carrier which are quite different from those at the facilities documented in Figures 9-20 and 9-21 all of which are extracted from the site displays in Figure 9-17. Note that the more "squared-off" switching displays for the SEA and DCA (Figure 9-23) correlate with the extended sinx/x roll-off of intermods in Figure 9-17. The SMO, ANN, and "A" switching displays are less squared (more dips and transcedental type of envelope) and relate to the rapid decay (more exponential) of intermods in Figure 9-17.

SMO

100 Hz BW, 10 kHz/Div

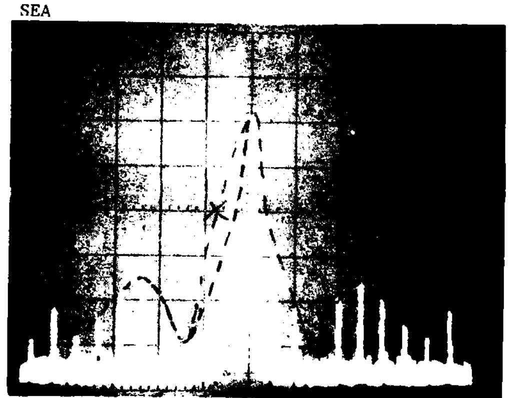


100 Hz BW, 10 kHz/Div

ANN

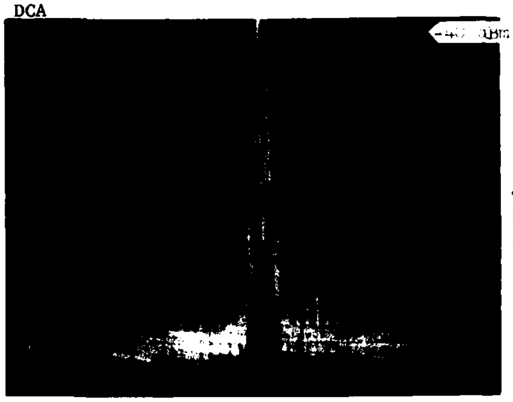
100 Hz BW, 10 kHz/Div

SEA



300 Hz BW, 20 kHz/Div

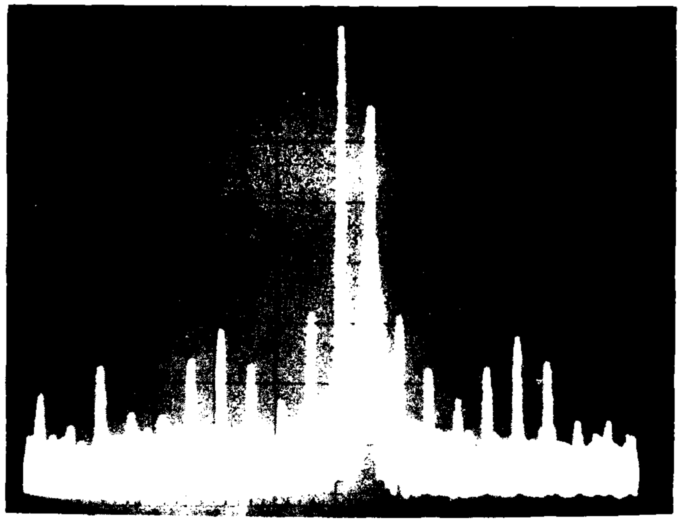
DCA



10 kHz/Div, 300 Hz IF BW, 100 Hz [illegible]

Figure 9-17 <u>DVOR carrier and sideband carrier with related intermod products distributed at 10 kHz intervals.</u> Note the correlation between the SMO and "A", rapid decay of intermod envelope and the hollowed out, 1500 Hz switching peak spectra in Figures 9-21 and 9-22. The sinx/x decay roll-off of the SEA and DCA facilities correlates with the more squared off (higher centered) switching peak spectra in Figures 9-20 and 9-23.

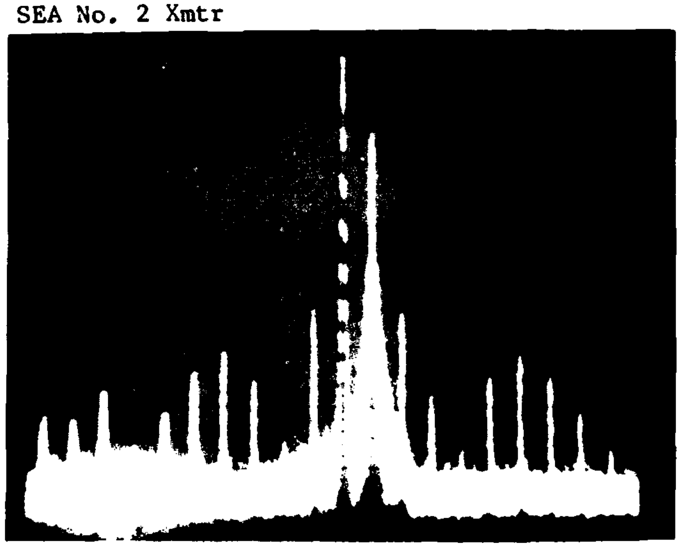
SEA No. 1 Xmtr.



300 Hz BW, 20 kHz/div

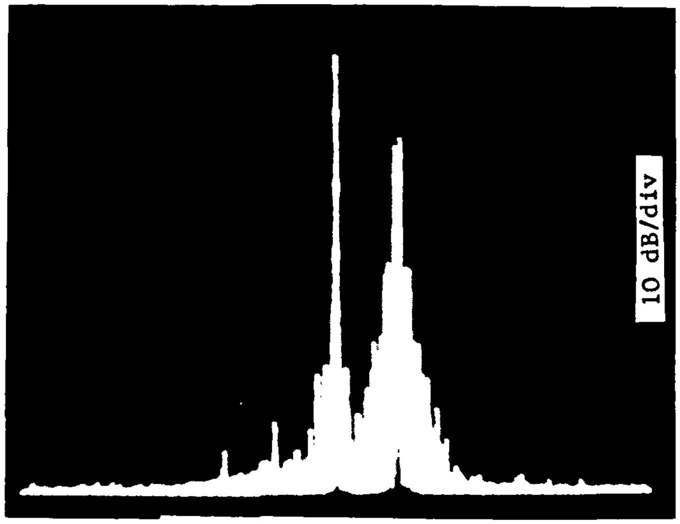
Figure 9-18 Comparison of number one and two transmitters at the SEA facility indicates little change in the radiated emissions.

SEA No. 2 Xmtr



300 Hz BW, 20 kHz/div

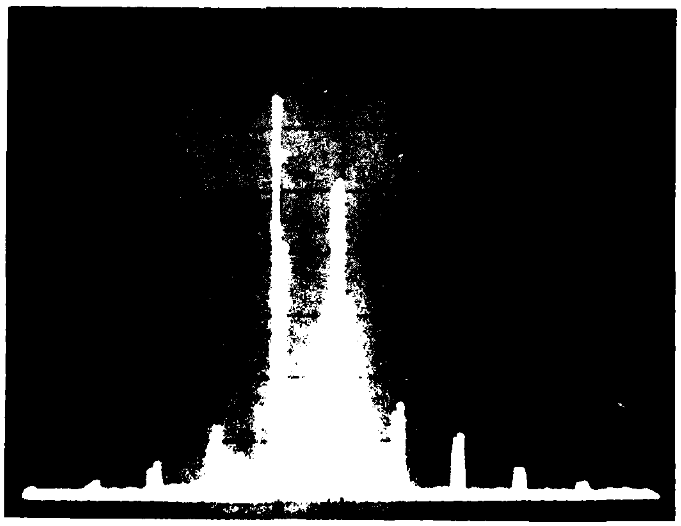
"A" No. 1 Xmtr.



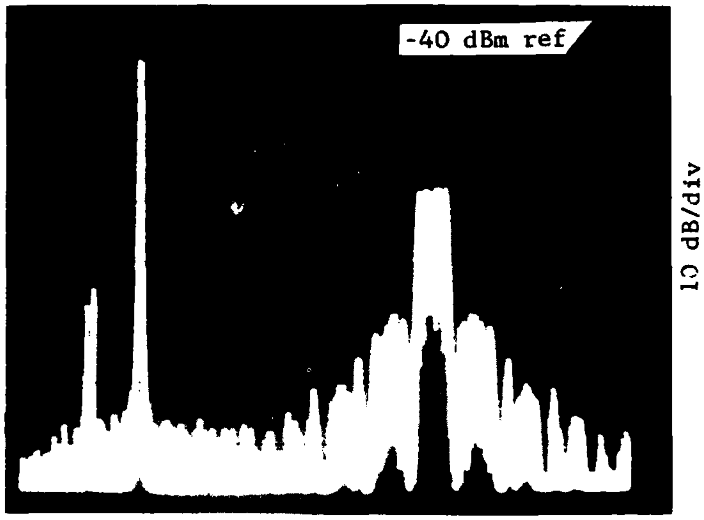
100 Hz BW, 10 kHz/div

Figure 9-19 Comparison of number one and two transmitters at Facility "A" indicates a significant difference in intermods.

"A" No. 2 Xmtr

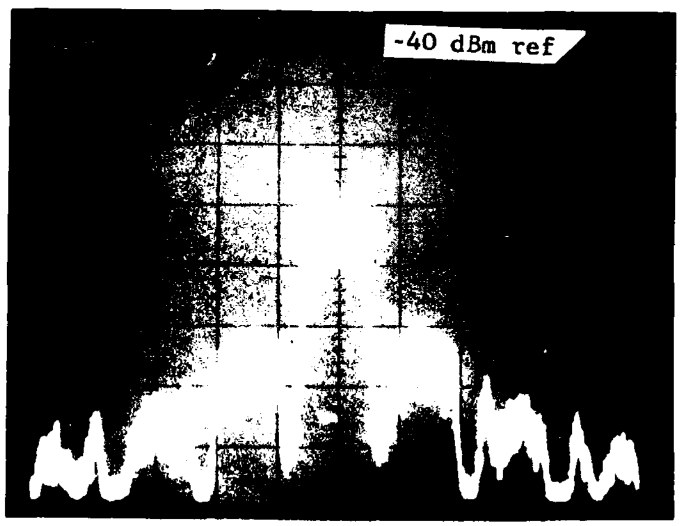


100 Hz BW, 10 kHz/div



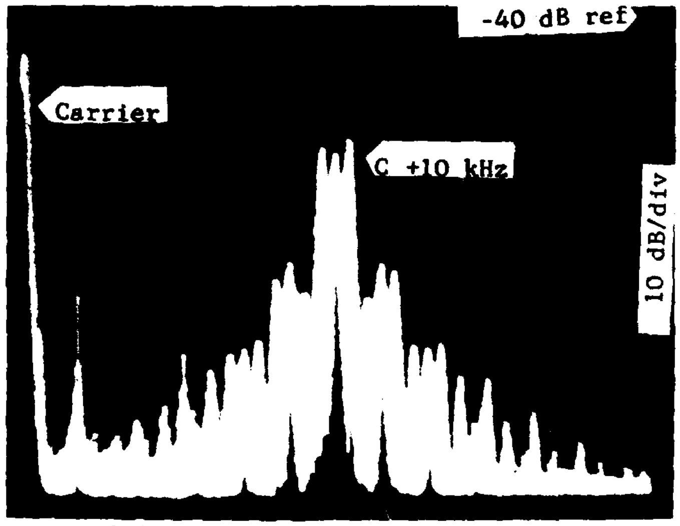
30 Hz BW, 2 kHz/div, 10 sec/div

Figure 9-20 SEA 1500 Hz switching transients on the 10 kHz variable signal carrier. The spike 2 kHz below the main carrier is probably voice occuring as the sweep moved past at 10 sec/div.



30 Hz BW, 1 kHz/div, 10 sec/div

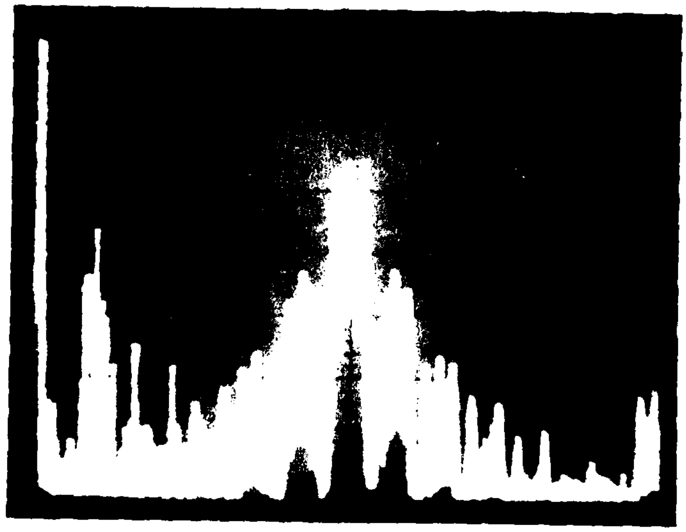
"A" No. 1 transmitter

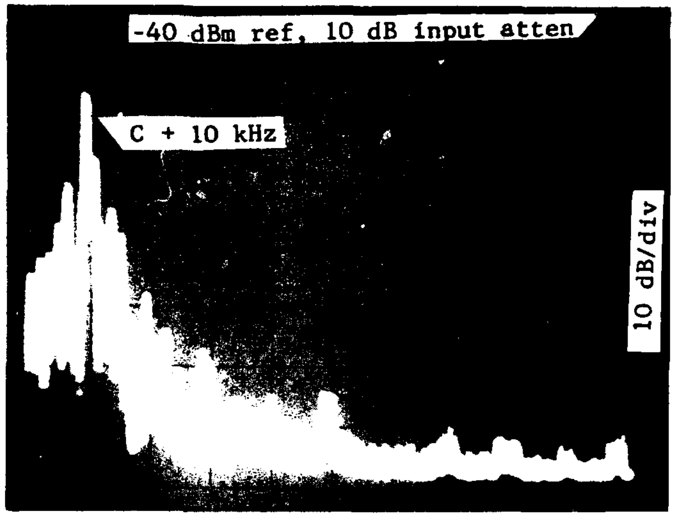


100 Hz BW, 2 kHz/div, 5 sec/div

Figure 9-21 Facility "A" 1500 Hz switching transients on the 10 kHz variable signal carrier indicate little difference between transmitters 1 and 2. Note the triple-peak ordered pattern compared to the flatter-noisier peak in Figure 9-20.

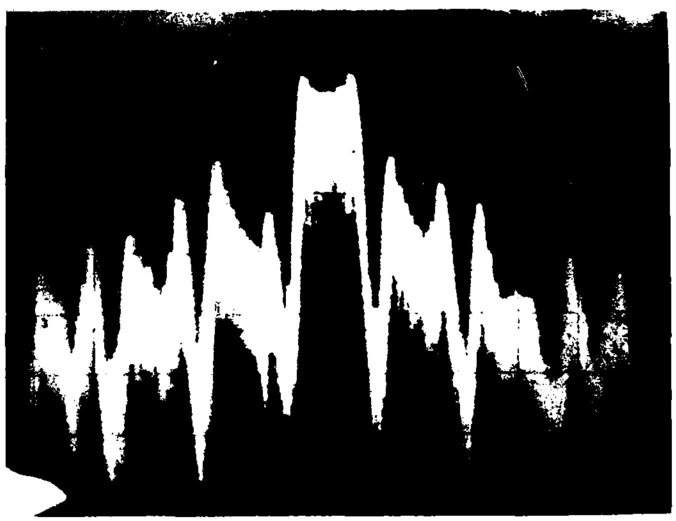
"A" No. 2 transmitter



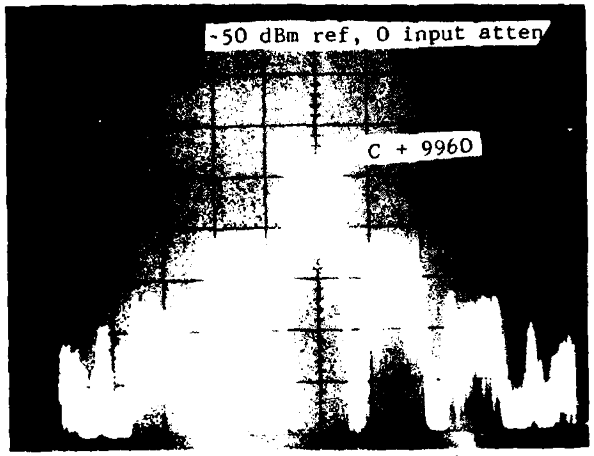


100 Hz BW, 5 kHz/div, 10 sec/div

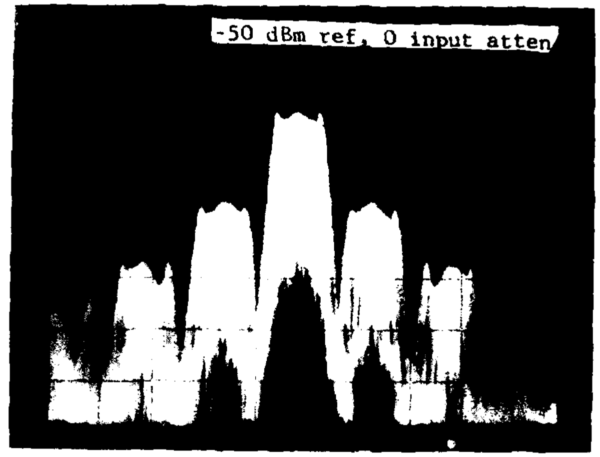
Figure 9-22. SMO DVOR 9960 Hz variable signal carrier 1500 Hz switching transients. The low amplitude center sections of each peak in the lower display correlates with the rapid decay of higher ordered (20, 30, 40 kHz...etc.) intermods in the upper display.



30 Hz BW, 1 kHz/div, 10 sec/div

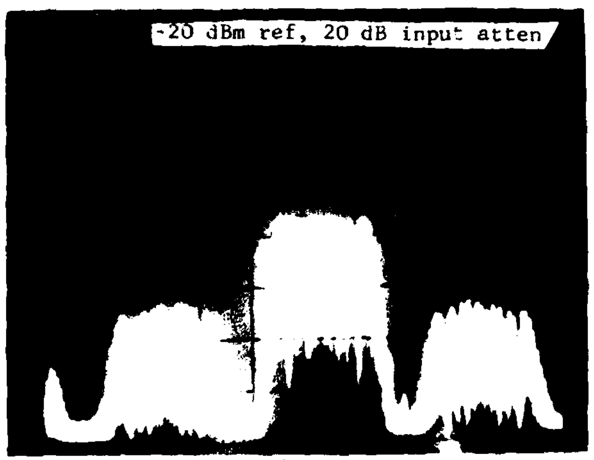


30 Hz BW, 1 kHz/div, 10 sec/div

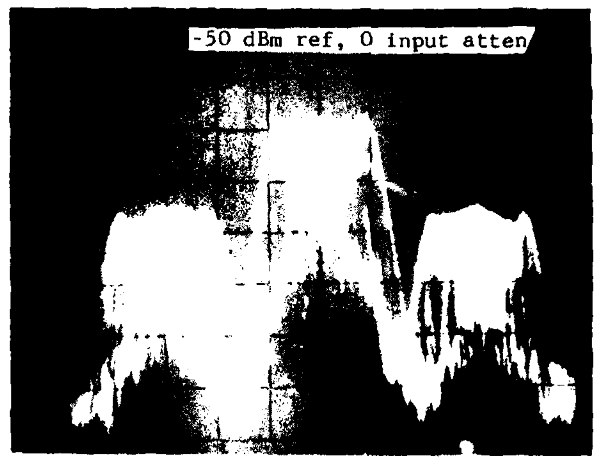


100 Hz BW, 1 kHz/div, 10 sec/div

Figure 9-23. DCA DVOR 1500 Hz switching spectra about the C + 9960 Hz carrier
Note how the high centered portion of the relatively squared peaks correlates with the sinx/x type roll-off of higher ordered intermods in Figure 9-17.



10 Hz BW, 500 Hz/div, 10 sec/div



100 Hz BW, 500 Hz/div, 5 sec/div

The shape of the 1500 Hz switching spectra is a function of the distributor pole gap shape, orientation, and spacing.

9.5 Spurious components in spectrum displays contributed by the measurement instrumentation. In section 9.2.2 considerations affecting valid spectrum measurements included mixer input levels, etc. to avoid generation of spurious components in the displays contributed by the instrumentation system. Figure 9-24 shows multiples of a conventional VOR emission spectrum repeated on either side of the desired signal. The problem appeared instantaneously, varied levels from time to time and cleared up alternately. The problem was a defective I.F. section in the analyzer which was permanently corrected with subsequent repair of the I.F. plug-in unit. In this situation the problem was not associated with poor operating technique; however, it is important to recognize an unusual display and determine that the VOR facility itself is not the source.

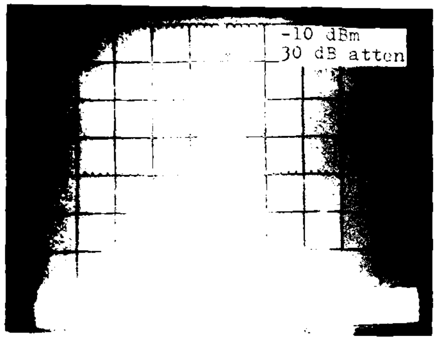
9.6 Optimum bandwidths for spectrum analyzer measurements of VOR and DVOR emissions. Annex 10 of the International Civil Aviation Organization (ICAO) paragraph 3.3.5.7 and the U.S. National Aviation Standard for the VORTAC system section 3.4.1.4 specify harmonic levels not to be exceeded with respect to the 9960 Hz component.

In the DVOR spectrum, the 9960 Hz spaced multiple products (20, 30, 40 kHz...etc.) are deviated the same amount as the FM sideband carrier so that the display amplitudes are correct as seen with a 1 kHz bandpass analyzer.

On conventional VOR spectrums a wider analyzer bandwidth such as 3 kHz could be selected, for example, to include the 2 and 3 kHz emission widths for correct display amplitude of the 20 and 30 kHz products, respectively; however, this would cause the 10 kHz FM component amplitude to appear too large if included in the same scan because of less rejection of carrier energy in the analyzer band-pass skirts. If the bandwidth is held constant at 1 kHz during a scan of all components in a conventional VOR spectrum, correction factors must be added to the display amplitudes of the wider deviation products to convey their true composite amplitudes. The magnitude of 30 Hz signal derived from slope detection of these 9960 multiple products on the selectivity skirt of a receiver tuned to the next adjacent channel is generally dependant on the amount of deviation. The approximate correction factors to be added to the analyzer 1 kHz bandwidth displays are indicated in Figure 9-11 for one facility widths of 2, 3, 4, and 5 kHz on the 20, 30, 40, and 50 kHz harmonics or multiple products, respectively, of the conventional VOR.

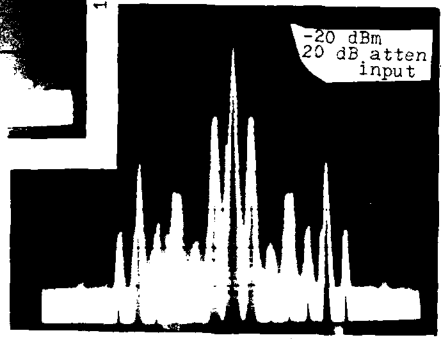
Inspection of Figure 9-11 indicates that a compromise BW choice of 1 kHz is beyond the knee of the relative change curves so that amplitude errors as a function of BW would be minimized.

Figure 9-24 VOR Spectrum with spurious components in the display generated in the analyzer IF unit. Note the lower amplitude spurious repetitions of the carrier and sidebands offset ± 50 kHz from the signal. A change of 10 dB input attenuation between the 11:56 and 11:59 displays for linearity check indicates corresponding changes in the input signal (but the lower amplitude components did not change as much, thus confirming that they are internally generated). A VOR signal above about -30 dBm at the mixer may begin to exhibit non-linear behavior in low amplitude components; however it is noted that the -27 dBm signal is only -47 dBm at the mixer because of the 20 dB input attenuation setting. The 11:59, 12:05 and 12:08 display varied without adjustment of analyzer settings. The spurious components made an abrupt rearrangement heard in the audio output of the analyzer between 12:05 and 12:08 displays. Shortly afterward the display cleared up by itself. The problem seems to be associated with the stabilizer circuit. Broadening the sweep, turning off the stabilizer, retuning, narrowing the sweep, turning on the stabilizer removes the spurious but causes the frequency to jump as the stabilizer is turned. A similar unit has been used over a period of years without this type of performance. A marked departure from the expected display is cause to question the measurement performance in the general case.



10 dB/div

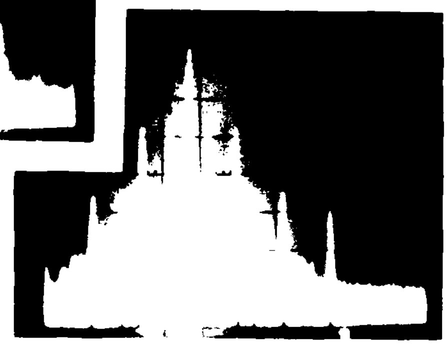
11:56



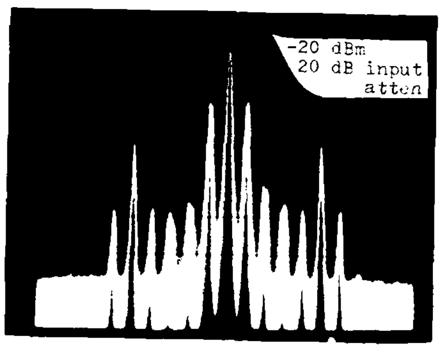
1 kHz BW, 20 kHz/div

11:59

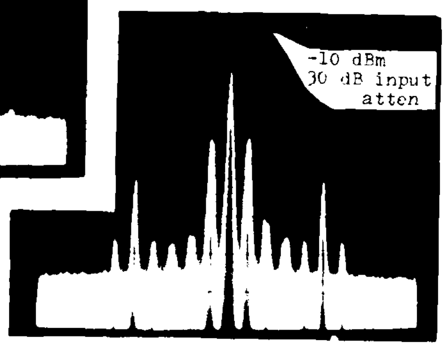
12:05



12:08



1:30



1:33

In the lower display the high amplitude spurious made a 10 dB change during linearity check similar to that of the signal; however, the lower amplitude spurious did not change linearly.

An alternate approach provides better signal detail but requires an analyzer bandwidth of 10 Hz or less to resolve the VOR 30 Hz sideband lines. The display of typical DVOR 9960 Hz FM carrier with 30 Hz detail may show 3rd, 5th, 8th, and 11th order sideband components of relatively low amplitudes which is characteristic of a modulation index equal to 16. High amplitude groupings are represented by sideband orders 13, 14, and 15, for example, which are about one-quarter of the unmodulated carrier amplitude as determined by reference to bessel functions (Figure 9-8). This indicates that these amplitudes as seen in a 10 Hz analyzer display would produce a 1 kHz bandwidth display about 12 dB (20 log 4) greater (in the order of 13 dB, empiricaly in Figure 9-11). A similar procedure may be used on any of the FM components noting that the modulation index and sideband orders will be greater for the 20, 30, 40, etc. products in the conventional VOR spectrum. The FM component display amplitudes do not experience uniform increases for similar bandwidth ratio changes. For example, a change in bandwidth from 10 (sees one sideband primarily) to 30 Hz (sees 3 sidebands with some rejection) results in amplitude changes as discussed in section 9.3.6 and Figure 9-11 (representative of one facility).

<u>Analyzer bandwidth compromise for relative amplitude display conclusions:</u> The choice of a 1 kHz bandwidth for VOR spectrum measurements enables the relative amplitudes of the desired AM and FM signal components to be displayed. While some compromise of detail is incurred, the use of narrower bandwidths requires appreciably greater correction factors. If this BW is not available on some analyzers inspection of Figure 9-11 indicates that greater BW choices in the order of 2 or 3 kHz would also be satisfactory.

9.7 <u>Importance of radiated spectrum measurements for analytical and adjustment purposes to assist installation, maintenance, and inspection of VOR, DVOR facilities</u>. Spectrum displays of the VOR emission as received by the analyzer antenna contain valuable system performance information. These displays contain significant detail for analyzing the performance of various parts of the system as for example:

1. Space modulation: Unbalance of 30 and 9960 Hz sideband components (Fig. 9-3 top), % modulation (section 9.3.1)...

2. 60, 90, 120 Hz hum (Fig. 9-6) contributions to duantal, quadrantal, octantal...errors. . This needs some flight work to determine levels which are significant.

3. FM deviation (Fig. 9-8).

4. Audio voice and tone in harmonics (Figure 9-13).

5. Harmonic and intermod levels (20, 30, 40, 50 kHz...products Figures 9-9, 9-11 VOR: Fig 9-16 DVOR).

6. DVOR 1500 Hz switch transient spectra (Fig. 9-20, 9-21, 9-22, 9-23) importance to distributor adjustments....

7. Attenuation of modulation products (harmonics, intermods) in exponential and sinx/x manner-(Fig. 9-3, 9-9) VOR,and DVOR (Fig. 9-16, 9-17, 9-18, 9-19).

Once irregularities are detected in the radiated spectra additional "hard-wired" connections within the system can be made with the analyzer to isolate problems.

A basic set of VOR radiated spectrum displays taken from specified locations would have value in basic facility records. Subsequent display samples could be taken remotely without disturbing the facility. Comparison of these with the site record set then gives insight into system performance and thereby assists as a guide for maintenance and flight inspection activities.

VOR REFERENCE PUBLICATIONS

1. FAA Advisory Circular No. AC:00-31, 6/10/70, U.S. National Aviation Standard for the VORTAC System.

2. International Standards and Recommended Practices, Aeronautical Telecommunications, Annex 10 to the Convention on International Civil Aviation (ICAO).

3. FAÅ Handbook 6050.5A* Frequency Management Engineering Principles, Geographical Separation Criteria for VOR, DME, TACAN, ILS, and VOR Frequency Assignments, 3/12/1969.

4. IM P 6790.4 Installation Instructions for VHF Omniranges, 7/1/63, FAA document.

5. FAA Order, 6790.4 Maintenance of VHF Omnirange Equipment, 28 October 1965, reprinted 10 Sep 71.

6. IM P 6790.5 Installation Instructions for Doppler VHF Omniranges, 1/15/64, FAA document.

7. FAA Handbook 6700.11 VOR/VORTAC SITING CRITERIA, August 7, 1968.

* This handbook has been revised. The updated document is currently being reviewed. Publication of Order 6050.5B is expected in early 1979.